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**KEY POINTS**

- Good evidence-based practice dictates that clinicians always quantitate the extent of neuromuscular block by objective monitoring.
- The neuromuscular block should be adjusted to ensure optimal surgical conditions. In most procedures, one or two responses to train-of-four (TOF) stimulation will suffice. To avoid involuntary diaphragmatic movements, a deeper level of neuromuscular block is required (i.e., one to five responses to post-tetanic count [PTC]).
- Adequate recovery of postoperative neuromuscular function cannot be guaranteed without objective neuromuscular monitoring.
- Objective neuromuscular monitoring is essential for management of neuromuscular blockade intraoperatively and its reversal for postoperative care. Muscle relaxants should not be given in the intensive care unit without proper monitoring.
- It is impossible to exclude with certainty clinically significant residual neuromuscular block by clinical evaluation of recovery of neuromuscular function.
- Residual postoperative neuromuscular block causes decreased chemoreceptor sensitivity to hypoxia, functional impairment of the pharyngeal and upper esophageal muscles, impaired ability to maintain an open upper airway, and an increased risk of hypoxic events, as well as the development of postoperative pulmonary complications.
- Absence of tactile fade in the response to TOF stimulation, tetanic stimulation, and double-burst stimulation does not exclude significant residual block.
- To exclude clinically significant residual neuromuscular block, the TOF ratio must exceed 0.9 when measured mechanically or electromyographically and 1.0 when measured acceleromyographically.
- Antagonism of the neuromuscular block with a cholinesterase inhibitor should not be initiated before at least two to four responses to TOF stimulation are observed.
- Antagonism of the neuromuscular block achieved by rocuronium and vecuronium can be initiated at all levels of block with the selective relaxant binding agent sugammadex.
- If adequate recovery (TOF  $\geq$ 0.9-1.0) has not been documented objectively at the end of the surgical procedure, the neuromuscular block should be antagonized.

Our understanding of the pathophysiologic consequences of residual paralysis has improved over the last decades, and it is now generally accepted that even small degrees of residual paralysis (i.e., a train-of-four [TOF] ratio 0.7-0.9) may be clinically harmful.<sup>1-4</sup> As a consequence, the benchmark of adequate neuromuscular recovery has been revised several times; an adductor pollicis TOF ratio of 0.9 or greater is now required to exclude relevant residual neuromuscular block (i.e., paralysis). Clinically significant residual paralysis cannot be excluded using clinical criteria and it can persist postoperatively.<sup>5,6</sup> Objective monitoring of the degree of neuromuscular block associated with pharmacologic reversal reduces the incidence of residual paralysis and should be part of standard perioperative monitoring when neuromuscular blocking agents (NMBAs) are used.<sup>7-13</sup>

In awake patients, muscle power can be evaluated by tests of voluntary muscle strength, but this is impossible during anesthesia and recovery from anesthesia. Historically, anesthesiologists have used clinical tests to assess muscle power directly and to estimate neuromuscular function indirectly (muscle tone; feel of the anesthesia bag

as an indirect measure of pulmonary compliance, tidal volume, and inspiratory force). All these tests are influenced by factors other than the degree of neuromuscular block and, therefore, should not be used to evaluate recovery from neuromuscular blockade. Whenever precise information regarding the status of neuromuscular functioning is desired, the response of muscle to nerve stimulation should be assessed. This procedure also takes into account the considerable variation in individual response and sensitivity to muscle relaxants.

This chapter reviews the basic principles of neuromuscular monitoring and the requirements for effective use of nerve stimulators for peripheral nerve stimulation. It also describes the response to nerve stimulation during depolarizing (phase I and phase II) and nondepolarizing neuromuscular block, provides information about the level of neuromuscular blockade, and discusses the consequences of residual paralysis. Moreover, methods of evaluating evoked neuromuscular responses with and without the availability of recording equipment are discussed.

## Principles of Peripheral Nerve Stimulation

Neuromuscular monitoring is used to evaluate the effect of a NMBA. The muscle response after stimulation of its corresponding motor nerve is assessed. The most frequently assessed nerve-muscle unit is the ulnar nerve and the adductor pollicis muscle. The muscle response can be evaluated either qualitatively with a peripheral nerve stimulator or quantified with objective monitors. With the peripheral nerve stimulator, the observer evaluates the muscle response either tactically or visually, whereas with the monitor the response is objectively measured and displayed on a screen. Whatever method is used for neuromuscular monitoring, the clinician should be familiar with the following terms: supramaximal stimulation, calibration, impedance, and safety margin.

### SUPRAMAXIMAL STIMULATION

The reaction of a single muscle fiber to a stimulus follows an all-or-none pattern. In contrast, the response (the force of contraction) of the whole muscle depends on the number of muscle fibers activated. If a nerve is stimulated with sufficient intensity, all fibers supplied by the nerve will react, and the maximum response will be triggered. After administration of a neuromuscular blocking drug, the response of the muscle decreases in parallel with the number of fibers blocked. The reduction in response during constant stimulation reflects the degree of neuromuscular block.

For the preceding principles to work, the stimulus must be truly maximal throughout the whole period of monitoring; therefore, the electrical stimulus applied is usually at least 15% to 20% greater than that necessary for a maximal response. For this reason, the stimulus is said to be supramaximal. This compensates for potential changes in skin resistance intraoperatively and assures constant maximal stimulation throughout the procedure.

However, supramaximal electrical stimulation can be painful, which is not a concern during anesthesia, but during recovery the patient may be awake enough to experience the discomfort of nerve stimulation. Therefore, some researchers advocate stimulation with submaximal current during recovery. Although several investigations indicate that testing of neuromuscular function can be reliably performed postoperatively with submaximal stimulation,<sup>14,15</sup> the accuracy of such monitoring is unacceptable with that low current.<sup>15</sup>

### CALIBRATION

A device used for objective monitoring of the neuromuscular function should be calibrated before the NMBA is administered. Calibration adjusts the gain of the device to ensure that the observed response to supramaximal stimulation is within the measurement window of the device and as close as possible to the “100% control response.” The calibration procedure varies with the type of device used, but most often it is done with 1.0 Hz single-twitch stimulation. It is especially important to calibrate when the onset and recovery of the neuromuscular block are established with single-twitch stimulation.

In the TOF mode of nerve stimulation, calibration is considered less important because all four responses are amplified equally. Consequently, the TOF ratio is rarely influenced by calibration; however, in patients with very weak or strong responses to nerve stimulation, one or more responses to TOF stimulation might be out of the recording window, and the displayed TOF response might be incorrect. In some devices, supramaximal stimulation is established concurrently with the calibration procedure.

### IMPEDANCE

An alternative and novel option to ensure a constant maximum stimulus throughout the whole procedure is to control the impedance (resistance) of the skin. Indeed, as long as the resistance of the skin is below a threshold value, the neuromuscular monitoring device will stimulate with the same user-selected electrical current (i.e., 60 mA). For a maximum current of 60 mA, the maximal resistance of the skin should be equal to or lower than 5 kΩ. If the resistance of the skin is above this value, the monitor will not be able to stimulate the patient with the selected current. More recently, nerve stimulators have been introduced that indicate the level of skin impedance on the screen (e.g., TofScan by iDMed, Marseille, France). Using this approach, establishment of supramaximal stimulation is not needed to assure that nerve stimulation is effective and constantly maximal through the whole procedure.

### SAFETY MARGIN

Neuromuscular transmission has a substantial margin of safety. Neuromuscular block only becomes evident when 70% to 80% of acetylcholine receptors at the neuromuscular endplate are occupied by nondepolarizing NMBDs and to produce complete block, 90% to 95% of receptors must be occupied. Thus, the currently available equipment and the currently applied stimulation patterns allow only insight to this 70% to 95% range of receptor occupancy. This should be kept in mind, especially during recovery of neuromuscular block, where 70% of the acetylcholine receptors at the neuromuscular endplate may still be occupied but no longer detectable with neuromuscular monitoring.

## Types of Peripheral Nerve Stimulation

Neuromuscular function is monitored by evaluating the muscular response to supramaximal stimulation of a peripheral motor nerve. Theoretically, two types of stimulation can be used: electrical and magnetic. Electrical nerve stimulation is by far the most commonly used method in clinical practice, and it is described in detail in this chapter. In theory, magnetic nerve stimulation has several advantages over electrical nerve stimulation.<sup>2,16</sup> It is less painful and does not require physical contact with the body; however, the equipment required is bulky and heavy, it cannot be used for TOF stimulation, and it is difficult to achieve supramaximal stimulation with this method. As a result, magnetic nerve stimulation is not used in clinical anesthesia.

## Basic Considerations

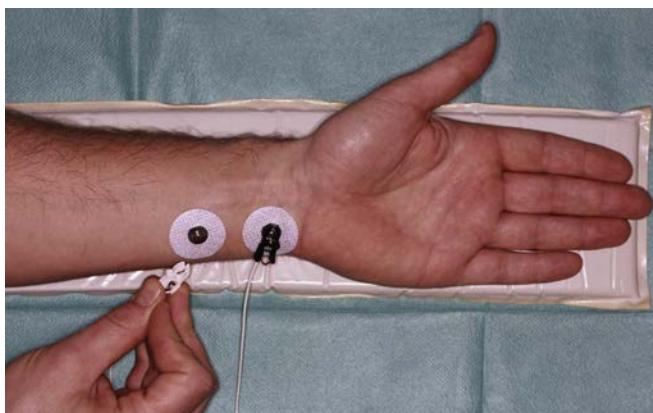
### STIMULATING ELECTRODES

Electrical impulses are transmitted from stimulator to nerve by means of surface or needle electrodes. Normally, disposable pre-gelled silver or silver chloride surface electrodes are used. The conducting area should be small, approximately 7 to 11 mm in diameter (Fig. 43.1). Otherwise, the current produced in the underlying nerve may not be adequate.<sup>17</sup> Ideally, the skin should be cleansed properly and preferably rubbed with an abrasive before application of the electrodes. When the selected current cannot be obtained with surface electrodes, needle electrodes can be used in a few exceptional cases. Although specially coated needle electrodes are commercially available, ordinary steel injection needles often suffice. A sterile technique should be used, and the needles should be placed subcutaneously to avoid direct injury to the underlying nerve.

### Sites of Nerve Stimulation and Different Muscle Responses

In principle, any superficially located peripheral motor nerve can be stimulated and the response to corresponding muscle measured. Choosing the site of neuromuscular monitoring depends on several factors: the site should be easily accessible during surgery, it should allow quantitative monitoring and finally, direct muscle stimulation should be avoided. Direct muscle stimulation is characterized by weak contractions without fade persisting even at a deep level of neuromuscular blockade. The risk is increased when the stimulation electrodes are directly attached over the muscle to be assessed. To prevent direct muscle stimulation, the nerve-muscle unit should be chosen so that the site of nerve stimulation and the site of the subsequent evaluation of the twitch response are topographically (anatomically) distinct.

In clinical anesthesia, the ulnar nerve is the gold standard as a stimulation site, but the median, posterior tibial, common peroneal, and facial nerves are also sometimes used. For stimulation of the ulnar nerve, the electrodes are best applied to the volar side of the wrist (see Fig. 43.1). The distal electrode should be placed approximately 1 cm proximal to the point at which the proximal flexion crease of the wrist crosses the radial side of the tendon to the flexor carpi ulnaris muscle. The proximal electrode should preferably be placed so that the distance between the centers of the two electrodes is 3 to 6 cm (see Fig. 43.1). With this placement of the electrodes, electrical stimulation normally elicits only finger flexion and thumb adduction. If one electrode is placed over the ulnar groove at the elbow, thumb adduction is often pronounced because of stimulation of the flexor carpi ulnaris muscle. When this latter placement of electrodes (sometimes preferred in small children) is used, the active negative electrode should be at the wrist to ensure maximal response. Polarity of the electrodes is less crucial when both electrodes are close to each other at the volar side of the wrist; however, placement of the negative electrode distally normally elicits the greatest neuromuscular response.<sup>18</sup> When the temporal branch of the facial



**Fig. 43.1** Stimulating electrodes with the appropriate contact area in the correct position over the ulnar nerve of the left forearm.

nerve is stimulated, the negative electrode should be placed over the nerve, and the positive electrode should be placed somewhere else over the forehead. When the posterior tibial nerve is stimulated, the electrodes should be placed close to the medial malleolus, with the same distance as described above and the negative electrode being placed distally.

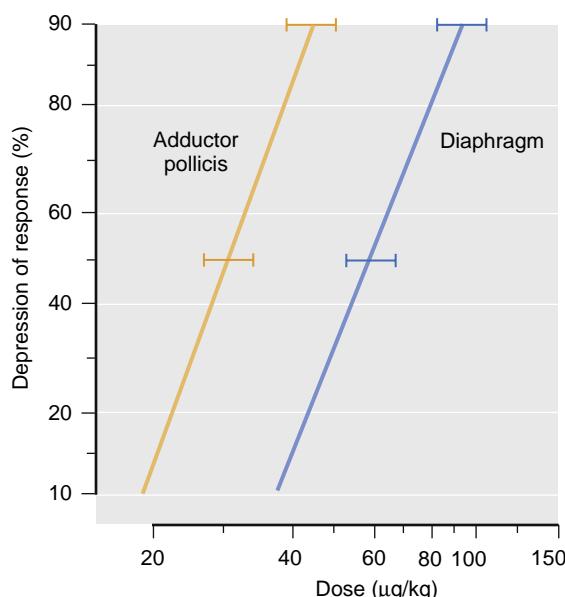
### NERVE-MUSCLE UNIT

Several nerve-muscle units may be chosen in clinical practice. Most often the ulnar nerve-adductor pollicis muscle is used.

**Ulnar nerve-adductor pollicis muscle:** This nerve-muscle unit is easily accessible intraoperatively if the arm is in the outstretched position and the hand in the supine position. The stimulatory response can be evaluated tactiley, visually, or by objective means. It has the lowest risk of direct muscle stimulation, because it ensures topographic separation of the stimulated nerve and the evaluated muscle by stimulating the ulnar nerve running along the median side of the arm and assessing the muscle response at the adductor pollicis muscle, which is indeed located on the lateral side of the hand.

**Posterior tibial nerve-flexor hallucis brevis muscle:** This nerve-muscle unit can be used for monitoring when the hands are inaccessible. The flexor hallucis brevis muscle produces flexion of the big toe following posterior tibial nerve stimulation. The characteristics (onset and recovery) of the neuromuscular block at the flexor hallucis brevis muscle is almost consistent with that of the adductor pollicis muscle.

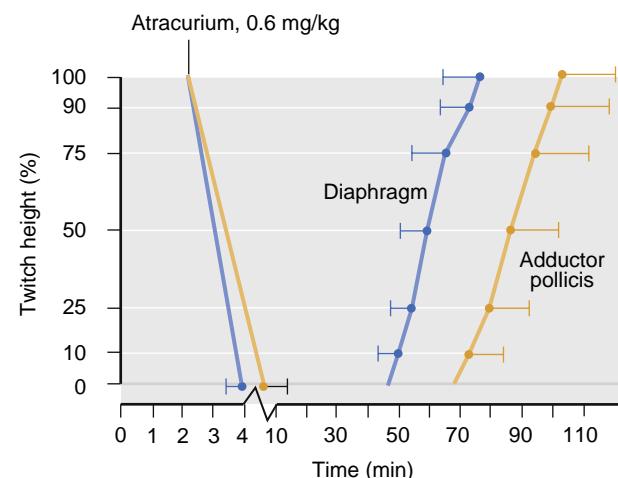
**Facial nerve-orbicularis oculi and facial nerve-corrugator supercilii muscle:** When the arms are tucked under surgical drapes, quite often the only accessible site for monitoring is the head. Two facial muscles can be used as monitoring sites: the orbicularis oculi muscle and the corrugator supercilii muscle. The former encircles the orbital opening; its stimulation through the zygomatic branches of the facial nerve causes the eyelids to close. Stimulation by the temporal branch of the facial nerve of the latter one draws the medial end of the eyebrow downward, producing wrinkling of the brow. However, because the facial nerve is in direct proximity to the intrinsic mimic muscles, the risk of direct muscle stimulation is significant. Therefore, care must be



**Fig. 43.2** The mean cumulative dose-response curve for pancuronium in two muscles shows that the diaphragm requires approximately twice as much pancuronium as the adductor pollicis muscle for the same amount of neuromuscular block. The depression in muscle response to the first stimulus in train-of-four nerve stimulation (probit scale) was plotted against dose (log scale). The force of contraction of the adductor pollicis was measured on a force-displacement transducer; response of the diaphragm was measured electromyographically. (From Donati F, Antzaka C, Bevan DR. Potency of pancuronium at the diaphragm and the adductor pollicis muscle in humans. *Anesthesiology*. 1986;65[1]:1-5.)

taken that the correct stimulatory response is assessed, and any other twitching muscle in the direct proximity of the stimulation electrodes is not falsely interpreted. Stimulation of the facial nerve can be accomplished with significantly lower currents: most often 25 to 30 mA are sufficient. Stimulation of these two muscles is technically difficult and the result often unsatisfactory in clinical practice.

Because different muscle groups have different sensitivities to neuromuscular blocking drugs, results obtained for one muscle cannot be automatically extrapolated to other muscles. However, most of the studies that are the base for dosing recommendations of NMBAs arise from measurement of the stimulation of the ulnar nerve. The diaphragm is among the most resistant of all muscles to both depolarizing<sup>19</sup> and nondepolarizing neuromuscular blocking drugs.<sup>20</sup> In general, the diaphragm requires 1.4- to 2.0-fold as much muscle relaxant as the adductor pollicis muscle for an identical degree of block (Fig. 43.2).<sup>20</sup> Also of clinical significance is that onset time is normally shorter for the diaphragm than for the adductor pollicis muscle, and the diaphragm recovers from paralysis more quickly than the peripheral muscles (Fig. 43.3).<sup>21</sup> The other respiratory muscles are less resistant than the diaphragm, as are the larynx and the corrugator supercilii muscles.<sup>22-24</sup> Most sensitive are the abdominal muscles, the orbicularis oculi muscle, the peripheral muscles of the limbs, and the geniohyoid, masseter, and upper airway muscles.<sup>1,25-27</sup> From a clinical point of view, the response of the corrugator supercilii to facial nerve stimulation reflects the extent of neuromuscular block of the laryngeal adductor muscles and abdominal muscles better than the response of the adductor pollicis to



**Fig. 43.3** Evolution of twitch height (mean  $\pm$  SD) of the diaphragm (blue circles) and the adductor pollicis muscle (yellow circles) in 10 anesthetized patients after the administration of atracurium (0.6 mg/kg). (From Pansard J-L, Chauvin M, Lebrault C, et al. Effect of an intubating dose of succinylcholine and atracurium on the diaphragm and the adductor pollicis muscle in humans. *Anesthesiology*. 1987;67[3]:326-330.)

ulnar nerve stimulation.<sup>24,28</sup> Furthermore, the upper airway muscles seem to be more sensitive than the peripheral muscles.<sup>25,26</sup> Although some investigations using acceleromyography (AMG) have indicated small differences in the response to TOF nerve stimulation in the hand (adductor pollicis muscle) compared to the leg (flexor hallucis brevis muscle), these differences are probably of little clinical significance.<sup>29,30</sup> When comparing different sites of stimulation, there might be large differences between contralateral limbs (e.g., arm-to-arm variation of  $\pm$  20%).<sup>31,32</sup>

Although the precise source of these differences is unknown, possible explanations may be variations in acetylcholine receptor density, acetylcholine release, acetylcholinesterase activity, fiber composition, innervation ratio (number of neuromuscular junctions), blood flow, and muscle temperature.

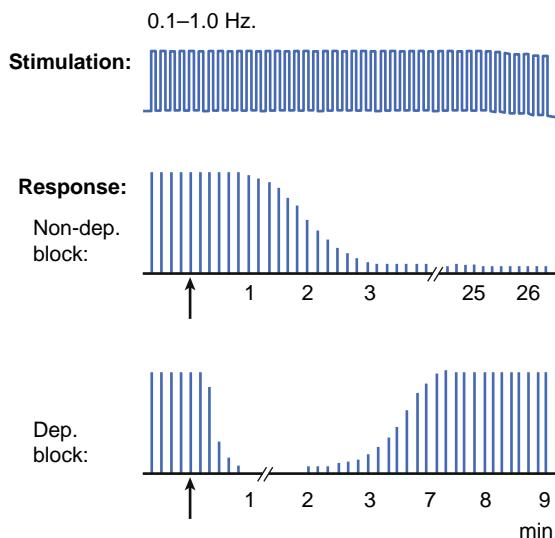
## Patterns of Nerve Stimulation

For the evaluation of the neuromuscular function, the most commonly used patterns are TOF stimulation, double-burst stimulation (DBS), and posttetanic count (PTC) stimulation. Single-twitch stimulation and tetanic stimulation are mainly used as a component in composite stimulation patterns (i.e., TOF, DBS, or PTC).

### SINGLE-TWITCH STIMULATION

**Background:** Single-twitch stimulation is the earliest and simplest pattern. The first device specifically developed to monitor the neuromuscular block, the “St. Thomas’s Hospital nerve stimulator,” could only deliver a single twitch.<sup>33</sup> For decades it remained the only established stimulation pattern to assess neuromuscular blockade intraoperatively.

**Stimulation pattern:** In the single-twitch mode of stimulation, single electrical stimuli are applied to a peripheral motor nerve at frequencies ranging from 1.0 Hz (once every second) to 0.1 Hz (once every 10 seconds; Fig. 43.4) and



**Fig. 43.4** Pattern of electrical stimulation and evoked muscle responses to single-twitch nerve stimulation (at frequencies of 0.1–1.0 Hz) after injection of nondepolarizing (Non-dep.) and depolarizing (Dep.) neuromuscular blocking drugs (arrows). Note that except for the difference in time factors, no differences in the strength of the evoked responses exist between the two types of block.

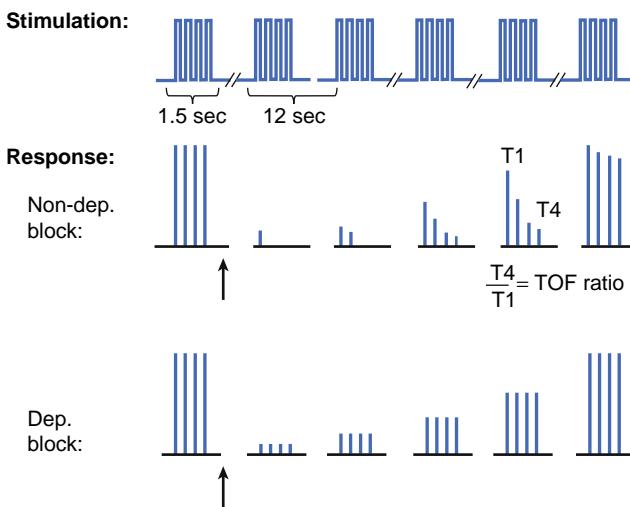
the subsequent muscle response is evaluated. The response to single-twitch stimulation depends on the frequency at which the individual stimuli are applied. If the rate of delivery is increased to greater than 0.15 Hz, the evoked response will gradually decrease and stabilize at a lower level. Therefore, results obtained with 1-Hz single-twitch stimulation cannot be compared with results obtained using, for example, 0.1-Hz single-twitch stimulation.<sup>34</sup> As a result, a frequency of 0.1 Hz is generally recommended.

**Clinical application:** To assess the degree of neuromuscular blockade after single-twitch stimulations, a comparison with a reference value recorded before administration of the NMBA is mandatory. Thus, without appropriate monitoring equipment, this stimulation pattern does not provide sufficient information of the level of block. In clinical practice, the single twitch stimulation has only limited value as a stand-alone stimulation pattern; it is mainly used as a component of the PTC stimulation and as 0.1 Hz single-twitch stimulation, it is sometimes used in scientific trials specifically to evaluate the time to onset of neuromuscular blockade. Moreover, it is the only stimulation pattern that allows, in conjunction with a monitoring device, assessing a depolarizing neuromuscular block after succinylcholine.

## TRAIN-OF-FOUR STIMULATION

**Background:** The TOF stimulation pattern was introduced by Ali and associates<sup>35,36</sup> during the early 1970s. They aimed to develop a tool providing clinically reliable information throughout all phases of neuromuscular blockade with simple nerve stimulator and without the need for a monitoring device.

**Stimulation pattern:** TOF stimulation consists of four supramaximal stimuli given every 0.5 seconds (2 Hz; Fig. 43.5) and each stimulus in the train causes the muscle to contract. The basis for evaluation is either the number of discernible responses after TOF stimulation (i.e., TOF count)

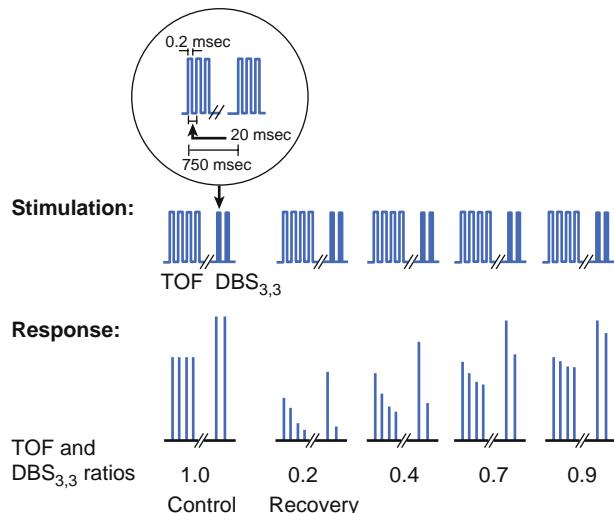


**Fig. 43.5** Pattern of electrical stimulation and evoked muscle responses to train-of-four (TOF) nerve stimulation before and after injection of nondepolarizing (Non-dep.) and depolarizing (Dep.) neuromuscular blocking drugs (arrows).

or the “fade” in the train of responses—that is, dividing the amplitude of the fourth response by the amplitude of the first response (i.e., TOF ratio). Without prior administration of a muscle relaxant, all four responses are normally the same: the TOF ratio is 1.0. During a partial nondepolarizing block, the TOF ratio decreases (fades) and is inversely proportional to the degree of block. During a partial depolarizing block, no fade occurs in the TOF response and the TOF ratio remains 1.0, independently of the level of depolarizing neuromuscular blockade. Fade in the TOF response after injection of succinylcholine signifies the development of a phase II block (discussed later in the section on depolarizing neuromuscular block).

When used continuously, an interval of at least 10 seconds should be allowed between each set (train) of four stimuli to avoid fade during the measurement.

**Application:** TOF stimulation is still the most frequently used stimulation pattern. The advantages of TOF stimulation are most apparent during a nondepolarizing neuromuscular block because the degree of block can be read directly from the TOF response even though a preoperative value is lacking. Clinically relevant information about the onset, surgical relaxation, and neuromuscular recovery can be obtained with the same stimulation pattern by using a simple peripheral nerve stimulator; the TOF count allows reliable assessment of the onset of neuromuscular block, and moderate blockade. Moreover, the TOF ratio can be taken as a measure of neuromuscular recovery from nondepolarizing blockade. TOF stimulation has some advantages over DBS and PTC stimulation; it is less painful and, unlike tetanic stimulation, does not generally influence subsequent monitoring of the degree of neuromuscular block. There are major limitations of the TOF stimulation pattern. First, the subjective assessment of the TOF ratio overestimates neuromuscular recovery, as the tactile or visual estimation of fade is accurate only if the TOF ratio is less than 0.4; in other words, at a TOF ratio between 0.4 and 0.9, fade cannot be detected either visually or tactically. Therefore, objective monitoring devices are needed to further quantify neuromuscular recovery and to reliably exclude residual



**Fig. 43.6** Pattern of electrical stimulation and evoked muscle responses to train-of-four (TOF) nerve stimulation and double-burst nerve stimulation (i.e., three impulses in each of two tetanic bursts,  $DBS_{3,3}$ ) before injection of muscle relaxants (control) and during recovery from nondepolarizing neuromuscular block. The TOF ratio is the amplitude of the fourth response to TOF divided by the amplitude of the first response. The  $DBS_{3,3}$  ratio is the amplitude of the second response to  $DBS_{3,3}$  divided by the amplitude of the first response. (See text for further explanation.)

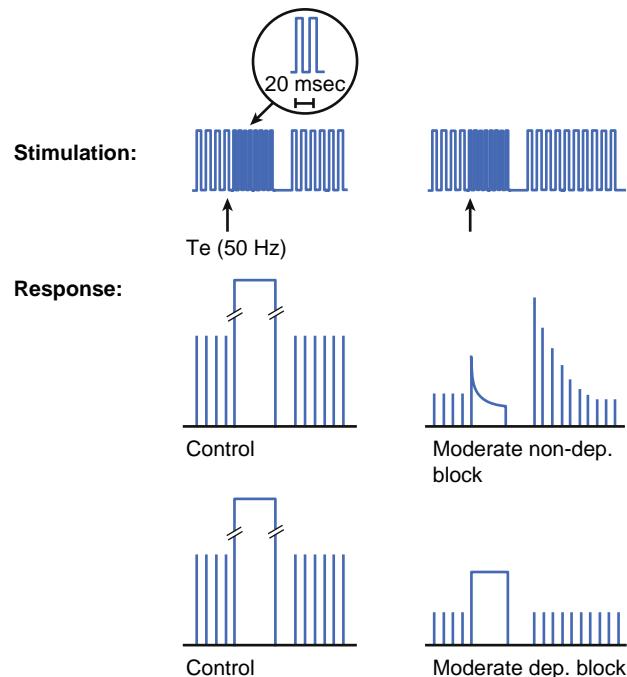
paralysis. Second, the TOF stimulation does not allow the clinician to quantify intense and deep levels of neuromuscular blockade (i.e., at no responses to TOF). Finally, the TOF stimulation does not allow monitoring of the depolarizing phase I blockade.

## DOUBLE-BURST STIMULATION

**Background:** DBS was developed by Viby-Mogensen and associates in 1989 to improve the tactile or visual evaluation of recovery from nondepolarizing neuromuscular blockade.

**Stimulation pattern:** DBS consists of two short bursts of 50-Hz tetanic stimulation separated by 750 ms, with a 0.2-ms duration of each square wave impulse in the burst (Fig. 43.6). The number of impulses in each burst can vary: in the  $DBS_{3,3}$  mode, there are three impulses in each of the two bursts, whereas in the  $DBS_{3,2}$  mode, the first burst had three impulses and the second burst consisted of only two impulses.<sup>37-39</sup> The individual twitches elicited by each burst blend together and are felt as one single muscle contraction. Thus, the response to DBS is two short muscle contractions and fade in the second burst compared to the first one is the basis for evaluation. In nonparalyzed muscle, both muscle contractions are of equal strength. In a partially paralyzed muscle, the second response is weaker than the first and corresponds to the typical TOF fade (see Fig 43.6). When measured mechanically, the TOF ratio correlates closely with the  $DBS_{3,3}$  ratio. Compared to  $DBS_{3,3}$ , tactile detection of fade is slightly improved with the  $DBS_{3,2}$  mode, especially at higher TOF ratios.

**Clinical application:** DBS was developed with the specific aim of improving manual (tactile or visual) detection of residual nondepolarizing block under clinical conditions,<sup>38</sup> or during recovery and immediately after surgery. Indeed,



**Fig. 43.7** Pattern of stimulation and evoked muscle responses to tetanic (50 Hz) nerve stimulation for 5 seconds ( $Te$ ) and posttetanic twitch stimulation (1.0 Hz; arrows). Stimulation was applied before the injection of neuromuscular blocking drugs and during moderate nondepolarizing (non-dep.) and depolarizing (dep.) blocks. Note the fade in the response to tetanic stimulation, plus the posttetanic facilitation of transmission during nondepolarizing block. During depolarizing block, the tetanic response is well sustained, and no posttetanic facilitation of transmission occurs.

tactile evaluation of the response to DBS is more accurate in detecting fade compared to TOF. However, a DBS is still insufficient to exclude reliably residual paralysis corresponding to a TOF ratio between 0.6 and 0.9.<sup>39-41</sup> Accordingly, DBS cannot replace objective monitoring.

## TETANIC STIMULATION

**Background:** Tetanic stimulation was proposed by Tassonyi in 1975<sup>42</sup> as an alternative method to evaluate residual neuromuscular blockade.

**Stimulation pattern:** Tetanic stimulation consists of high-frequency delivery of electrical stimuli (e.g., 50-100 Hz). The most commonly used pattern in clinical practice is 50-Hz stimulation given for 5 seconds, although some investigators have advocated the use of 100-Hz, or even 200-Hz stimulation for 1 second. In normal neuromuscular transmission, the observer detects one strong, sustained muscle contraction, and fade after tetanic stimulation is the basis for evaluation of nondepolarizing block. During a depolarizing block, the muscle response to 50-Hz tetanic stimulation for 5 seconds is sustained. In contrast, during a phase II block after the injection of succinylcholine, the response following tetanic stimulation is not sustained (i.e., fade occurs; Fig. 43.7).

Fade in response to tetanic stimulation is normally considered a presynaptic event. The traditional explanation is that at the start of tetanic stimulation, large amounts of acetylcholine are released from immediately available stores in the presynaptic nerve terminal. As these stores become

depleted, the rate of acetylcholine release decreases until equilibrium between mobilization and synthesis of acetylcholine is achieved. Despite this equilibrium, the muscle response to tetanic nerve stimulation is maintained (given normal neuromuscular transmission) because the acetylcholine released is many times greater than the amount necessary to evoke a response. However, when the “margin of safety”<sup>43</sup> at the postsynaptic membrane (i.e., the number of free cholinergic receptors) is reduced by nondepolarizing neuromuscular blocking drugs, a typical reduction in twitch height is seen with a fade, especially during repetitive stimulation. In addition to this postsynaptic block, nondepolarizing neuromuscular blocking drugs can also block presynaptic neuronal subtype acetylcholine receptors, thereby leading to impaired mobilization of acetylcholine within the nerve terminal.<sup>44</sup> This effect substantially contributes to fade in the response to tetanic (and TOF) stimulation. Although the degree of fade depends primarily on the degree of neuromuscular block, fade also depends on the frequency (Hz), the length (seconds) of stimulation, and on how often tetanic stimuli are applied. Unless these variables are kept constant, results from different studies using tetanic stimulation cannot be compared.

**Clinical application:** Traditionally, tetanic stimulation was proposed to evaluate residual neuromuscular block. While the sensitivity of tetanic stimulation to detect residual paralysis is about 70%, its specificity is only about 50%. Especially when anesthesia was maintained with volatile anesthetics, a marked fade can be observed despite adequate neuromuscular recovery or even without prior administration of a nondepolarizing NMBA. Hence, this test is of limited value for assessing neuromuscular recovery. Furthermore, tetanic stimulation is very painful, which limits its use in unanesthetized patients. In the late phase of neuromuscular recovery, tetanic stimulation can produce lasting antagonism of neuromuscular block in the stimulated muscle such that the response of the tested site may no longer be representative of other muscle groups.<sup>45</sup> For all these reasons, tetanic stimulation has little, if any, use in everyday clinical anesthesia, except as a component in DBS and PTC stimulation.

## POSTTETANIC COUNT STIMULATION

**Background:** PTC stimulation was developed by Viby-Mogensen to allow tactile or visual evaluation of profound nondepolarizing neuromuscular blockade that does not respond to TOF stimulation.<sup>46</sup>

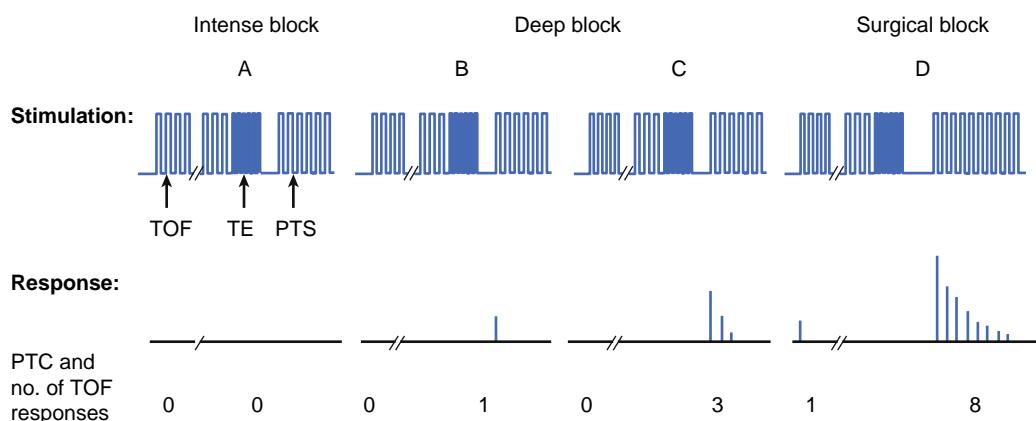
**Stimulation pattern:** PTC is a composite stimulation pattern composed by a tetanic stimulation (50 Hz for 5 seconds) followed by 10 to 15 single twitches (i.e., PTC twitches) given at 1 Hz starting 3 seconds after the end of tetanic stimulation.<sup>46</sup> It is based on a phenomenon called “posttetanic potentiation”: tetanic stimulation leads to a transient, exaggerated release of acetylcholine that briefly shifts the ratio of acetylcholine and NMBA at the motor endplate in favor of acetylcholine. Even if no twitch response has been discernible prior to the tetanic stimulation, noticeable muscle contractions might occur briefly after tetanic stimulation (see Fig. 43.7). The basis for evaluation of the PTC is the count of these discernible posttetanic twitches.

The response to PTC stimulation depends primarily on the degree of neuromuscular block. It also depends on the frequency and duration of tetanic stimulation, the length of time between the end of tetanic stimulation and the first posttetanic stimulus, the frequency of the single-twitch stimulation, and probably the duration of single-twitch stimulation before tetanic stimulation. When the PTC method is used, these variables should be kept constant. Because of interference between PTC stimulation and the actual neuromuscular block within the monitored hand, tetanic stimulation should ideally not be performed more often than every 6 minutes.<sup>46</sup>

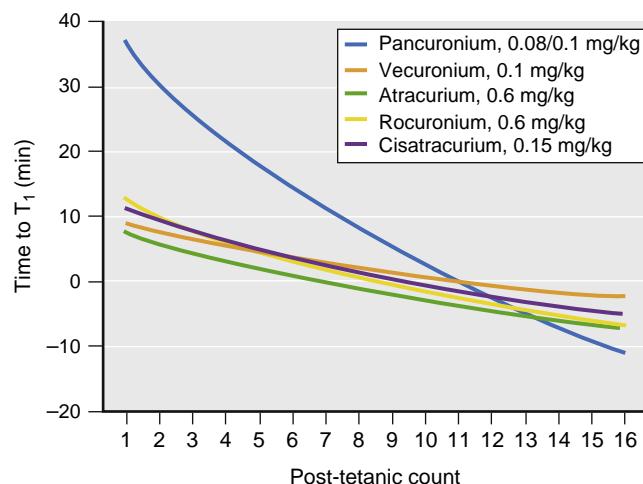
**Clinical application and limitation:** Moderate levels of neuromuscular blockade (i.e., TOF count between 1 and 4) are not sufficient to reliably prevent reactions of the diaphragm and/or laryngeal muscles after stimulation. Both muscles are rather resistant to the effect of nondepolarizing NMBA. Therefore, more profound levels of neuromuscular blockade are needed in clinical situations where any bucking or coughing in response to tracheal stimulation or sudden diaphragmatic movements during surgery should be avoided. Only PTC stimulation allows assessment of these degrees of neuromuscular blockade. During intense block, there is no response to either tetanic or posttetanic stimulation (Fig. 43.8). As the period of intense neuromuscular block dissipates, the first response to posttetanic twitch stimulation occurs and is followed by a gradual return of posttetanic twitches until the first response to TOF stimulation reappears. The PTC should be 3 or less if a deep block is required for clinical reasons; at 6 to 10 PTC, the return of the first TOF response is most often imminent (Fig. 43.9).<sup>46-50</sup> Because tetanic stimulation should not be performed more often than every 6 minutes, this stimulation pattern cannot be applied continuously.

## Equipment

Although many nerve stimulators are commercially available, not all meet the basic requirements for clinical use. The stimulus should produce a monophasic and rectangular waveform, and the length of the pulse should not exceed 0.2 to 0.3 ms. A pulse exceeding 0.5 ms may stimulate the muscle directly or cause repetitive firing. Stimulation at a constant current is preferable to stimulation at a constant voltage because current is the determinant of nerve stimulation. Furthermore, for safety reasons, the nerve stimulator should be operated by a rechargeable battery, include a battery check, and be able to generate 60 to 70 mA, but not more than 80 mA. Some commercially available stimulators can deliver just 25 to 50 mA and provide a constant current only when skin resistance ranges from 0 to 2.5 kΩ. This is a limitation, as skin resistance can increase to approximately 5 kΩ, especially during lower skin temperature. The high skin resistance can cause the current delivered to the nerve to decrease below the supramaximal level and lead to a decrease in the response to stimulation. Ideally, the nerve stimulator should have a built-in warning system, or a current level display that alerts the user when the selected current is not delivered to the nerve. Alternatively, the impedance should be indicated at the screen. The polarity of the electrodes should be indicated, and the



**Fig. 43.8** Pattern of electrical stimulation and evoked muscle responses to train-of-four (TOF) nerve stimulation, 50-Hz tetanic nerve stimulation for 5 seconds (TE), and 1.0-Hz posttetanic twitch stimulation (PTS) during four different levels of nondepolarizing neuromuscular block. During intense block of peripheral muscles (A), no response to any of the forms of stimulation occurs. During less pronounced block (deep block, B and C), there is still no response to TOF stimulation, but posttetanic facilitation of transmission is present. During surgical block (D), the first response to TOF appears and posttetanic facilitation increases further. The posttetanic count (see text) is 1 during very deep block (B), 3 during less deep block (C), and 8 during surgical (or moderate) block (D).



**Fig. 43.9** Relationship between the posttetanic count and time when onset of train-of-four (T<sub>1</sub>) is likely to be elicited for various neuromuscular blocking agents. (From El-Orbany MI, Joseph JN, Salem MR. The relationship of post-tetanic count and train-of-four responses during recovery from intense cisatracurium-induced neuromuscular block. *Anesth Analg*. 2003;97[1]:80–84.)

apparatus should be capable of delivering the following modes of stimulation: TOF (as both a single train and in a repetitive mode, with TOF stimulation being given every 10–20 seconds), and PTC. Some recent nerve stimulators switch automatically between TOF and PTC, depending on the level of neuromuscular blockade. If the nerve stimulator does not allow objective measurement of the response to TOF stimulation, at least one DBS mode should be available, preferably DBS<sub>3,2</sub>.

## Peripheral Nerve Stimulator

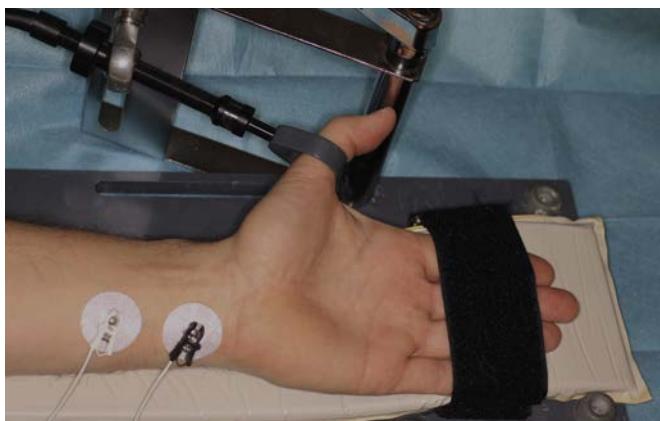
Peripheral nerve stimulators only allow stimulation of the target nerve; the subsequent muscular response is assessed subjectively either tactiley or visually. When

applying TOF stimulation and evaluating the TOF count, the peripheral nerve stimulator may deliver clinically useful information about the onset of neuromuscular block or the need for an additional dose of relaxant. Moreover, the clinician could be guided for the timing and dosing of reversal agents. It is in the determination of full neuromuscular recovery these devices have clinical limitations. It is impossible to reliably exclude residual paralysis. A simple nerve stimulator acts only as a guide and should not be used as a diagnostic tool to exclude residual paralysis.

## Objective Monitors

Objective monitors measure the evoked responses objectively and display it on a screen.

Several methods may be used for objective clinical monitoring of neuromuscular function: evoked mechanical response of the muscle (mechanomyography [MMG]), evoked electrical response of the muscle (electromyography [EMG]), acceleration of the muscle response (AMG), evoked electrical response in a piezoelectric film sensor attached to the muscle (kinemyography [KMG]), measurement of pressure changes in blood pressure cuff after contractions of the upper arm muscles (cuff pressure modality [CPM]), measurement of pressure change of a spherical balloon after hand contraction (compressomyography [CMG]), and measurement of low-frequency sounds evoked by the muscle contraction (phonomyography [PMG]). The different methods are described below. For further information on recording evoked responses, the reader is referred to guidelines for good clinical research practice in pharmacodynamic studies of neuromuscular blocking drugs.<sup>17</sup> The only objective monitors currently available are based on AMG, EMG, CPM, and KMG. The use of computer-guided administration of neuromuscular blocking drugs and “closed loop control” systems has been suggested, but no systems are commercially available.<sup>51,52</sup>



**Fig. 43.10 The setup for mechanomyography.** The response to nerve stimulation is measured using a force transducer (TD-100; Biometer, Odense, Denmark) placed at the proximal phalanx of the thumb.

## MECHANOMYOGRAPHY

MMG measures the isometric contraction of a muscle after stimulation of the corresponding nerve. A transducer converts the force of an isometric contraction into an electrical signal. For correct and reproducible measurement, the muscle contraction needs to be isometric. In clinical anesthesia, this condition is most easily achieved by measuring the force of contraction of the thumb after the application of a resting tension of 200 to 300 g (a preload) to the thumb. When the ulnar nerve is stimulated, the thumb (the adductor pollicis muscle) acts on a force-displacement transducer (Fig. 43.10). The force of contraction is then converted into an electrical signal, which is amplified, displayed, and recorded. The arm and hand should be rigidly fixed, and care should be taken to prevent overloading of the transducer. In addition, the transducer should be placed in correct relation to the thumb (i.e., the thumb should always apply tension along the length of the transducer). It is important to remember that the response to nerve stimulation depends on the frequency with which the individual stimuli are applied and that the time used to achieve a stable control response may influence subsequent determination of the onset time and duration of block.<sup>17</sup> Generally, the reaction to supramaximal stimulation increases during the first 8 to 12 minutes after commencement of the stimulation (staircase phenomenon). Therefore, in clinical studies, recording of the control response (before injection of muscle relaxant) should not be made until the response has stabilized for 8 to 12 minutes or a 2- or 5-second 50-Hz tetanic stimulation has been given.<sup>53</sup> Even then, twitch response often recovers to 110% to 150% of the control response after paralysis with succinylcholine. This increase in response, possibly caused by a change in the contractile response of the muscle, normally disappears within 15 to 25 minutes.

Although there are numerous methods for mechanical recording of evoked mechanical responses, not all meet the criteria outlined. MMG is recognized as the gold standard of neuromuscular monitoring.<sup>17</sup>

Despite this status, there is no commercially available neuromuscular monitor for daily clinical use based on this principle. This type of monitor is relegated to research purpose only.



**Fig. 43.11 The setup for electromyography (NMT ElectroSensor, Datex-Ohmeda, Helsinki, Finland) for recording the compound action potential from the adductor pollicis muscle.**

## ELECTROMYOGRAPHY

EMG is the oldest technique used for quantification of neuromuscular blockade. Evoked EMG records the compound muscle action potentials produced by stimulation of a peripheral nerve. The compound action potential is an electrical activity that for many years could be detected only by means of a preamplifier and a storage oscilloscope. Modern neuromuscular transmission analyzers are able to make online electronic analyses and graphic presentations of the EMG response.

The evoked EMG response is most often obtained from muscles innervated by the ulnar or the median nerves. Stimulating electrodes are applied as in force measurements. Most often, the evoked EMG response is obtained from the thenar or hypothenar eminence of the hand or from the first dorsal interosseous muscle of the hand, preferably with the active electrode over the motor point of the muscle (Fig. 43.11). The signal picked up by the analyzer is processed by an amplifier, a rectifier, and an electronic integrator. The results are displayed either as a percentage of control or as a TOF ratio.

Two new sites for recording the EMG response have been introduced: the larynx and the diaphragm.<sup>54,55</sup> Using a noninvasive disposable laryngeal electrode attached to the tracheal tube and placed between the vocal cords, it is possible to monitor the onset of neuromuscular block in the laryngeal muscles. However, the method is mainly of interest in clinical research when investigating onset times of the laryngeal muscles. In paravertebral surface diaphragmatic EMG, the recording electrodes are placed on the right of vertebrae T12/L1 or L1/L2 for monitoring the response of the right diaphragmatic crux to transcutaneous stimulation of the right phrenic nerve at the neck.<sup>54-57</sup> As is the case with surface laryngeal EMG, surface diaphragmatic EMG is mainly of interest in clinical research.

Evoked electrical and mechanical responses represent different physiologic events. Evoked EMG records changes in the electrical activity of one or more muscles, whereas evoked MMG records changes associated with excitation-contraction coupling and contraction of the muscle as well. For these reasons, the results obtained with these methods may differ.<sup>57,58</sup> Although evoked EMG responses generally correlate well with evoked mechanical responses,<sup>38</sup> marked differences can occur, especially in the response to succinylcholine and in the TOF ratio during recovery from a nondepolarizing block.<sup>38,57,59</sup>

In theory, recording of evoked EMG responses has several advantages over recording of evoked mechanical responses. Equipment for measuring-evoked EMG responses is easier to set up, the response reflects only factors influencing neuromuscular transmission, and the response can be obtained from muscles not accessible to mechanical recording. However, evoked EMG does entail some difficulties. Although high-quality recordings are possible in most patients, the results are not always reliable. For one thing, improper placement of electrodes can result in inadequate pickup of the compound EMG signal. If the neuromuscular transmission analyzer does not allow observation of the actual waveform of the compound EMG, determining optimal placement of the electrodes is difficult. Another source of unreliable results may be that fixation of the hand with a preload on the thumb might be more important than is generally appreciated, inasmuch as changes in the position of the electrodes in relation to the muscle can affect the EMG response. In addition, direct muscle stimulation sometimes occurs. If muscles close to the stimulating electrodes are stimulated directly, the recording electrodes can pick up an electrical signal even though neuromuscular transmission is completely blocked. Another difficulty is that the EMG response often does not return to the control value. Whether this situation is the result of technical problems, inadequate fixation of the hand, or changes in temperature is unknown (Fig. 43.12). Finally, the evoked EMG response is highly sensitive to electrical interference, such as that caused by diathermy.

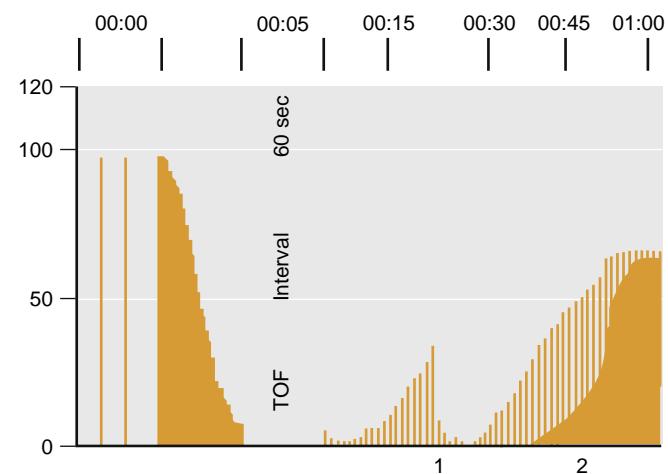
Currently, to our knowledge, there are only a few EMG-based monitors available for clinical use, but more devices are under development.

## ACCELEROMYOGRAPHY

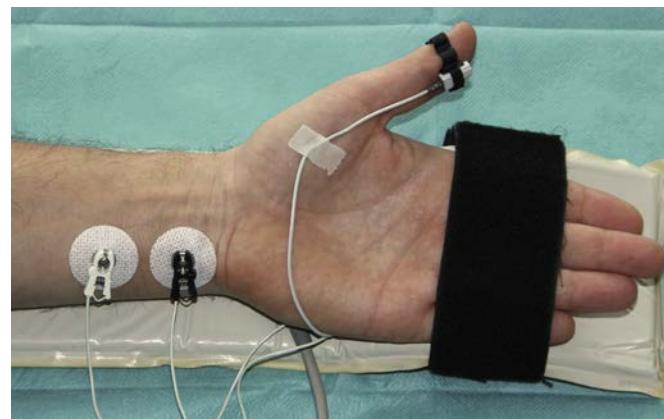
AMG was developed specifically for clinical use and is widely practiced. The technique of AMG is based on Newton's second law: force = mass  $\times$  acceleration, it measures the isotonic acceleration of the stimulated muscle.<sup>60</sup> If mass is constant, acceleration is directly proportional to force. Accordingly, after nerve stimulation, one can measure not only the evoked force but also acceleration of the thumb.

AMG uses a piezoelectric ceramic wafer with electrodes on both sides. Exposure of the electrode to a force generates an electrical voltage proportional to acceleration of the electrode. Consequently, when an accelerometer is fixed to the thumb and the ulnar nerve is stimulated, an electrical signal is produced whenever the thumb moves (Fig. 43.13). This signal can be analyzed in a specially designed analyzer<sup>61</sup> or displayed on a recording system.

AMG is a simple method of analyzing neuromuscular function, both in the operating room and in the intensive care unit. Although good correlation exists between the TOF ratio measured by this method and the TOF ratio measured with a force-displacement transducer or EMG,<sup>60,62,63</sup> measurements made via AMG are not directly comparable with results obtained by the other two methods.<sup>63-69</sup> When AMG is used with a free-moving thumb, as originally suggested,<sup>60</sup> wide limits of agreements in twitch height (T1) and TOF ratio and differences in the onset and recovery course of block between AMG and MMG have been found. Moreover, the AMG control TOF ratio is consistently higher than



**Fig. 43.12** Evoked electromyographic printout from a Relaxograph (Datex-Ohmeda, Helsinki, Finland). Initially, single-twitch stimulation was given at 0.1 Hz, and vecuronium (70  $\mu$ g/kg) was administered intravenously for tracheal intubation. After approximately 5 minutes, the mode of stimulation was changed to train-of-four (TOF) stimulation every 60 seconds. At a twitch height (first twitch in the TOF response) of approximately 30% of control (marker 1), 1 mg of vecuronium was given intravenously. At marker 2, 1 mg of neostigmine was given intravenously, preceded by 2 mg of glycopyrrolate. The printout also illustrates the common problem of failure of the electromyographic response to return to the control level. (Courtesy Datex-Ohmeda, Helsinki, Finland.)



**Fig. 43.13** The setup of accelerometry without preload (TOF Watch, Biometer, Odense, Denmark). The response to nerve stimulation is measured with a small piezoelectric acceleration transducer placed distally on the volar site of the thumb.

when measured with a force-displacement transducer. In accordance with this, several studies have indicated that when using AMG, the TOF ratio indicative of sufficient post-operative neuromuscular recovery is 1.0 rather than 0.90, as when measured by MMG or EMG in the adductor pollicis muscle.<sup>6,68,70-72</sup> In contrast to MMG and EMG, the control baseline TOF value before administration of a neuromuscular blocking drug is most often 1.1 to 1.2 when measured with AMG, and in some patients is as high as 1.4. A high control baseline value probably indicates that the TOF ratio necessary for excluding residual curarization is equally higher. For instance, in a patient with a high control baseline value (e.g., TOF = 1.2), it is to be expected that a higher TOF ratio during recovery is necessary to exclude residual



**Fig. 43.14** The setup of acceleromyography with preload (TOF Watch with Hand Adapter, Biometer, Odense, Denmark). The piezoelectric acceleration transducer is placed in the Hand Adapter. The stretching wing ensures that the thumb does not touch the palm of the hand.

block compared with a patient with a low control baseline value (e.g., TOF = 0.95). It is generally accepted that the TOF ratio should be at least 0.90 to exclude clinically significant residual paralysis; using the preceding example, a TOF ratio of 1.08 (90% of 1.2) would represent safe recovery in the first patient, whereas a TOF ratio of 0.86 (90% of 0.95) would suffice in the other patient. To overcome such problems, it has been suggested to refer the actually obtained TOF ratios during recovery to the baseline control TOF ratio (normalization).<sup>67,72-76</sup> Currently, no commercially available monitors can “normalize” the TOF ratio automatically. Intuitively, for excluding residual block using AMG, a TOF ratio of at least 1.0 should be targeted to exclude residual block.<sup>67,68,72,74</sup>

One reason for the wide limits of agreement between AMG and MMG is probably and paradoxically connected with one of the originally claimed advantages of the method, that fixation of the hand could be reduced to a minimum as long as the thumb could move freely.<sup>60</sup> In clinical practice, it is often not possible to ensure that the thumb can move freely and that the position of the hand does not change during the surgical procedure. The evoked response can therefore vary considerably. Several solutions have been proposed, but the use of an elastic preload on the thumb improves the precision without compromising the agreement between results obtained with AMG and MMG (Fig. 43.14).<sup>67,68</sup> Several studies have indicated that objective monitoring with AMG reduces and almost eliminates the problem of postoperative residual neuromuscular block.<sup>67,77-81</sup>

When the thumb is not available for monitoring during surgery, some clinicians prefer to monitor the AMG response of the orbicularis oculi or the corrugator supercilii in response to facial nerve stimulation.<sup>28</sup> However, neuromuscular monitoring of both sites with AMG is subject to both large uncertainty regarding the extent of paralysis and high risk of direct muscle stimulation, and it cannot be recommended for routine monitoring. It provides only a rough estimate of the degree of block of the peripheral muscles.<sup>82,83</sup>

AMG was one of the first widely distributed commercially available monitors and has therefore become the

standard for qualitative monitoring in the clinical setting. Today, AMG devices are available as portable monitors as well as integrated in the anesthesia monitor.

Recently, AMG monitors with three-dimensional piezoelectric transducers were introduced, which sense the motion of the thumb in all directions,<sup>83a,83b</sup> and not just in one plane. This might further improve the reliability of the AMG technology. This novel method has been compared to the TOF-Watch (one-dimensional AMG) in two small studies. Although both studies showed some disagreement between the two methods, the authors agreed that the three-dimensional monitor may be used in clinical practice. An advantage seems to be that the monitors' integrated internal check-up ensuring that all components including the piezoelectric element are functional is developed. The newest monitors also display the impedance and calculate automatically a modified normalized TOF ratio. Hopefully, the new generation of AMG monitors becomes even more user-friendly and more reliable.

## KINEMYOGRAPHY

The technique of KMG is based on the principle that stretching or bending a flexible piezoelectric film (e.g., one attached to the thumb) in response to nerve stimulation generates a voltage that is proportional to the amount of stretching or bending.<sup>84,85</sup>

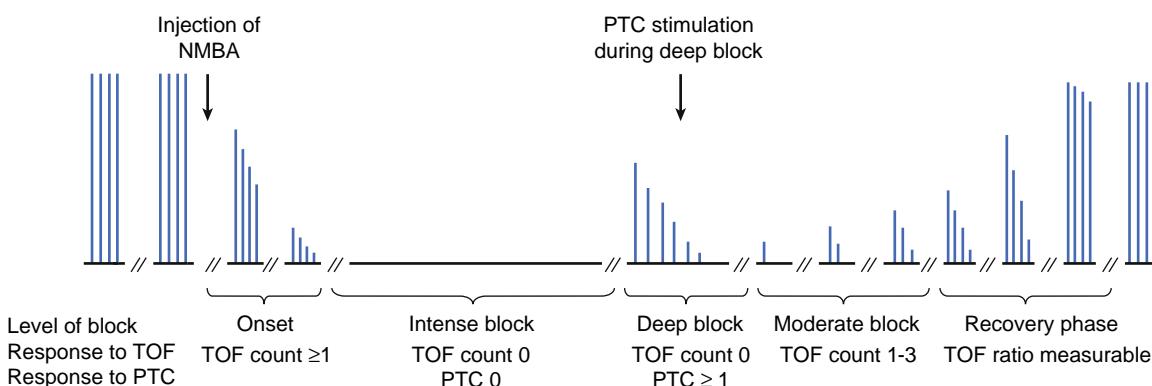
Few studies have evaluated the function of these monitors.<sup>84-86</sup> Limited data indicate not only a good relationship between results obtained with KMG, AMG, and MMG, but also wide limits of agreement between the methods. Therefore, although KMG may be a valuable clinical tool, the values obtained in an individual patient with this method can vary from those obtained with MMG or AMG. Only one device based on this principle is available commercially in two sizes (adult and pediatric): the NMT MechanoSensor (Datex-Ohmeda, Helsinki, Finland).

## CUFF PRESSURE MODALITY (CPM)

The cuff modality detects changes in cuff pressure due to muscle contraction. Electrodes integrated into a blood pressure cuff stimulate the brachial plexus at the humeral level. The subsequent bulk contraction of the upper arm generates pressure change in the blood pressure cuff which is analyzed and displayed at the monitor. However, only limited data are currently available and further clinical investigations are needed to prove the reliability and reproducibility of the new monitoring modality. One monitor based on this technology is commercially available: the TOF-Cuff NMT monitor (RGB Medical devices, Madrid, Spain).

## COMPRESSOMYOGRAPHY

CMG measures pressure changes in a hand-held balloon. Following ulnar nerve stimulation, the force of muscle contraction of the hand muscles is transmitted to a balloon secured in the patient's hand. Despite encouraging results of the only publication investigating the device,<sup>49</sup> this technique has not been further developed and is not commercially available.



**Fig. 43.15** Levels of block after a normal intubating dose of a nondepolarizing neuromuscular blocking agent (NMBA) as classified by posttetanic count (PTC) and train-of-four (TOF) stimulation. During intense (profound) block, there are no responses to either TOF or PTC stimulation. During deep block, there is response to PTC but not to TOF stimulation. Intense (profound) block and deep block together constitute the “period of no response to TOF stimulation.” Reappearance of the response to TOF stimulation heralds the start of moderate block. Finally, when all four responses to TOF stimulation are present and a TOF ratio can be measured, the recovery period has started. (From Fuchs-Buder T, Claudio C, Skovgaard LT, et al. Good clinical research practice in pharmacodynamic studies of neuromuscular blocking agents II: The Stockholm revision. *Acta Anaesthesiol Scand*. 2007;51[7]:789–808.)

## PHONOMYOGRAPHY

PMG measures the intrinsic low-frequency sounds of muscle contraction with special microphones following nerve stimulation. PMG has been evaluated for clinical and research purposes by one study group. This group reports good correlation between evoked acoustic responses and those obtained with more traditional methods of recording, such as MMG, EMG, and AMG.<sup>31,87–92</sup> A potential advantage of PMG, however, is that the method can be applied not only to the adductor pollicis muscle, but also to other muscles of clinical interest such as the diaphragm, larynx, and eye muscles. In addition, the ease of application is attractive. However, PMG-based monitors are not currently commercially available.

## Evaluation of Recorded Evoked Responses

In daily clinical practice, the recorded response to TOF stimulation and PTC stimulation are typically used to explain how to evaluate the degree of neuromuscular block during clinical anesthesia.

### NONDEPOLARIZING NEUROMUSCULAR BLOCK

After injection of a nondepolarizing neuromuscular blocking drug in a dose sufficient for smooth tracheal intubation, TOF recording demonstrates four phases, or levels, of neuromuscular block: intense block, deep block, moderate or surgical block, and recovery (Fig. 43.15).

#### Intense Neuromuscular Block

Intense or profound neuromuscular block occurs within 3 to 6 minutes of injection of an intubating dose of a nondepolarizing muscle relaxant, depending on the drug and the dose given. This phase is also called the “period of no response” because no response to any pattern of nerve stimulation occurs. The length of this period varies, again depending primarily on the duration of action of the muscle relaxant and the dose given. The sensitivity of the patient to the drug also affects the period of no response. An intense

block cannot be antagonized with a cholinesterase inhibitor (e.g., neostigmine), and only a high dose of sugammadex (16 mg/kg) can antagonize an intense block caused by rocuronium or vecuronium.<sup>93,94</sup>

#### Deep Neuromuscular Block

Intense neuromuscular block is followed by a period of deep neuromuscular block, characterized by absence of response to TOF stimulation, but with the presence of at least one response to PTC stimulation (i.e., PTC  $\geq 1$ ; compare with Fig. 43.8). To avoid diaphragmatic movements and thus, to assure surgical stillness and improve surgical space conditions during laparoscopic abdominal procedures, deep neuromuscular blockade corresponding to  $\leq 3$  PTC responses is recommended.<sup>49</sup> Although prediction of the duration of a deep neuromuscular block is difficult, correlation usually exists between PTC stimulation and the time until reappearance of the first response to TOF stimulation (see Fig. 43.9). Attempts to reverse a deep neuromuscular block with neostigmine are usually impossible. However, a deep neuromuscular block caused by rocuronium or vecuronium can be antagonized completely within a few minutes using a dose of sugammadex of 4 mg/kg.<sup>95–97</sup>

#### Moderate Neuromuscular Block

Moderate neuromuscular block begins when the first response to TOF stimulation appears. This phase is characterized by a gradual return of the four responses to TOF stimulation. Furthermore, good correlation exists between the degree of neuromuscular block and the number of responses to TOF stimulation. When only one response is detectable, the degree of neuromuscular block (the depression in twitch tension) is 90% to 95%. When the fourth response reappears, neuromuscular block is usually 60% to 85%.<sup>98,99</sup> The presence of one or two responses in the TOF pattern normally indicates sufficient relaxation for most surgical procedures. During light anesthesia, however, patients may move, buck, or cough; therefore, a deeper block (or a deeper level of anesthesia) may be necessary when elimination of sudden movements or facilitation of surgery is necessary.

Antagonism of neuromuscular block with neostigmine should usually not be attempted when the block is intense or deep. Even if some reversal occurs, it will often be inadequate, regardless of the dose of neostigmine administered.<sup>100</sup> Furthermore, after the administration of large doses of muscle relaxants, reversal of the block with neostigmine to clinically normal activity is not always possible if only one TOF response is present. In general, antagonism with neostigmine should not be initiated before all four responses after TOF stimulation are observed. Even then, sufficient recovery may take time and cannot be guaranteed unless documented using objective monitoring.<sup>101-103</sup>

Antagonism of moderate block induced by rocuronium and vecuronium can be achieved with a small dose of sugammadex (2 mg/kg) within a few minutes.<sup>104-106</sup> However, the reappearance of neuromuscular blockade has been reported by anesthesiologists from Japan<sup>107</sup> when the 2 mg/kg dose has been used. However, they did not monitor the degree of neuromuscular blockade; did the reappearance of neuromuscular blockade occur because of inadequate monitoring or too small a dose of sugammadex? Although the antagonism of neuromuscular block from sugammadex seems to be fast and predictable, neuromuscular monitoring is mandatory for proper dosing, and objective monitoring should still be used until the TOF ratio is 0.9 to 1.0.

### Recovery from Neuromuscular Block

Return of the fourth response in the TOF heralds the recovery phase. During neuromuscular recovery, a reasonably good correlation exists between the actual TOF ratio and clinical observation, but the relationship between the TOF ratio and signs and symptoms of residual block varies greatly among patients.<sup>81,100</sup> When the TOF ratio is 0.4 or less, the patient is generally unable to lift the head or arm. Tidal volume may be normal, but vital capacity and inspiratory force is reduced. When the ratio is 0.6, most patients are able to lift their head for 3 seconds, open their eyes widely, and stick out their tongue, but vital capacity and inspiratory force are often still reduced. At a TOF ratio of 0.7 to 0.75, the patient can normally cough sufficiently and lift the head for at least 5 seconds, but grip strength may still be as low as about 60% of control.<sup>108</sup> When the ratio is 0.8 and higher, vital capacity and inspiratory force are normal.<sup>36,109-111</sup> The patient may, however, still have diplopia, blurred vision, and facial weakness (Table 43.1).<sup>81,108</sup>

However, the TOF ratio must exceed 0.90 when recorded with MMG or EMG, and 1.0 when using AMG to exclude clinically important residual neuromuscular block.<sup>1,3,38,67,68,70,112-116</sup> Moderate degrees of neuromuscular block can impair carotid body chemosensitivity to hypoxia with absent ventilatory response to arterial desaturation.<sup>3,112,114,116</sup> Moreover, residual block (TOF < 0.90) is associated with functional impairment of the pharyngeal and upper esophageal muscles, which most probably predisposes to regurgitation and aspiration of gastric contents.<sup>1</sup> Eikermann and colleagues<sup>4</sup> have documented that partial neuromuscular block, even to a degree that does not evoke dyspnea or oxygen desaturation, can decrease inspiratory upper airway volume and can evoke partial inspiratory airway collapse.<sup>4</sup> Also, residual block (TOF < 0.70) caused by the long-acting muscle relaxant pancuronium is

**TABLE 43.1** Clinical Signs and Symptoms of Residual Paralysis in Awake Volunteers after Mivacurium-Induced Neuromuscular Block

Train-of-Four Ratio	Signs and Symptoms
0.70-0.75	Diplopia and visual disturbances Decreased handgrip strength Inability to maintain apposition of the incisor teeth "Tongue depressor test" negative
0.75-0.80	Inability to sit up without assistance Severe facial weakness
0.80-0.85	Speaking a major effort Overall weakness and tiredness
0.85-0.90	Diplopia and visual disturbances Generalized fatigue

From Kopman AF, Yee PS, Neuman GG. Relationship of the train-of-four fade ratio to clinical signs and symptoms of residual paralysis in awake volunteers. *Anesthesiology*. 1997;86(4):765-761.

a significant risk factor for the development of postoperative pulmonary complications (Table 43.2 and Fig. 43.16).<sup>113</sup> Intraoperative neuromuscular monitoring, followed by appropriate pharmacological reversal, reduces the risk of residual neuromuscular block and results in fewer patients with hypoxic events or airway obstruction in the post-anesthesia care unit.<sup>80</sup> Even in volunteers without sedation or impaired consciousness, a TOF ratio of 0.90 or less can impair the ability to maintain the airway.<sup>77,108,117</sup> Even small degrees of residual block are unpleasant for patients, causing symptoms such as general weakness and blurred vision.<sup>81</sup> In summary, adequate recovery of neuromuscular function requires the return of an MMG or EMG TOF ratio to at least 0.90, and an AMG TOF ratio to at least 1.0 (or normalized to 0.90),<sup>74</sup> which cannot be guaranteed without objective neuromuscular monitoring.<sup>78,79,81,118-121</sup>

### DEPOLARIZING NEUROMUSCULAR BLOCK (PHASE I AND II BLOCKS)

Fade and posttetanic facilitation are the basis for evaluation of all stimulation patterns applied in clinical practice (i.e., TOF, DBS, and PTC stimulation). It is important to realize that during depolarizing neuromuscular phase I block, neither fade nor posttetanic facilitation occurred. Thus, the usually applied stimulation patterns do not allow assessment of depolarizing neuromuscular block. After TOF stimulation, all four responses are reduced at the same degree, no fade occurred, and all four disappear simultaneously. Thus, independently of the degree of depolarizing neuromuscular block, the TOF-ratio remains 1 and the TOF-count is either 4 or 0.

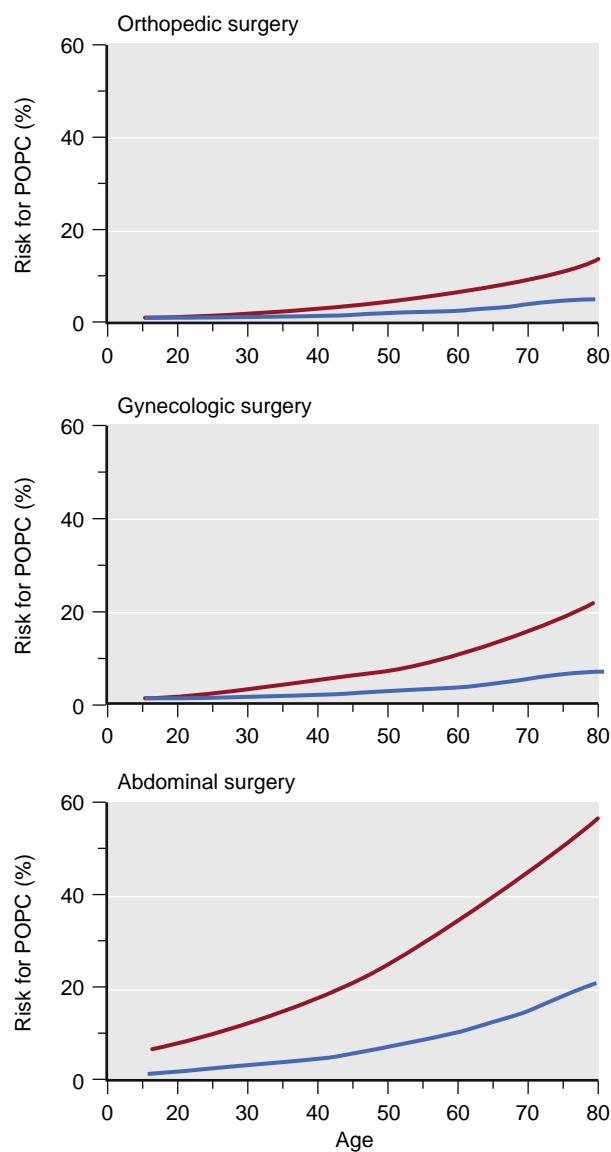
Patients with normal plasma cholinesterase activity who are given a moderate dose of succinylcholine (0.5-1.5 mg/kg) undergo a typical depolarizing neuromuscular block (phase I block; i.e., the response to TOF or tetanic stimulation does not fade, and no posttetanic facilitation of

**TABLE 43.2** Relationship Between Train-of-Four Ratio at the First Postoperative Recording and Postoperative Pulmonary Complications

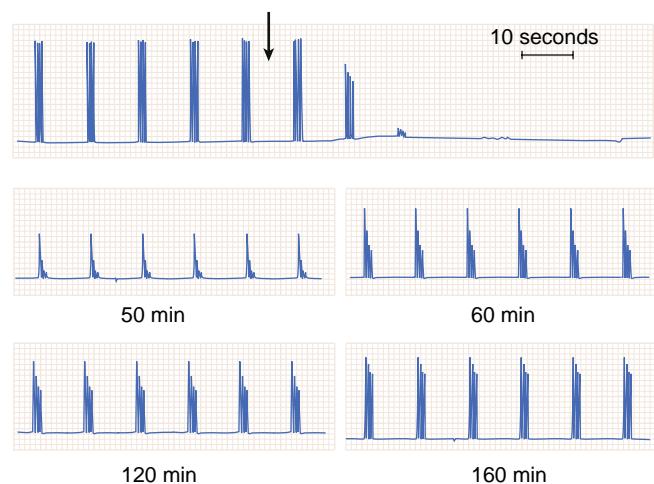
PANCURONIUM (n = 226)				ATRACURIUM OR VECURONIUM (n = 450)			
		PATIENTS WITH POPC				PATIENTS WITH POPC	
No. of patients	n	%	No. of Patients	n	%		
TOF $\geq$ 0.70	167	8	4.8	426	23	5.4	
TOF < 0.70	59	10	16.9*	24	1	4.2	

\* $P < .02$  versus patients in the same group with a train-of-four ratio of 0.70 or greater.

Results from a prospective, randomized, and blinded study of postoperative pulmonary complications (POPC) in a total of 691 adult patients undergoing abdominal, gynecologic, or orthopedic surgery and receiving either pancuronium, atracurium, or vecuronium.<sup>82</sup> In 4 of the 46 patients with POPC (1 in the pancuronium group and 3 in the atracurium and vecuronium groups), the train-of-four (TOF) ratio was not available. Because there were no significant differences in the two groups of patients given the intermediate-acting muscle relaxants, the data from these groups are pooled.



**Fig. 43.16** Predicted probabilities of a postoperative pulmonary complication (POPC) in different age groups in orthopedic, gynecologic, and major abdominal surgery with duration of anesthesia of less than 200 minutes. The red lines represent patients with residual neuromuscular block (train-of-four [TOF] < 0.70) after the administration of pancuronium; the blue lines represent patients with a TOF of 0.70 or greater after the administration of pancuronium, as well as all patients after the administration of atracurium and vecuronium, independent of the TOF ratio at the end of anesthesia.<sup>113</sup>



**Fig. 43.17** Typical recording of the mechanical response to train-of-four ulnar nerve stimulation after injection of 1 mg/kg of succinylcholine (arrow) in a patient with genetically determined abnormal plasma cholinesterase activity. The prolonged duration of action and the pronounced fade in the response indicate a phase II block.

transmission occurs. All four responses are reduced at the same degree [TOF ratio is 1.0] or 0). In contrast, some patients with genetically determined abnormal plasma cholinesterase activity who are given the same dose of succinylcholine undergo a nondepolarizing-like block characterized by fade in the response to TOF and tetanic stimulation and the occurrence of posttetanic facilitation of transmission (Fig. 43.17). This type of block is called a *phase II block* (dual, mixed, or desensitizing block). In addition, phase II blocks sometimes occur in genetically normal patients after repetitive bolus doses or a prolonged infusion of succinylcholine. Therefore, in a clinical setting, TOF stimulation can be used to distinguish depolarizing phase I block and phase II block. Patients with normal plasma cholinesterase activity would recover from the neuromuscular block within a few minutes, showing four equally weak responses (TOF ratio 1.0), which quickly become stronger (still at TOF ratio 1.0). In contrast, patients with abnormal plasma cholinesterase activity and subsequent phase II block would not recover quickly and will return with a TOF count of 1, slowly increasing to 2, 3, and last 4 counts—then having a fade of TOF (TOF-ratio < 1.0) during recovery as seen with nondepolarizing block.

From a therapeutic point of view, a phase II block in normal patients must be differentiated from a phase II block in patients with abnormal cholinesterase activity. In healthy patients, a phase II block can be antagonized by administering a cholinesterase inhibitor a few minutes after discontinuation of succinylcholine. In patients with abnormal genotypes, however, the effect of intravenous injection of a cholinesterase inhibitor (e.g., neostigmine) is unpredictable because it inhibits acetylcholinesterase and plasma-cholinesterase. For example, neostigmine can potentiate the block dramatically, temporarily improve neuromuscular transmission, and then potentiate the block or partially reverse the block, all depending on the time elapsed since administration of succinylcholine and the dose of neostigmine given. Therefore, unless the cholinesterase genotype is known to be normal, antagonism of a phase II block with a cholinesterase inhibitor should be undertaken with extreme caution. Even if neuromuscular function improves promptly, patient surveillance should continue for at least 1 hour.

## Use of Nerve Stimulators in Daily Clinical Practice

Whenever a neuromuscular blocking drug is administered to a patient, objective monitoring of the evoked response using recording equipment is the best way to evaluate the neuromuscular block.<sup>121a</sup> However, tactile and visual evaluation are still common forms of clinical neuromuscular monitoring, not least when recording equipment is not available or considered unreliable. The following is a description of how to use nerve stimulators with or without recording equipment (objective monitoring).

### PREPARATIONS BEFORE INDUCTION OF ANESTHESIA AND ADMINISTRATION OF THE NEUROMUSCULAR BLOCKING AGENT

First, for reliable stimulation, careful cleansing of the skin and proper placement and fixation of electrodes are essential. When the ulnar nerve is used for nerve stimulation, one should take advantage of the fact that the nerve follows the artery by placing the electrodes above the pulse. This placement gives the best response (see Fig. 43.1). Second, every effort should be taken to prevent central cooling, as well as cooling of the extremity being evaluated. Both central and local surface cooling of the adductor pollicis muscle can reduce twitch tension and the TOF ratio.<sup>122-124</sup> Peripheral cooling can affect nerve conduction, decrease the rate of release of acetylcholine and muscle contractility, increase skin impedance, and reduce blood flow to the muscles, thus decreasing the rate of removal of muscle relaxant from the neuromuscular junction. These factors might account for the occasional and pronounced difference in muscle response between a cold extremity and the contralateral warm extremity.<sup>125</sup>

### USE OF A NERVE STIMULATOR DURING INDUCTION OF ANESTHESIA

The nerve stimulator should be attached to the patient before induction of anesthesia but should not be turned on until after the patient is unconscious.

Single-twitch stimulation at 1 Hz can be used initially when seeking supramaximal stimulation. However, after supramaximal stimulation has been ensured and before the muscle relaxant is injected, the recording equipment (when using objective monitoring) should be calibrated to ensure that the response is in the measurement window and the response to 1 Hz stimulation is set to 100%. Currently, all commercially available devices have an automatic calibration modus. Without calibration, the recorded response to nerve stimulation might differ significantly from the visual or tactile response throughout all levels of neuromuscular block; therefore, the mode of stimulation should be changed to TOF (or 0.1-Hz twitch stimulation). When the response to this stimulation is observed (the control response), the neuromuscular blocking drug is injected. However, devices with integrated impedance measurement do not need calibration, but at least one TOF stimulation without NMBA should be registered, allowing to normalize the recovery TOF-ratio. Although the trachea is often intubated when the response to TOF stimulation disappears, postponement of this procedure for 30 to 90 seconds, depending on the muscle relaxant used, usually produces better conditions.

When possible, the response to nerve stimulation should be evaluated at the thumb (rather than at the fifth finger). Direct stimulation of the muscle often causes subtle movement of the fifth finger when no response is present at the thumb. Finally, the different sensitivities of various muscle groups to neuromuscular blocking drugs should always be kept in mind.

### USE OF A NERVE STIMULATOR DURING SURGERY

If tracheal intubation is facilitated by the administration of succinylcholine, no more muscle relaxant should be given until the response to nerve stimulation reappears or the patient shows other signs of returning neuromuscular function. If plasma cholinesterase activity is normal, the muscle response to TOF nerve stimulation reappears within 4 to 8 minutes.

When a nondepolarizing neuromuscular drug is used for tracheal intubation, a longer-lasting period of intense block usually follows. During this period of no response to TOF and single-twitch stimulation, the time until the return of response to TOF stimulation can be evaluated by PTC (see Fig. 43.9 and Fig. 43.18).

For most surgical procedures requiring muscle relaxation, it is not necessary to have a deep or intense block, provided that the patient is adequately anesthetized. If a nondepolarizing relaxant is used, a moderate level of neuromuscular block with one or two responses to TOF stimulation is sufficient. However, because the respiratory muscles (including the diaphragm) are more resistant to neuromuscular blocking drugs than the peripheral muscles are, the patient may breathe, hiccup, or even cough at this moderate level of block. Moreover, tonus of the diaphragm might impede the surgical conditions, especially during abdominal laparoscopic surgery. To ensure paralysis of the diaphragm, neuromuscular block of the peripheral muscles must be deep so that the PTC is 1-3 at the thumb.

The disadvantages of sustaining a deep or intense neuromuscular block is that at these levels of block, the muscles

	During induction			During surgery				In the recovery room
	Thiopental/propofol	Supramaximal stimulation	Tracheal intubation	Intense blockade	Deep blockade	Moderate blockade	Reversal	
Single twitch		1.0 Hz	0.1 Hz					
TOF				1.0 Hz		1.0 Hz	1.0 Hz	?
PTC					1.0 Hz	1.0 Hz		
DBS								1.0 Hz

**Fig. 43.18** Diagram showing when the different modes of electrical nerve stimulation can be used during clinical anesthesia. *Dark areas* indicate appropriate use and *light areas*, less effective use. Modes of nerve stimulation are train-of-four (TOF) stimulation; posttetanic count (PTC); double-burst stimulation (DBS); and the question mark (?), indicating that TOF is less useful in the recovery room unless measured with mechanomyography, electromyography, or acceleromyography. (See text for further explanation.)

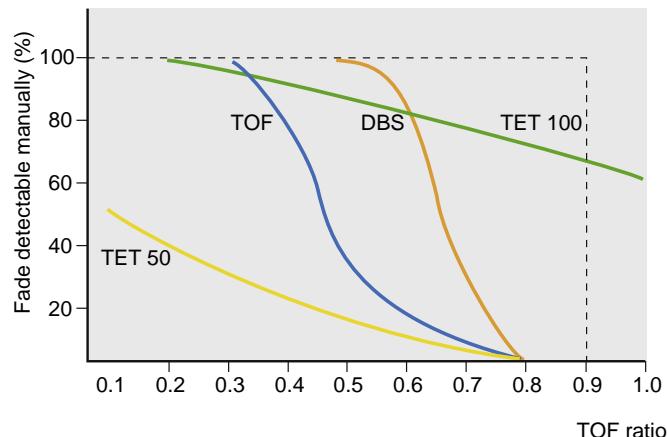
are completely paralyzed and the patient cannot signal awareness with voluntary or involuntary movements. Another disadvantage is that deep or intense block cannot readily be reversed by neostigmine. Only sugammadex can reverse a deep or intense neuromuscular block (if caused by rocuronium or vecuronium).

### USE OF A NERVE STIMULATOR DURING REVERSAL OF NEUROMUSCULAR BLOCK

Antagonism of nondepolarizing neuromuscular block is most often facilitated with a cholinesterase inhibitor, such as neostigmine, or with the selective relaxant binding agent sugammadex when the neuromuscular block is achieved using rocuronium or vecuronium.

Antagonism with neostigmine should not be initiated before at least all four responses to TOF stimulation are present. Reversal of neuromuscular block will not be hastened and can possibly be delayed by giving neostigmine when no response to peripheral nerve stimulation is present. Moreover, even when there are four responses to TOF stimulation, the reversal is slow and insufficient in some patients. With a large dose of neostigmine (e.g., 5 mg/70 kg), the median time to achieve a TOF ratio of 0.90 is 15 to 20 minutes, and it will take approximately 90 to 120 minutes to achieve a TOF ratio of 0.90 in 95% of the patients after an intermediate-acting neuromuscular blocking drug (e.g., rocuronium).<sup>126</sup> Conversely, a large dose of neostigmine after full recovery might give a paradoxical block with decreasing TOF ratio.<sup>127-131</sup>

When rocuronium or vecuronium is used, the selective relaxant binding drug sugammadex can be used for reversal.<sup>104,105</sup> Sugammadex encapsulates rocuronium and vecuronium with a high affinity, thereby antagonizing the neuromuscular blocking effect. Three different doses of sugammadex are recommended according to the level of block. A large dose (16 mg/kg) is given during intense block (no response to PTC stimulation),<sup>93,94</sup> a medium dose (4 mg/kg) during deep block (at least one response to PTC),<sup>95-97</sup> and a low dose (2 mg/kg) during moderate block (two or more responses to TOF stimulation).<sup>104-106</sup> In most patients,



**Fig. 43.19** Fade detectable by feel in the response to train-of-four (TOF), double-burst stimulation (DBS<sub>3,3</sub>), and 50- and 100-Hz tetanic stimulation (TET 50 and TET 100) in relation to the true TOF ratio, as measured mechanically. The axis indicates the percentage of instances in which fade can be detected at a given TOF ratio.<sup>37,59,72</sup> It appears that it is not possible to exclude residual neuromuscular block by any of the methods. (See text for further explanation.)

all levels of neuromuscular block are reversed within 2 to 5 minutes. However, appropriate dosing requires neuromuscular monitoring and residual neuromuscular block can be excluded only with objective monitoring (TOF ratio, 0.9-1.0), even after routine use of sugammadex.<sup>107,132</sup>

During recovery of neuromuscular function, when all four responses to TOF stimulation can be felt, an estimation of the TOF ratio can be attempted. However, manual (tactile) evaluation of the response to TOF stimulation (Fig. 43.19) is not sensitive enough to exclude the possibility of residual neuromuscular block.<sup>37,72,118,133</sup> Greater sensitivity is achieved with DBS<sub>3,3</sub>, but even absence of manual fade in the DBS<sub>3,3</sub> response does not exclude clinically significant residual block (i.e., TOF 0.6-0.9).<sup>41,72</sup> Moreover, some patients might suffer from residual block, even after recovery to a TOF ratio of 0.9 to 1.0.<sup>77,81</sup> Therefore, manual evaluation of responses to nerve stimulation should always be considered in relation to reliable clinical signs and symptoms of residual neuromuscular block (Box 43.1).

### BOX 43.1 Clinical Tests of Postoperative Neuromuscular Recovery

#### Unreliable

- Sustained eye opening
- Protrusion of the tongue
- Arm lift to the opposite shoulder
- Normal tidal volume
- Normal or nearly normal vital capacity
- Maximum inspiratory pressure less than 40-50 cm H<sub>2</sub>O

#### More Reliable, But Still Not Excluding Residual Neuromuscular Block

- Sustained head lift for 5 s
- Sustained leg lift for 5 s
- Sustained handgrip for 5 s
- Sustained “tongue depressor test”
- Maximum inspiratory pressure

## When to Use a Peripheral Nerve Stimulator

In clinical practice, significant residual block can be excluded with certainty only if an objective method of neuromuscular monitoring is used.<sup>78,79</sup> Therefore, good evidence-based practice dictates that clinicians should always quantitate the extent of neuromuscular recovery by objective monitoring.<sup>7-13</sup> Only a TOF ratio of 0.90 to 1.00 measured by objective monitoring ensures a low risk of clinically significant residual block.

However, in many departments, clinicians do not have access to equipment for measuring the degree of block.<sup>134</sup> How then to evaluate and, as far as possible, exclude a clinically significant postoperative block? First, long-acting neuromuscular blocking drugs should not be used. Second, the tactile response to TOF nerve stimulation should be

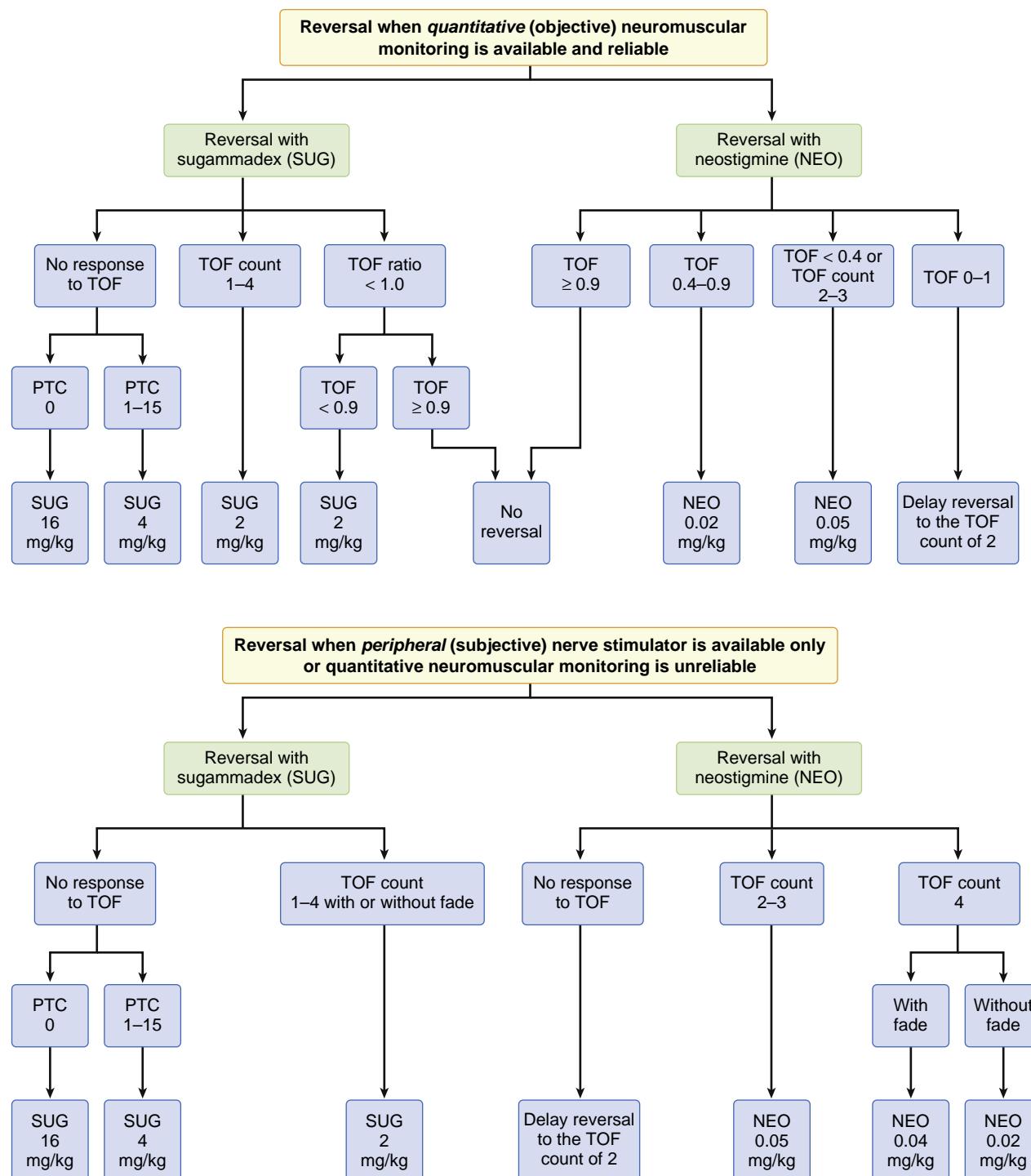
evaluated during surgery. Third, if possible, total twitch suppression should be avoided. The neuromuscular block should be managed so that there are always one or two tactile TOF responses. Fourth, the block should be antagonized at the end of the procedure, preferably with sugammadex if rocuronium or vecuronium have been used. When using neostigmine, reversal should not be initiated before at least two to four responses to TOF stimulation are present. Fifth, during recovery, tactile evaluation of the response to DBS is preferable to tactile evaluation of the response to TOF stimulation because it is easier to manually assess fade in the DBS than in the TOF response. Sixth, the clinician should recognize that the absence of tactile fade in both the TOF and DBS responses does not exclude significant residual block. Finally, reliable clinical signs and symptoms of residual block (see [Box 43.1](#)) should be considered in relation to the response to nerve stimulation. [Fig. 43.20](#) shows how to minimize the risk of residual block with or without objective monitoring.<sup>135</sup>

In view of the uncertainty connected with the use of clinical tests of postoperative neuromuscular recovery and tactile evaluation of the response to nerve stimulation, all patients receiving neuromuscular blocking drugs should be monitored with an objective monitor. Whether the functioning of such a neuromuscular transmission analyzer is based on EMG, MMG, AMG, CPM, CMG, or PMG is not crucial as long as the apparatus is used appropriately.

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 Complete references available online at [expertconsult.com](http://expertconsult.com).



**Fig. 43.20** Suggestion to diminish the incidence of residual curarization by neostigmine (NEO) or sugammadex (SUG) according to the level of block, determined with a nerve stimulator (quantitative or peripheral). Note that only a quantitative measured TOF ratio of 0.90 to 1.00 ensures low risk of clinically significant residual block. PTC, Posttetanic count; TOF, train-of-four. (Modified from Kopman AF, Eikermann M. Antagonism of non-depolarising neuromuscular block: current practice. *Anaesthesia*. 2009;64[Suppl 1]:22–30.)

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CARLOS A. ARTIME and CARIN A. HAGBERG

## KEY POINTS

- One of the fundamental responsibilities of the anesthesiologist is to mitigate the adverse effects of anesthesia on the respiratory system by maintaining airway patency and ensuring adequate ventilation and oxygenation. The term *airway management* refers to this practice and is a cornerstone of anesthesia.
- Successful airway management requires a range of knowledge and skill sets—specifically, the ability to predict difficulty with airway management and to formulate an airway management strategy, as well as the skills to execute that strategy using the wide array of airway devices available.
- The American Society of Anesthesiologists' *Practice Guidelines for Management of the Difficult Airway* and the accompanying Difficult Airway Algorithm provide guidelines for the evaluation of the airway and preparation for difficult airway management and can guide clinical decision making when an anesthesiologist is faced with a known or potentially difficult airway. Cognitive aids, such as the Vortex approach, are useful to help implement airway algorithms in an emergency situation.
- A detailed understanding of airway anatomy is essential for the anesthesia provider.
- A complete evaluation of the airway and knowledge of difficult airway predictors can alert the anesthesiologist to the potential for difficulty with airway management and allow for appropriate planning.
- Apneic oxygenation can be used to prolong the duration of apnea without desaturation and is increasingly being adopted during the management of both difficult and routine airways.
- Application of local anesthesia to the airway or induction of general anesthesia is usually required to facilitate airway management, to provide comfort for the patient, and to blunt airway reflexes and the hemodynamic response to airway instrumentation.
- Over the past 30 years, the laryngeal mask airway (LMA) has emerged as one of the most important developments in airway devices.
- Tracheal intubation establishes a definitive airway, provides maximal protection against aspiration of gastric contents, and allows for positive-pressure ventilation with higher airway pressures than via a face mask or supraglottic airway.
- Flexible scope intubation of the trachea in an awake, spontaneously ventilating, and cooperative patient is the *gold standard* for the management of the difficult airway.
- Invasive airways are indicated as a rescue technique when attempts at establishing a noninvasive airway fail. The anesthesia practitioner should become proficient with techniques for transtracheal jet ventilation and cricothyrotomy.
- Extubation is a critical component of airway management with the potential for significant complications. The plan for extubation of the trachea must be preemptively formulated and includes a strategy for reintubation should the patient be unable to maintain an adequate airway after extubation.

## Introduction

General anesthesia is associated with various effects on the respiratory system, including the loss of airway patency, loss of protective airway reflexes, and hypoventilation or apnea. Therefore one of the fundamental responsibilities of the anesthesiologist is to establish airway patency and to ensure adequate ventilation and oxygenation. The term *airway management* refers to the practice of establishing and securing a patent airway and is a cornerstone of anesthetic practice. Traditionally, ventilation via a mask and tracheal

intubation have been the foundation of airway management; however, in the past 30 years, the laryngeal mask airway (LMA) has emerged as one of the most important developments in airway devices.

Because failure to secure a patent airway can result in hypoxic brain injury or death in only a few minutes, difficulty with airway management has potentially grave implications. Analysis of the American Society of Anesthesiologists (ASA) Closed Claims Project database has demonstrated that the development of an airway emergency increases the odds of death or brain damage by 15-fold.<sup>1</sup>

Although the proportion of claims attributable to airway-related complications has decreased over the past 3 decades, airway complications are still the second-most common cause of claims.<sup>2</sup> In 2011, the Royal College of Anaesthetists and the Difficult Airway Society (DAS) of the United Kingdom reported the results of the 4th National Audit Project (NAP4), a 1-year audit aimed at determining the incidence of major complications of airway management in anesthesia. NAP4 identified 133 major airway-related events in the perioperative period resulting in 16 deaths—a mortality incidence of 1 per 180,000 anesthetics—a number that could be as high as 1 per 50,000 anesthetics when underreporting is considered.<sup>3</sup> The most common airway problems in the NAP4 study were failure, delay, or difficulty in securing the airway; aspiration of gastric contents; and extubation-related complications. Poor assessment of the airway, poor planning, and a lack of personal and/or institutional preparedness for managing difficulty with airway management were the most common contributing factors.<sup>4</sup>

Studies such as these highlight the importance of successful airway management, which requires a range of knowledge and skill sets—specifically, the ability to predict difficulty with airway management, to formulate an airway management strategy, and to have the skills necessary to execute that strategy using the wide array of available airway devices.<sup>5</sup> Development of these skills should be an ongoing endeavor for all anesthesiologists. As with any manual skill, continued practice improves performance and may reduce the likelihood of complications. New airway devices are continually being introduced into the clinical arena, each with unique properties that may be advantageous in certain situations. Becoming familiar with new devices under controlled conditions is important for the anesthesiology practitioner—the difficult airway is not an appropriate setting during which to experiment with a new technique.

## ALGORITHMS FOR MANAGEMENT OF THE DIFFICULT AIRWAY

### The American Society of Anesthesiologists Algorithm

In 1993, the ASA published the first *Practice Guidelines for Management of the Difficult Airway*, which was written with the intent to “facilitate the management of the difficult airway and to reduce the likelihood of adverse outcomes.”<sup>6</sup> The most recent update to this report, published in 2013, defines the difficult airway as “the clinical situation in which a conventionally trained anesthesiologist experiences difficulty with ventilation of the upper airway via a mask, difficulty with tracheal intubation, or both” and provides guidelines for the evaluation of the airway and preparation for difficult airway management, including a Difficult Airway Algorithm (DAA) intended to guide clinical decision making when an anesthesiologist is faced with a known or potential difficult airway (Fig. 44.1).<sup>7</sup> The ASA DAA begins with a consideration of the relative clinical merits and feasibility of four basic management choices: (1) awake intubation versus intubation after induction of general anesthesia, (2) noninvasive techniques versus invasive techniques (i.e., surgical or percutaneous airway) for the initial approach to intubation, (3) video-assisted laryngoscopy (VAL) as an initial approach to intubation, and (4) preservation versus ablation of spontaneous ventilation.

The ASA DAA does not follow a linear decision-making tree, as the advanced cardiac life support (ACLS) algorithms do. It can be better understood and remembered by considering it as three separate scenarios: (1) predicted difficult airway (awake intubation), (2) difficult intubation with adequate oxygenation/ventilation (the “non-emergency” pathway), and (3) difficult intubation without adequate oxygenation/ventilation (the “cannot intubate, cannot oxygenate” [CICO] scenario or the “emergency” pathway).

### Other Difficult Airway Algorithms

In addition to the ASA, several different national anesthesia societies have published their own guidelines for management of the difficult airway, including the Difficult Airway Society (DAS) from the United Kingdom,<sup>8</sup> the Canadian Airway Focus Group (CAFG),<sup>9,10</sup> the French Society of Anesthesia and Intensive Care (SFAR),<sup>11</sup> the German Society of Anesthesiology and Intensive Care Medicine (DGAI),<sup>12</sup> the Italian Society for Anesthesia and Intensive Care (SIAARTI),<sup>13</sup> and the Japanese Society of Anesthesiologists.<sup>14</sup> All of these include recommendations for the prediction of the difficult airway and suggest awake intubation as a management strategy (with the exception of the DAS guidelines) and all incorporate algorithms for both unanticipated difficult intubation with adequate oxygenation and the CICO scenario. Common elements include a focus on awakening the patient in the setting of a difficult intubation with adequate ventilation, the use of the LMA as a rescue for difficult mask ventilation, and emergency front of neck access (FONA) in the CICO scenario. The primary differences in these algorithms are in specific details, such as the number of intubation attempts suggested, the specific alternate devices recommended for difficult intubation, and the organization of the algorithm.<sup>15</sup>

### Human Factors and Cognitive Aids

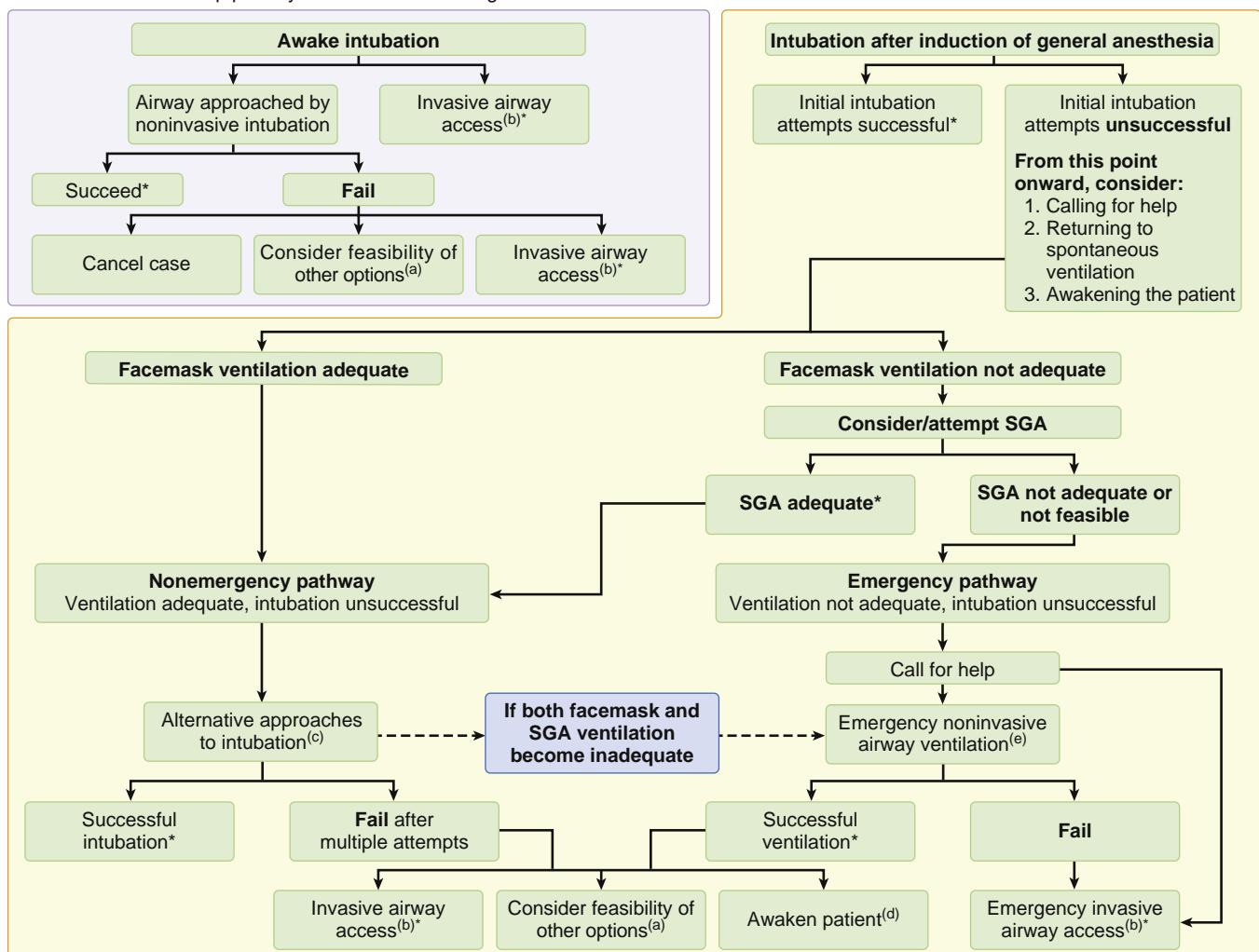
There has been growing attention to the influence of “human factors” on difficult airway management—namely, human behaviors, abilities, shortcomings, and biases as well as individual and team performance. Studies such as NAP4 have shown that these human factors contribute to an adverse airway outcome in over 40% of cases.<sup>3</sup> The use of airway checklists, preprocedural team briefings, and cognitive aids are all strategies for addressing human factor challenges.<sup>16</sup>

The Vortex approach, conceived by Dr. Nicholas Chrimes, a specialist anaesthetist in Melbourne, Australia, is one such cognitive aid designed to facilitate management of the unanticipated difficult airway.<sup>17</sup> Rather than relying on complex algorithms that are based on decision trees, the Vortex model utilizes a visual aid in the shape of a funnel or vortex (Fig. 44.2) to guide the airway practitioner through the three basic nonsurgical airway techniques (face-mask ventilation, supraglottic airway [SGA], and tracheal intubation). If after an “optimal attempt” at each of these nonsurgical modalities alveolar oxygen delivery has not been achieved, then one “travels down the vortex,” and an emergency surgical airway is indicated. Because this strategic approach is more conceptual, it is simple enough to be utilized and recalled during a stressful airway emergency.

## Functional Airway Anatomy

A detailed understanding of airway anatomy is essential for the anesthesiologist. Various aspects of airway

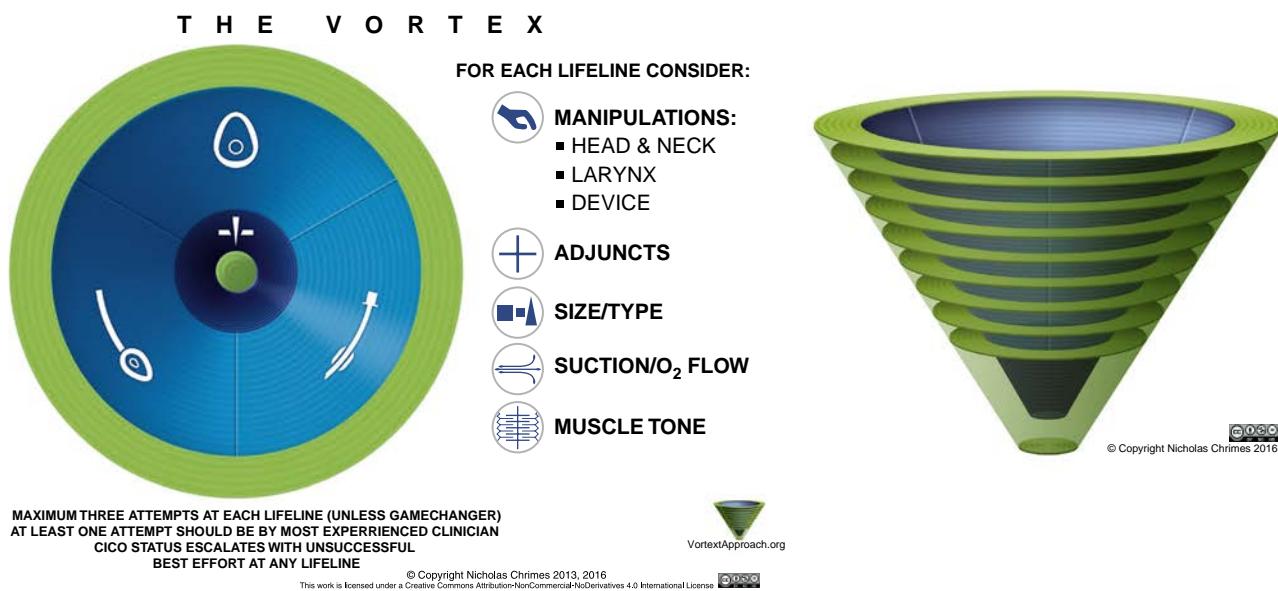
1. Assess the likelihood and clinical impact of basic management problems:
  - Difficulty with patient cooperation or consent
  - Difficult mask ventilation
  - Difficult supraglottic airway placement
  - Difficult laryngoscopy
  - Difficult intubation
  - Difficult surgical airway access
2. Actively pursue opportunities to deliver supplemental oxygen throughout the process of difficult airway management.
3. Consider the relative merits and feasibility of basic management choices:
  - Awake intubation vs. intubation after induction of general anesthesia
  - Noninvasive technique vs. invasive techniques for the initial approach to intubation
  - Video-assisted laryngoscopy as an initial approach to intubation
  - Preservation vs. ablation of spontaneous ventilation
4. Develop primary and alternative strategies:



\*Confirm ventilation, tracheal intubation, or SGA placement with exhaled CO<sub>2</sub>.

- Other options include (but are not limited to): surgery using facemask or supraglottic airway (SGA) anesthesia (e.g., LMA, ILMA, laryngeal tube), local anesthesia infiltration, or regional nerve blockade. Pursuit of these options usually implies that mask ventilation will not be problematic. Therefore these options may be of limited value if this step in the algorithm has been reached via the Emergency Pathway.
- Invasive airway access includes surgical or percutaneous airway, jet ventilation, and retrograde intubation.
- Alternative difficult intubation approaches include (but are not limited to): video-assisted laryngoscopy, alternative laryngoscope blades, SGA (e.g., LMA or ILMA) as an intubation conduit (with or without fiberoptic guidance), fiberoptic intubation, intubating stylet or tube changer, light wand, and blind oral or nasal intubation.
- Consider re-preparation of the patient for awake intubation or canceling surgery.
- Emergency noninvasive airway ventilation consists of a SGA.

**Fig. 44.1** The American Society of Anesthesiologists' Difficult Airway Algorithm. (From Apfelbaum JL, Hagberg CA, Caplan RA, et al. Practice guidelines for management of the difficult airway: an updated report by the American Society of Anesthesiologists Task Force on Management of the Difficult Airway. *Anesthesiology*. 2013;118:251–270.)



A

B

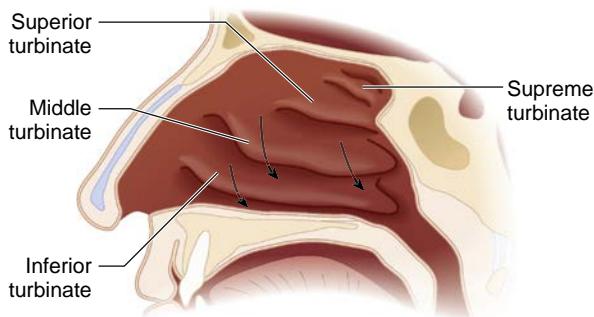
**Fig. 44.2** (A) The Vortex implementation tool. (B) Lateral aspect of the Vortex in three dimensions, demonstrating the funnel concept. (From Chrimes N. The Vortex: a universal 'high-acuity implementation tool' for emergency airway management. *Br J Anaesth.* 2016;117:i20–i27.)

management depend on a working knowledge of the anatomy involved, including airway assessment, preparation of the airway for awake intubation, and the proper use of airway devices. Knowledge of normal anatomy and anatomic variations that may render airway management more difficult helps with the formulation of an airway management plan. Because some critical anatomic structures may be obscured during airway management, the anesthesiologist must be familiar with the interrelationship between different airway structures.

The airway can be divided into the upper airway, which includes the nasal cavity, the oral cavity, the pharynx, and the larynx; and the lower airway, which consists of the tracheobronchial tree.

## NASAL CAVITY

The airway begins functionally at the naris, the external opening of the nasal passages. The nasal cavity is divided into the right and left nasal passages (or fossae) by the nasal septum, which forms the medial wall of each passage. The septum is formed by the septal cartilage anteriorly and by two bones posteriorly—the ethmoid (superiorly) and the vomer (inferiorly). Nasal septal deviation is common in the adult population<sup>18</sup>; therefore the more patent side should be determined before passing instrumentation through the nasal passages. The lateral wall of the nasal passages is characterized by the presence of three turbinates (or conchae) that divide the nasal passage into three scroll-shaped meatuses (Fig. 44.3). The inferior meatus, between the inferior turbinate and the floor of the nasal cavity, is the preferred pathway for passage of nasal airway devices<sup>19</sup>; improper placement of objects in the nose can result in avulsion of a turbinate.<sup>20,21</sup> The roof of the nasal cavity is formed by the cribriform plate, part of the ethmoid bone. This fragile structure, if fractured, can result in communication between the nasal and intracranial cavities and a resultant leakage of cerebrospinal fluid. Because the mucosal



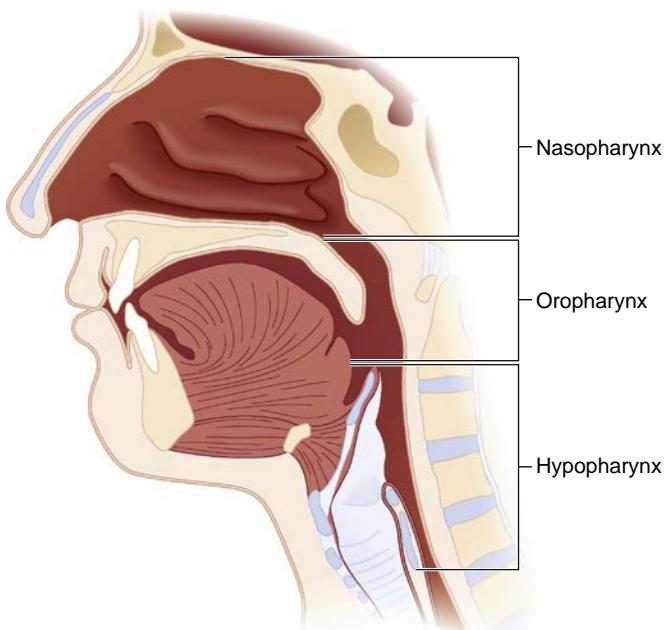
**Fig. 44.3** Lateral wall of the nasal cavity. (From Redden RJ. Anatomic considerations in anesthesia. In: Hagberg CA, ed. *Handbook of Difficult Airway Management*. Philadelphia: Churchill Livingstone; 2000, p. 3, Fig. 1.2.)

lining of the nasal cavity is highly vascular, vasoconstrictor should be applied, usually topically, before instrumentation of the nose to minimize epistaxis. The posterior openings of the nasal passages are the choanae, which lead into the nasopharynx.

## ORAL CAVITY

Because of the relatively small size of the nasal passages and the significant risk of trauma, the mouth is often used as a conduit for airway devices. Many airway procedures require adequate mouth opening, which is accomplished by rotation within the temporomandibular joint (TMJ) and subsequent opening by sliding (also known as *protrusion* or *subluxation*) of the condyles of the mandible within the TMJ.<sup>22</sup>

The oral cavity leads to the oropharynx and is inferiorly bounded by the tongue and superiorly by the hard and soft palates. The hard palate, formed by parts of the maxilla and the palatine bone, makes up the anterior two thirds of the roof of the mouth; the soft palate (velum palatinum), a fibromuscular fold of tissue attached to the hard palate, forms the posterior one third of the roof of the mouth.



**Fig. 44.4** Sagittal section through the head and neck showing the subdivisions of the pharynx. (From Redden RJ. Anatomic considerations in anesthesia. In: Hagberg CA, ed. *Handbook of Difficult Airway Management*. Philadelphia: Churchill Livingstone; 2000, p. 7, Fig. 1.6.)

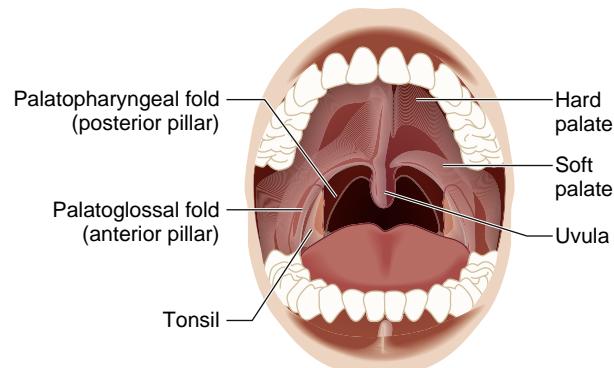
The tongue is anchored to various structures by its extrinsic musculature; of these, the most clinically relevant to the anesthesiologist is the genioglossus, which connects the tongue to the mandible. The jaw-thrust maneuver uses the sliding component of the TMJ to move the mandible and the attached tongue anteriorly, thereby relieving airway obstruction caused by the posterior displacement of the tongue into the oropharynx.<sup>22</sup>

Beneath the tongue, the mylohyoid muscles separate the floor of the mouth into the sublingual space superiorly and the submental space inferiorly. Cellulitis (Ludwig's angina) or hematoma formation in these spaces can cause elevation and posterior displacement of the tongue and resultant airway obstruction.<sup>23</sup>

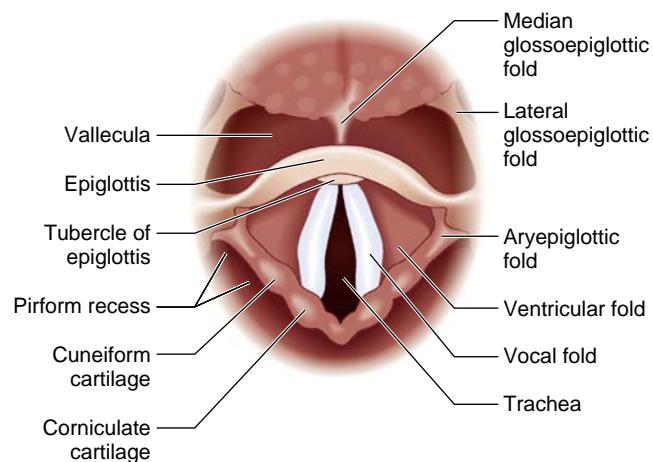
## PHARYNX

The pharynx is a muscular tube that extends from the base of the skull down to the level of the cricoid cartilage and connects the nasal and oral cavities with the larynx and esophagus. The posterior wall of the pharynx is made up of the buccopharyngeal fascia, which separates the pharynx from the retropharyngeal space. Improper placement of a gastric or tracheal tube can result in laceration of this fascia and the formation of a retropharyngeal dissection.<sup>24,25</sup> The pharyngeal musculature in the awake patient helps maintain airway patency; loss of pharyngeal muscle tone is one of the primary causes of upper airway obstruction during anesthesia.<sup>26,27</sup> A chin lift with mouth closure increases longitudinal tension in the pharyngeal muscles, counteracting the tendency of the pharyngeal airway to collapse.<sup>28</sup>

The pharynx can be divided into the nasopharynx, the oropharynx, and the hypopharynx (Fig. 44.4). Along the superior and posterior walls of the nasopharynx are the adenoid tonsils, which can cause chronic nasal obstruction



**Fig. 44.5** Oral cavity and oropharynx. (From Redden RJ. Anatomic considerations in anesthesia. In: Hagberg CA, ed. *Handbook of Difficult Airway Management*. Philadelphia: Churchill Livingstone; 2000, p. 8, Fig. 1.7.)

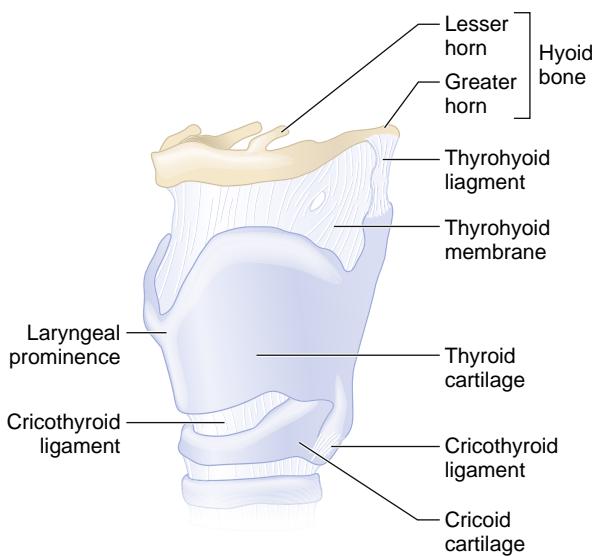


**Fig. 44.6** Larynx as visualized from the hypopharynx. (From Redden RJ. Anatomic considerations in anesthesia. In: Hagberg CA, ed. *Handbook of Difficult Airway Management*. Philadelphia: Churchill Livingstone; 2000, p. 8, Fig. 1.8.)

and, when enlarged, can cause difficulty passing airway devices. The nasopharynx ends at the soft palate; this region is termed the *velopharynx* and is a common site of airway obstruction in both awake and anesthetized patients.<sup>26</sup> The oropharynx begins at the soft palate and extends inferiorly to the level of the epiglottis. The lateral walls contain the palatoglossal folds and the palatopharyngeal folds, also termed the *anterior* and *posterior faucial (tonsillar) pillars*, respectively; these folds contain the palatine tonsils, which can hypertrophy and cause airway obstruction (Fig. 44.5). The base of the tongue lies in the anterior aspect of the oropharynx, connected to the epiglottis by the glossoepiglottic folds, which bound paired spaces known as the *valleculae* (although these are frequently referred to as a single space called the *vallecula*). The hypopharynx begins at the level of the epiglottis and terminates at the level of the cricoid cartilage, where it is continuous with the esophagus. The larynx protrudes into the hypopharynx, creating two piriform recesses on either side (Fig. 44.6).

## LARYNX

The larynx is a complex structure of cartilage, muscles, and ligaments that serves as the inlet to the trachea and



**Fig. 44.7** Cartilaginous and membranous components of the larynx. (From Redden RJ. Anatomic considerations in anesthesia. In: Hagberg CA, ed. *Handbook of Difficult Airway Management*. Philadelphia: Churchill Livingstone; 2000, p. 10, Fig. 1.9.)

performs various functions, including phonation and airway protection. The cartilaginous framework of the larynx is made up of nine separate cartilages: the thyroid and cricoid cartilages; the paired arytenoid, corniculate, and cuneiform cartilages; and the epiglottis. They are joined by ligaments, membranes, and synovial joints, and are suspended by the hyoid bone via the thyrohyoid ligaments and membrane (Fig. 44.7).

The thyroid cartilage is the largest of these cartilages and supports most of the soft tissues of the larynx. The superior thyroid notch and the associated laryngeal prominence (*Adam's apple*) are appreciable from the anterior neck and serve as important landmarks for percutaneous airway techniques and laryngeal nerve blocks. The cricoid cartilage, at the level of the sixth cervical vertebra, is the inferior limit of the larynx and is anteriorly connected to the thyroid cartilage by the cricothyroid membrane (CTM). It is the only complete cartilaginous ring in the airway. The arytenoid cartilages articulate with the posterior cricoid and are the posterior attachments for the vocal cords.

When viewed from the pharynx, as during direct laryngoscopy (DL), the larynx begins at the epiglottis, which is a cartilaginous flap that serves as the anterior border of the laryngeal inlet. It functions to divert food away from the larynx during the act of swallowing, although its role in this regard is not essential to prevent tracheal aspiration.<sup>29</sup> The anterior surface of the epiglottis is attached to the upper border of the hyoid bone by the hyoepiglottic ligament. The laryngeal inlet is bound laterally by the aryepiglottic folds, and posteriorly by the corniculate cartilages and the interarytenoid notch (see Fig. 44.6).

The space inferior to the laryngeal inlet down to the inferior border of the cricoid cartilage is the laryngeal cavity. The ventricular folds (also referred to as the *vestibular folds* or *false vocal cords*) are the most superior structure within the laryngeal cavity. Beneath these are the true vocal cords, which attach to the arytenoids posteriorly and the thyroid cartilage anteriorly, where they join together to form the

anterior commissure. The space between the vocal cords is termed the *glottis*; the portion of the laryngeal cavity above the glottis is known as the *vestibule*, and the portion inferior to the vocal cords is known as the *subglottis*.

## TRACHEA AND BRONCHI

The trachea begins at the level of the cricoid cartilage and extends to the carina at the level of the fifth thoracic vertebra; this length is 10 to 15 cm in the adult. It consists of 16 to 20 C-shaped cartilaginous rings that open posteriorly and are joined by fibroelastic tissue; the trachealis muscle forms the posterior wall of the trachea. At the carina, the trachea bifurcates into the right and left mainstem bronchi. In the adult, the right mainstem bronchus branches off at a more vertical angle than the left mainstem bronchus, resulting in a greater likelihood of foreign bodies and endotracheal tubes (ETTs) entering the right bronchial lumen.<sup>30</sup>

## Airway Assessment

Although the anesthesia provider should always be prepared for potential difficulty with airway management, the ability to predict the difficult airway in advance is obviously desirable. Certain physical findings or details from the patient's history can be prognostic of difficulty with mask ventilation, supraglottic airway placement, laryngoscopy, tracheal intubation, or the performance of a surgical airway. No single test has been devised to predict a difficult airway accurately 100% of the time; however, a complete evaluation of the airway and knowledge of the difficult airway predictors can alert the anesthesiologist to the potential for difficulty and allow for appropriate planning.

## TRADITIONAL METRICS

Airway assessment should begin with a directed patient history whenever possible.<sup>7</sup> One of the most predictive factors for difficult intubation is a history of previous difficulty with intubation.<sup>31</sup> On the other hand, a history of a previously easy airway does not rule out the possibility of difficulty with ventilation or intubation. In either case, the patient interview should specifically address changes in weight, symptomatology, and pathologic conditions since the last induction of an anesthetic (if there was one), and attempts should be made at obtaining prior anesthetic records—they may yield useful information concerning airway management. The presence of pathologic states that increase the risk of a difficult airway should be elicited by performing a medical history. A focused review of systems can alert the anesthesiologist to other potential factors that may predict difficult airway management; for example, a history of snoring has been shown to be predictive of difficult mask ventilation.<sup>32,33</sup>

A physical examination of the airway should be preoperatively performed, when possible, to detect any physical characteristics that may suggest a difficult airway.<sup>7</sup> The specific characteristics that should be evaluated in this examination are listed in Box 44.1.

The visual inspection of the face and neck should focus on any physical characteristics that may indicate the potential

### BOX 44.1 Components of the Physical Examination of the Airway

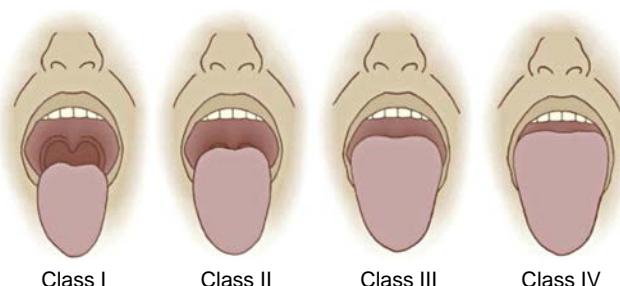
- Visual inspection of the face and neck
- Assessment of mouth opening
- Evaluation of oropharyngeal anatomy and dentition
- Assessment of neck range of motion (ability of the patient to assume the sniffing position)
- Assessment of the submandibular space
- Assessment of the patient's ability to slide the mandible anteriorly (test of mandibular prognathism)

for difficulty with airway management. These include obvious facial deformities, neoplasms involving the face or neck, facial burns, a large goiter, a short or thick neck, or a receding mandible. The presence of a beard has been shown to be associated with difficult ventilation attributable to the difficulty in obtaining a mask seal.<sup>32,33</sup> Cervical collars or cervical traction devices can interfere with both mask ventilation and DL. A neck circumference greater than 43 cm (17 inches) is associated with difficulty with tracheal intubation<sup>34</sup>; Brodsky demonstrated that a large neck circumference is, in fact, more predictive of difficulty with tracheal intubation than a high body mass index (BMI).<sup>35</sup>

Assessment of mouth opening and inspection of the oropharyngeal anatomy is achieved by instructing the patient to open his or her mouth as wide as possible. An interincisor distance of less than 3 cm (or 2 fingerbreadths), as measured from the upper to the lower incisors with maximal mouth opening, can suggest the possibility of difficult intubation<sup>7</sup>; some studies have used 4 or 4.5 cm as the cutoff.<sup>36</sup> A thorough inspection of the oropharynx can help identify pathologic characteristics that may result in difficulty with intubation, such as neoplasm, a high arched palate, or macroglossia. In 1983, Mallampati and associates described a clinical sign to predict difficult tracheal intubation based on the size of the base of the tongue.<sup>37</sup> A Mallampati classification of I to III is assigned, based on the visibility of the fau-  
cial pillars, uvula, and soft palate when the patient is seated upright with the head neutral, the mouth open, the tongue protruded, and no phonation.<sup>38</sup> Higher scores on the Mallampati classification indicate poor visibility of the oropharyngeal structures attributable to a large tongue relative to the size of the oropharyngeal space, and, subsequently, a more difficult laryngoscopy. The modified Mallampati classification described by Samsoon and Young,<sup>39</sup> which adds a fourth classification, is the most commonly used airway assessment test in current anesthesia practice and is defined as follows (Fig. 44.8):

- Class I: Faucial pillars, uvula, and soft palate are visualized.
- Class II: Base of the uvula and soft palate are visualized.
- Class III: Soft palate only is visualized.
- Class IV: Hard palate only is visualized.

As a stand-alone test, the modified Mallampati classification is insufficient for accurate prediction of difficult intubation; however, it may have clinical utility in combination with other difficult airway predictors.<sup>40</sup> Some studies support obtaining a Mallampati score with the head in full extension to improve the predictive value of the test.<sup>38,41</sup>



**Fig. 44.8** Modified Mallampati classification as described by Samsoon and Young. Classes are differentiated on the basis of the structures visualized: class I—soft palate, fauces, uvula, tonsillar pillars; class II—soft palate, fauces, uvula; class III—soft palate, base of the uvula; class IV—soft palate not visible. (From Mallampati SR. Recognition of the difficult airway. In: Benumof JL, ed. *Airway Management Principles and Practice*. St Louis: Mosby; 1996, p. 132.)

A Mallampati *zero* classification has been proposed when the epiglottis can be visualized during examination of the oropharynx; this finding is usually associated with easy laryngoscopy,<sup>42,43</sup> although difficulty with airway management attributable to a large, floppy epiglottis in patients with a Mallampati zero classification can occur.<sup>44,45</sup>

An examination of dentition should be performed when the oropharyngeal anatomy is being evaluated.<sup>7</sup> Relatively long upper incisors can impair DL. Poor dentition and loose teeth increase the risk of dental trauma and present a risk of tooth dislodgment with subsequent aspiration; very loose teeth should be removed before laryngoscopy. Cosmetic dental work, such as veneers, caps, crowns, and bridges, are particularly susceptible to damage during airway management. Edentulousness is predictive of easy tracheal intubation but potentially difficult mask ventilation.<sup>46</sup>

The ideal positioning for DL is achieved by cervical flexion and atlantooccipital extension and is most commonly referred to as the *sniffing position*<sup>47</sup> (see Direct Laryngoscopy: Preparation and Positioning). Assessment of a patient's ability to assume this position should be included in the airway examination; an inability to extend the neck at the atlanto-occipital joint is associated with difficult intubation.<sup>48</sup> Head and neck mobility can also be quantitatively assessed by measuring the sternal distance between the sternal notch and the point of the chin with the head in full extension and the mouth closed. Distances less than 12.5 cm are associated with difficult intubation.<sup>49</sup> An assessment of overall neck range of motion can be performed by measuring the angle created by the forehead when the neck is fully flexed and then fully extended; a measurement of less than 80 degrees is predictive of difficult intubation.<sup>50</sup>

During DL, the tongue is displaced into the submandibular space; glottic visualization may be inadequate if this space is diminished because of a small mandible. This scenario is frequently referred to as an *anterior larynx*. A thyromental distance of less than 6.5 cm (3 fingerbreadths), as measured from the thyroid notch to the lower border of the mentum, is indicative of reduced mandibular space and may predict difficulty with intubation.<sup>36,49</sup> Compliance of this space should also be assessed; a lack of compliance or the presence of a mass is a nonreassuring finding.<sup>7</sup>

Tests of the ability for mandibular protraction (prognathism) have predictive value and should be included in the airway assessment. The inability to extend the lower

incisors beyond the upper incisors may be indicative of difficult laryngoscopy.<sup>51</sup> A similar evaluation, the upper lip bite test (ULBT) described by Khan and colleagues, has been shown to predict difficult laryngoscopy with higher specificity and less interobserver variability than the Mallampati classification; an inability of the lower incisors to bite the upper lip is associated with more difficult laryngoscopy.<sup>52,53</sup>

Although individual airway tests are limited by low sensitivity and positive predictive value, some multivariable assessments have been shown to have higher predictive power. The Mallampati score has been shown to have improved predictive value when combined with thyromental, sternal, and/or interincisor distances.<sup>49</sup> Models that use several risk factors, such as the Wilson risk sum score (weight, head and neck movement, jaw movement, receding mandible, and buck teeth) and the El-Ganzouri risk index (mouth opening, thyromental distance, Mallampati class, neck movement, prognathism, weight, and history of difficult intubation) have been developed in an attempt to improve the predictive value of airway assessment.<sup>50,54</sup> On the other hand, a recent large database study of an airway risk index that utilizes seven independent risk factors found that it does not improve prediction of difficult intubation.<sup>55</sup> Langeron and associates developed a computer-assisted model that uses complex interactions among several risk factors (BMI, mouth opening, thyromental distance, Mallampati class, and receding mandible) to predict difficult intubation more accurately than other models based on simpler statistical analyses.<sup>56</sup>

## NEW MODALITIES

Owing to the poor sensitivity and specificity of traditional metrics for airway assessment, a number of new modalities are being studied. The use of point-of-care ultrasonography for the prediction of difficult laryngoscopy and intubation has shown some promise in small studies, but its overall value has yet to be established.<sup>57</sup> Computed tomographic images of the head and neck can be used to create three-dimensional virtual endoscopic images that can be used for planning difficult airway management, particularly for patients with complex airway pathology.<sup>58</sup> Early studies of facial image analysis have also shown promise for the use of this technology in predicting difficult intubation.<sup>59</sup>

## Physiologic Concepts for Airway Management

### PREOXYGENATION

With the induction of anesthesia, hypoxemia can quickly develop as a result of hypoventilation or apnea in combination with decreases in functional residual capacity (FRC) attributable to the supine position, muscle paralysis, and the direct effects of the anesthetic agents themselves. Preoxygenation, the process of replacing nitrogen in the lungs with oxygen, provides an increased length of time before hemoglobin desaturation occurs in an apneic patient. This lengthened *apnea time* provides an improved margin of safety while the anesthesiologist secures the airway and resumes ventilation. Adequate preoxygenation is essential when mask ventilation after the induction of anesthesia is

contraindicated or anticipated to be difficult, when intubation is anticipated to be difficult, and in patients with a smaller FRC (i.e., patients who are obese or pregnant).<sup>60</sup> Because difficulty with airway management can unexpectedly occur, routine preoxygenation before induction of general anesthesia is recommended.<sup>61</sup>

Preoxygenation is typically performed via a face mask attached to either the anesthesia machine or a Mapleson circuit. To ensure adequate preoxygenation, 100% oxygen must be provided at a flow rate high enough to prevent rebreathing (10 to 12 L/min), and no leaks around the face mask must be present. An end-tidal concentration of oxygen greater than 90% is considered to maximize apnea time. With maximal preoxygenation, the time to oxyhemoglobin desaturation below 80% can vary from 9 minutes in a healthy, nonobese adult to 3 minutes or less in children or obese adults.<sup>62</sup>

Two primary methods are used to accomplish preoxygenation. The first method uses tidal volume ventilation through the face mask for 3 minutes, which allows the exchange of 95% of the gas in the lungs.<sup>60</sup> The second method uses vital capacity breaths to achieve adequate preoxygenation more rapidly. Four breaths over 30 seconds is not as effective as the tidal volume method but may be acceptable in certain clinical situations; eight breaths over 60 seconds has been shown to be more effective.<sup>60</sup>

Transnasal humidified rapid-insufflation ventilatory exchange (THRIVE) at 60 L/min for 3 minutes has been demonstrated to be as effective as tidal volume preoxygenation by face mask (see Apneic Oxygenation).<sup>63</sup> Head-up positioning has been shown to improve the quality of preoxygenation in both obese<sup>64</sup> and nonobese patients.<sup>65</sup> The use of noninvasive positive-pressure ventilation (PPV) for preoxygenation also prolongs apnea time.<sup>66,67</sup>

### APNEIC OXYGENATION

Apneic oxygenation is a physiologic phenomenon by which oxygen from the oropharynx or nasopharynx diffuses down into the alveoli as a result of the net negative alveolar gas exchange rate resulting from oxygen removal and carbon dioxide excretion during apnea. Assuming the airway is patent and oxygen is insufflated through the nose and/or mouth, oxygenation occurs, prolonging apnea time beyond that of standard face-mask preoxygenation.<sup>68</sup>

Oxygen can be insufflated at up to 15 L/min with nasal cannulae (nasal oxygen during efforts securing a tube [NO DESAT])<sup>69</sup> or with a catheter placed through the nose or mouth with the tip in the pharynx (pharyngeal oxygen insufflation).<sup>70</sup> Studies have demonstrated that these techniques are effective in delaying oxyhemoglobin desaturation in morbidly obese patients<sup>71,72</sup> and during emergency tracheal intubation.<sup>73,74</sup>

THRIVE involves the administration of warmed, humidified oxygen, allowing higher oxygen flow rates than the previously described techniques—up to 70 L/min. These higher flows extend the apnea time even further and improve the clearance of carbon dioxide, preventing the potential development of severe respiratory acidosis. In 25 patients with a difficult airway at risk for rapid desaturation, THRIVE was used to achieve a median apnea time of 14 minutes, with a range of 5 to 65 minutes, and an average rate of carbon dioxide rise of only 1.1 mm Hg per minute.<sup>63</sup>

## PULMONARY ASPIRATION OF GASTRIC CONTENTS

In 1946, Mendelson was the first to describe aspiration pneumonitis attributable to the pulmonary aspiration of acidic gastric secretions in pregnant women undergoing anesthesia.<sup>75</sup> This potentially fatal complication, occasionally referred to as Mendelson syndrome, has since been the intense focus of preventive efforts among the anesthesia community. Prevention of aspiration of gastric contents is primarily accomplished by adherence to established preoperative fasting guidelines, premedication with drugs that may decrease the risk of aspiration pneumonitis, and specialized induction techniques, which are discussed later in this chapter.

Traditionally, patients who were scheduled for elective procedures requiring sedation, regional anesthesia, or general anesthesia were instructed to remain NPO (Latin for *nulla per os* or *nothing by mouth*) after midnight to ensure an empty stomach to decrease the risk of regurgitation. Based on evidence that allowing ingestion of clear liquids 2 to 4 hours before surgery resulted in lower gastric volumes and higher gastric pH, the ASA published *Practice Guidelines for Preoperative Fasting and the Use of Pharmacologic Agents to Reduce the Risk of Pulmonary Aspiration* in 1999 that liberalized the traditional NPO policy and allowed clear liquids up to 2 hours before beginning elective procedures requiring anesthesia. The guidelines, most recently updated in 2017, recommend 4 hours of fasting from breast milk and 6 hours of fasting from solid foods, infant formula, and nonhuman milk.<sup>76</sup> Fried or fatty foods may require longer fasting times (e.g., 8 hours or more).<sup>76</sup> Although the ASA guidelines do not specifically address chewing gum, hard candies, or smoking, guidelines published by the European Society of Anaesthesiology on the topic do not recommend delaying the start of anesthesia if a patient has consumed any of these immediately before the induction of anesthesia.<sup>77</sup>

The routine use of drugs as prophylaxis against aspiration pneumonitis is not recommended by the ASA guidelines<sup>76</sup> but may be beneficial in patients with specific risk factors for aspiration, such as a full stomach, symptomatic gastroesophageal reflux disease (GERD), hiatal hernia, presence of a nasogastric tube, morbid obesity, diabetic gastroparesis, or pregnancy.<sup>78,79</sup> The goal of aspiration prophylaxis is twofold: to decrease gastric volume and to increase gastric fluid pH. Commonly used agents include nonparticulate antacids (e.g., Bicitra), promotility drugs (e.g., metoclopramide), and H<sub>2</sub>-receptor antagonists. These drugs may be used alone or in combination.<sup>80</sup>

## AIRWAY REFLEXES AND THE PHYSIOLOGIC RESPONSE TO INTUBATION OF THE TRACHEA

One of the most important teleologic functions of the larynx is that of airway protection, which is primarily provided by the glottic closure reflex. This reflex is triggered by sensory receptors in the glottic and subglottic mucosa and results in strong adduction of the vocal cords.<sup>81</sup> An exaggerated, maladaptive manifestation of this reflex, referred to as *laryngospasm*, is a potential complication of airway management. Laryngospasm is usually provoked by glossopharyngeal or vagal stimulation attributable to airway instrumentation

or vocal cord irritation (e.g., from blood or vomitus) in the setting of a light plane of anesthesia (stage II of the Guedel classification), but it can also be precipitated by other noxious stimuli and can persist well after the removal of the stimulus. Treatment of laryngospasm includes removal of airway irritants, deepening of the anesthetic, and the administration of a rapid-onset neuromuscular blocking drug (NMBD), such as succinylcholine.<sup>82</sup> Continuous positive airway pressure with 100% oxygen is commonly cited as a therapeutic maneuver, although the pressure may push the aryepiglottic folds closer together and may actually promote laryngospasm by acting as a mechanical stimulus.<sup>83,84</sup> Bilateral pressure at the *laryngospasm notch* between the condyle of the mandible and the mastoid process can be effective at treating laryngospasm by causing an intense, painful stimulus, which may function to terminate laryngospasm by arousing a semiconscious patient or by activating autonomic pathways.<sup>82</sup>

The tracheobronchial tree also possesses reflexes to protect the lungs from noxious substances. Irritation of the lower airway by a foreign substance activates a vagal reflex-mediated constriction of bronchial smooth muscle, resulting in bronchospasm. Untreated bronchospasm can result in an inability to ventilate because of an extremely elevated airway resistance. Treatment includes a deepening of anesthetic with propofol or a volatile agent and the administration of inhaled  $\beta_2$ -agonist or anticholinergic medications. Administration of intravenous (IV) lidocaine has been studied, but the evidence does not support its use for treatment of bronchospasm.<sup>85</sup>

Tracheal intubation, as well as laryngoscopy and other airway instrumentation, provides an intense noxious stimulus via vagal and glossopharyngeal afferents that results in a reflex autonomic activation, which is usually manifested as hypertension and tachycardia in adults and adolescents; in infants and small children, autonomic activation may result in bradycardia. Hypertension and tachycardia are usually of short duration; however, they may have consequences in patients with significant cardiac disease. Central nervous system activation as a result of airway management results in increases in electroencephalographic (EEG) activity, cerebral metabolic rate, and cerebral blood flow, which may result in an increase in intracranial pressure in patients with decreased intracranial compliance.<sup>85</sup>

## Anesthesia for Airway Management

To facilitate airway management, some form of anesthesia is usually required to provide comfort for the patient, to blunt airway reflexes, and to blunt the hemodynamic response to airway instrumentation. Most commonly, airway management is performed after induction of general anesthesia. Alternatively, an *awake* technique, which entails establishing an airway (including tracheal intubation) by using local anesthesia of the airway and/or sedation, can be used to meet these goals when clinically indicated. In emergency scenarios where the patient is obtunded or comatose, such as in the event of acute respiratory or cardiac arrest, anesthetic drugs may not be required.

## AIRWAY MANAGEMENT AFTER THE INDUCTION OF GENERAL ANESTHESIA

Airway management is usually performed after the induction of general anesthesia if the anesthesiologist determines that it is safe to do so. Several pharmacologic techniques are used for the induction of anesthesia, each with its own implications for airway management. The decision of which induction technique to use should be made with careful consideration of the specific clinical circumstances at hand.

### Standard Intravenous Induction with Neuromuscular Blockade

The most common technique for induction of general anesthesia is the standard IV induction, which entails the administration of a rapid-acting IV anesthetic, followed by an NMBD. Muscle relaxation achieved by the administration of NMBDs improves intubating conditions by facilitating laryngoscopy, preventing both reflex laryngeal closure and coughing after intubation.<sup>22,86</sup>

Propofol is the most frequently used IV anesthetic drug; other options include etomidate, ketamine, thiopental, and midazolam. The choice of drug depends on a variety of factors including the patient's hemodynamic status, comorbidities, and allergies, as well as drug pharmacokinetics, side effects, physician preference, and availability.<sup>87</sup> Whether the choice of an anesthetic drug has any effect on the quality of intubating conditions when NMBDs are also administered is not well established. Studies comparing propofol, etomidate, and thiopental in combination with NMBDs showed no difference in intubating conditions between the different anesthetics.<sup>88,89</sup> On the other hand, one study, during which patients received cisatracurium, showed that larger doses of propofol were associated with improved intubating conditions, as compared with smaller doses.<sup>90</sup>

For many years, succinylcholine was the most frequently used NMBD for routine IV induction<sup>87</sup>; however, nondepolarizing NMBDs have gained greater popularity attributable to the risk of adverse effects from succinylcholine administration, including bradycardia, myalgia, hyperkalemia, increased intracranial pressure, and increased intragastric pressure.<sup>91</sup> Succinylcholine, the only depolarizing NMBD in clinical use, has the benefit of a rapid onset combined with a short duration of action, and it is currently used most often when those properties are desired. Most notably, succinylcholine is still commonly used in the setting of a suspected difficult airway; its short duration of action theoretically allows for the resumption of spontaneous ventilation before severe hypoxia develops in a preoxygenated patient, although evidence suggests that this may not predictably occur.<sup>92</sup>

Nondepolarizing NMBDs are the more frequently used relaxants for routine IV induction of anesthesia.<sup>91</sup> The most commonly used nondepolarizing NMBDs in current practice—rocuronium, vecuronium, and cisatracurium—are notable for having a favorable safety profile with relatively few side effects. The primary limitation of these drugs is a significantly longer duration of action; once administered, a functional airway must be established within minutes to avoid life-threatening hypoxia. Sugammadex is a selective relaxant-binding agent for rocuronium that has

the ability to reverse profound neuromuscular blockade rapidly in a time comparable with spontaneous recovery from succinylcholine (also see Chapter 28).<sup>93</sup>

Traditional teaching in the United States has advocated withholding NMBDs until the ability to mask ventilate has been established. If ventilation via a mask cannot be achieved, a preoxygenated patient can then theoretically resume spontaneous ventilation or be awakened before the onset of hypoxia.<sup>94</sup> This practice has been increasingly questioned in the literature in part because of a number of studies demonstrating that ventilation via a mask is *not* rendered more difficult by muscle relaxation<sup>95,96</sup>; rather, mask ventilation is, in fact, facilitated by muscle relaxation.<sup>97</sup> One issue with the traditional paradigm is that the theoretical advantage of the practice—the ability to awaken the patient if mask ventilation fails—is rarely used.<sup>98</sup> The desire to preserve that ability may, in fact, result in giving an inadequate dose of anesthetic during induction, resulting in a difficult mask ventilation situation when one would not have otherwise occurred.<sup>98</sup> Delaying the administration of NMBDs can result in the onset of hypoxia before spontaneous recovery (with succinylcholine) or reversal (with sugammadex) is possible.

The authors do not recommend withholding NMBDs in patients who are predicted to be easy to mask ventilate and/or intubate. For patients in whom difficulty with both mask ventilation and intubation are predicted, awake intubation or inhalation induction of anesthesia should be considered, and the administration of NMBDs is best withheld until the ability to ventilate is proven.

### Rapid-Sequence Induction and Intubation

Rapid-sequence induction and intubation (often simply referred to as *rapid sequence induction* [RSI] in the anesthesia literature) is a specialized method of IV induction commonly used when an increased risk of gastric regurgitation and pulmonary aspiration of gastric contents exists. After adequate preoxygenation and while cricoid pressure is applied, an induction dose of IV anesthetic is rapidly followed by 1 to 1.5 mg/kg of IV succinylcholine, and the trachea is intubated without attempts at PPV. The goal is to achieve optimal intubating conditions rapidly to minimize the length of time between the loss of consciousness (LOC) and securing of the airway with a cuffed endotracheal tube (ETT). Cricoid pressure, eponymously referred to as the Sellick maneuver after the physician who first described it, involves the application of pressure at the cricoid ring to occlude the upper esophagus, thereby preventing the regurgitation of gastric contents into the pharynx.<sup>99</sup> The recommended force to be applied is 10 Newtons (N) while the patient is awake, increased to 30 N after LOC. These values are based on esophageal manometry on patients undergoing induction of anesthesia and cadaver studies of safe amounts of pressure.<sup>100</sup> RSI is widely practiced and approaches a standard of care in patients with a full stomach (i.e., when NPO guidelines have not been observed) and in the setting of bowel obstruction.<sup>101,102</sup> RSI has historically been recommended for patients who are pregnant, starting in the second trimester,<sup>103</sup> but this dogma has been called into question.<sup>104,105</sup> Other clinical situations for which RSI may be considered due to a higher than normal risk for aspiration of gastric contents, include poorly controlled GERD,

presence of a nasogastric tube, morbid obesity, and diabetic gastroparesis. RSI is also a useful induction technique when mask ventilation is predicted to be difficult, but intubation is not, such as with an edentulous, bearded patient with an otherwise reassuring airway examination.

Some common variations to RSI have developed from the technique first described in 1970.<sup>106</sup> When succinylcholine is contraindicated or its side effects are undesired, RSI can be accomplished using nondepolarizing NMBDs (rocuronium 1.0 to 1.2 mg/kg or vecuronium 0.3 mg/kg); these doses provide adequate intubating conditions in less than 90 seconds.<sup>107,108</sup> The primary disadvantage with the nondepolarizing NMBDs used to be the prolonged duration of neuromuscular blockade; however, since the introduction of sugammadex these agents are increasingly employed in place of succinylcholine for RSI (also see [Chapters 27 and 28](#)). Although traditional RSI calls for induction with a fixed dose of thiopental, the use of other anesthetics such as propofol, etomidate, or ketamine is common. Some advocate for the titration of the chosen anesthetic agent to LOC rather than the delivery of a fixed, predetermined dose.<sup>101</sup>

The application of cricoid pressure is the most controversial aspect of RSI.<sup>101</sup> Opponents point to studies demonstrating that cricoid pressure results in a decrease in lower esophageal sphincter tone, potentially increasing the risk for regurgitation,<sup>109</sup> and to magnetic resonance imaging (MRI) studies showing that cricoid pressure does not, in fact, result in compression of the esophagus, but rather a lateral displacement.<sup>110</sup> Cricoid pressure also worsens laryngeal visualization during DL, potentially lengthening the time to intubation and increasing the risk of pulmonary aspiration, and can result in occlusion of the subglottic airway, resulting in difficulty with tracheal intubation or mask ventilation.<sup>111</sup> On the other hand, advocates argue that properly applied cricoid pressure is effective in reducing the risk of aspiration and that reports of problems are due to incorrect application. The authors of an MRI study of cricoid pressure argue that the position of the esophagus is irrelevant because the effectiveness of cricoid pressure is due to occlusion of the hypopharynx.<sup>112</sup> In general, because of the relatively low risk of application of cricoid pressure, its use is encouraged for RSI unless glottic visualization proves difficult, in which case it can be easily released.

The term *modified RSI* is frequently used, but no standardized definition exists. A survey of anesthesia residents and attending anesthesiologists in the United States showed that the term was most commonly used to refer to the use of mask ventilation in conjunction with cricoid pressure.<sup>113</sup> Indications for this technique include patients at risk for rapid development of hypoxemia (e.g., patients who are obese, pregnant, or critically ill; pediatric patients) in emergent situations during which preoxygenation cannot be satisfactorily completed, or when a longer time to acceptable intubating conditions is required because of the use of standard doses of nondepolarizing NMBDs. Although the effect of PPV with cricoid pressure applied in terms of gastric insufflation of air is not definitively known, gentle PPV (inspiratory pressure <20 cm water [H<sub>2</sub>O]) in conjunction with cricoid pressure may be acceptable in these clinical scenarios.<sup>114</sup>

## Inhalational Induction of Anesthesia

Another option for the induction of general anesthesia is inhalational induction with volatile anesthetic. This technique is commonly used in pediatric anesthesia to provide a painless, needle-free experience for the child. In adults, an inhalational induction of anesthesia is used when IV access is not available or when the specific advantages of the technique are desirable. Advantages of an inhalational induction of anesthesia are the maintenance of spontaneous ventilation and the potential for gradual changes in the depth of anesthesia and associated respiratory and cardiovascular effects.<sup>22</sup> Inhalational induction of anesthesia has also been used for RSI, with a rapid-onset NMBD administered at LOC<sup>115</sup> (also see [Chapter 27](#)).

Sevoflurane is currently the most commonly used volatile anesthetic for inhalational induction because of its lack of pungency and low blood:gas solubility, allowing for a smooth induction of anesthesia that can provide suitable conditions for airway management with or without adjuvant drugs such as NMBDs or opioids.<sup>116</sup> The two principal techniques for sevoflurane induction of anesthesia are a *tidal volume induction*, in which patients are instructed to breathe normally through the face mask, and a *vital capacity induction*, in which patients are instructed to exhale to residual volume and then take a vital capacity breath from the face mask. High delivered concentrations of sevoflurane (8%) are used for vital capacity induction, whereas tidal volume inductions may start with lower sevoflurane concentrations before the concentration is increased. Nitrous oxide (N<sub>2</sub>O) can be used with either method to speed induction via the second-gas effect.<sup>117</sup> Both methods are effective and can be used for either LMA placement or tracheal intubation.<sup>116</sup> Deep levels of anesthesia are required to achieve satisfactory intubating conditions when using sevoflurane as a sole induction agent, increasing the risk of adverse effects, such as hypotension. The administration of propofol,<sup>118</sup> rapid-onset opioids,<sup>119,120</sup> NMBDs,<sup>121</sup> and ketamine<sup>122</sup> have all been shown to improve intubating conditions and allow for lower end-tidal concentrations of sevoflurane.

Halothane, which is still used in developing countries, can also be used for inhalational induction of anesthesia.<sup>123</sup> One main disadvantage of halothane is its high blood:gas partition coefficient, which leads to relatively long induction times. It also can produce cardiac dysrhythmias, myocardial depression, and halothane-induced hepatitis. Because of the inability to achieve deep levels of anesthesia with halothane as a result of its side effects, the use of NMBDs, opioids, or both, is often required.<sup>116</sup> The use of desflurane for inhalational induction of anesthesia is limited by its tendency to cause airway irritation, although reports of its use for induction in combination with opioids has been reported.<sup>124,125</sup>

## Intravenous Induction Without Neuromuscular Blocking Drugs

IV induction of general anesthesia without the use of NMBDs is commonly used for LMA placement but can be used to achieve satisfactory intubating conditions as well. This technique is useful when the use of succinylcholine is contraindicated and the prolonged recovery time from nondepolarizing NMBDs is undesirable and their reversal not possible

(e.g., when sugammadex is not available). Of the commonly available IV anesthetics, propofol is the best suited for induction without muscle relaxation because of its unique ability to suppress airway reflexes and to produce apnea.<sup>126,127</sup> Larger doses are required, however, when propofol is used as a sole anesthetic, increasing the risk of significant hypotension. Improvement of intubating conditions and smaller doses of propofol are possible when rapid-onset opioids (e.g., alfentanil, remifentanil) or IV magnesium are administered.<sup>128,129</sup> Remifentanil is more effective than comparable doses of alfentanil<sup>128</sup>; in combination with propofol 2 mg/kg, remifentanil 4 to 5 µg/kg can reliably provide good-to-excellent intubating conditions.<sup>130</sup> When combined with cricoid pressure and an avoidance of mask ventilation, this induction technique can be used for RSI.<sup>131</sup>

Disadvantages of this technique include a potentially more frequent incidence of difficult intubation,<sup>132</sup> pronounced hemodynamic side effects such as bradycardia and hypotension, and an increased risk for laryngeal morbidity.<sup>86,133</sup> This technique also introduces the risk of opioid-induced muscle rigidity resulting in difficulty with mask ventilation. Although this risk is commonly attributed to chest wall rigidity, studies in intubated patients and patients with tracheostomies have shown that decreases in pulmonary compliance due to chest wall rigidity are not sufficient to explain an inability to mask ventilate after a large dose of an opioid.<sup>134,135</sup> Examination of the vocal cords during induction with opioids has shown that vocal cord closure is the primary cause of difficult ventilation after opioid-induced anesthesia.<sup>136,137</sup> Treatment with small doses of NMBD or topical lidocaine (laryngotracheal anesthesia [LTA]) can be effective in relaxing the vocal cords to allow for mask ventilation and/or intubation.<sup>136</sup>

## AIRWAY MANAGEMENT IN AN AWAKE (NON-ANESTHETIZED) PATIENT

As noted in the ASA DAA, a consideration of whether the airway should be secured before or after induction of general anesthesia is one of the basic management choices that should be considered when an airway management plan is being devised.<sup>7</sup> The benefits of awake airway management include the preservation of pharyngeal muscle tone and patency of the upper airway, the maintenance of spontaneous ventilation, an ability to obtain a quick neurologic examination, and a safeguard against aspiration attributable to the preservation of protective airway reflexes.<sup>138</sup> In general, when difficult mask ventilation and difficult intubation are expected, the safest approach to airway management is to secure the airway while the patient remains awake.<sup>7</sup> Other indications for awake airway management include the risk of severe aspiration of gastric contents, facial or airway trauma, severe hemodynamic instability, and unstable cervical spine pathology.<sup>139</sup>

Because of the nature of these indications, tracheal intubation is most often chosen as the goal of awake airway management; however, awake placement of an LMA for diagnostic bronchoscopy has been described. The most useful technique for awake intubation is the flexible scope intubation (FSI),<sup>138</sup> although other techniques have been successfully used, including VAL<sup>140</sup> optical stylets,<sup>141</sup> lighted stylets,<sup>142</sup> intubating LMAs,<sup>143</sup> and retrograde intubation (RI).<sup>144</sup>

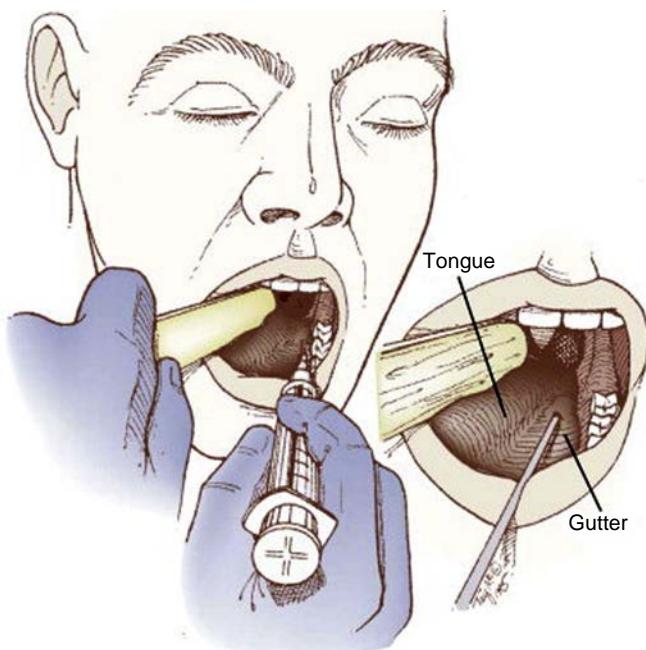
Topical application of local anesthetic to the airway should, in most cases, be the primary anesthetic for awake airway management.<sup>138</sup> Lidocaine is the most commonly used local anesthetic for awake airway management because of its rapid onset, high therapeutic index, and availability in a wide variety of preparations and concentrations.<sup>145,146</sup> Benzocaine and Cetacaine (a topical application spray containing benzocaine, tetracaine, and butamben; Cetylite Industries, Pennsauken, NJ) provide excellent topical anesthesia of the airway, but their use is limited by the risk of methemoglobinemia, which can occur with as little as 1 to 2 seconds of spraying.<sup>147</sup> Topical cocaine is primarily used for anesthesia and vasoconstriction of the nasal mucosa during awake nasotracheal intubation.<sup>148</sup> A mixture of lidocaine 3% and phenylephrine 0.25%, which can be made by combining lidocaine 4% and phenylephrine 1% in a 3:1 ratio, has similar anesthetic and vasoconstrictive properties as topical cocaine and can be used as a substitute.<sup>149</sup>

Topical application of local anesthetic should primarily be focused on the base of the tongue (pressure receptors here act as the afferent component of the gag reflex), the oropharynx, the hypopharynx, and the laryngeal structures; anesthesia of the oral cavity is unnecessary. If a nasotracheal intubation is planned, then the nasal cavity should also be topicalized. Before topical application of local anesthetic to the airway, administration of an anticholinergic agent should be considered to aid in the drying of secretions, which helps improve both the effectiveness of the topical local anesthetic and visualization during laryngoscopy. Glycopyrrolate is usually preferred because it has less vagolytic effects than atropine at doses that inhibit secretions and does not cross the blood-brain barrier. It should be administered as early as possible to maximize its effectiveness.

Direct application of topical cocaine, lidocaine 4% with epinephrine, or lidocaine 3%/phenylephrine 0.25% solution via cotton swabs or cotton pledgets is effective for anesthesia of the nasal mucosa. Oropharyngeal anesthesia can be achieved by the direct application of local anesthetic or by the use of an atomizer or nebulizer. Topical application of local anesthetic to the larynx can be achieved by directed atomization of a local anesthetic or by the *spray-as-you-go* (SAYGO) method, which involves intermittently injecting local anesthetic through the suction port or working channel of a flexible intubation scope (FIS) or optical stilet, as it is advanced toward the trachea.

Topical application of local anesthetic to the airway mucosa using one or more of these methods is often sufficient. If supplemental anesthesia is required, then a variety of nerve blocks may be used. Three of the most useful are the glossopharyngeal nerve block, superior laryngeal nerve block, and translaryngeal block.

The glossopharyngeal nerve supplies sensory innervation to the posterior third of the tongue, vallecula, the anterior surface of the epiglottis, and the posterior and lateral walls of the pharynx, and is the afferent pathway of the gag reflex. To block this nerve, the tongue is displaced medially, forming a gutter (glossogingival groove). A 25-gauge spinal needle is inserted at the base of the anterior tonsillar pillar, just lateral to the base of the tongue, to a depth of 0.5 cm (Fig. 44.9). After negative aspiration for blood or air, 2 mL of 2% lidocaine is injected. The process is then repeated

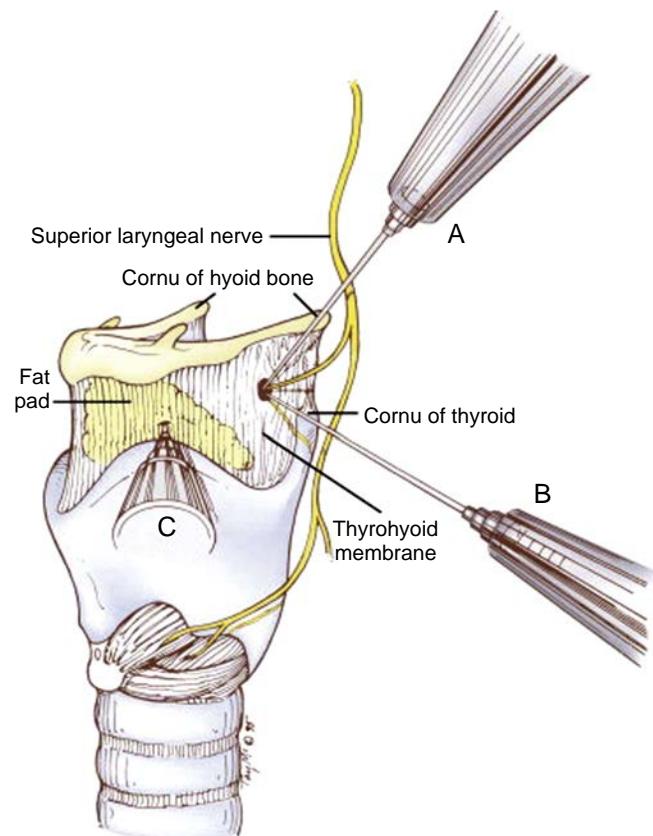


**Fig. 44.9** Left glossopharyngeal nerve block. (Reprinted from Artine CA, Sanchez A. Preparation of the patient for awake intubation. In: Hagberg CA, Artine CA, Aziz M, eds. *Hagberg and Benumof's Airway Management*. 4th ed. Philadelphia: Elsevier; 2018. From Difficult airway teaching aids, Irvine, University of California, Department of Anesthesia.)

on the contralateral side.<sup>138</sup> The same procedure can be performed noninvasively with cotton-tipped swabs soaked in 4% lidocaine; the swabs are held in place for 5 minutes (Video 44.1).

The superior laryngeal nerve, a branch of the vagus nerve, provides sensory input from the lower pharynx and the upper part of the larynx, including the glottic surface of the epiglottis and the aryepiglottic folds. Blockade of this nerve may be achieved using one of three landmarks (Fig. 44.10). Using either the superior cornu of the hyoid or the superior cornu of the thyroid cartilage, a 25-gauge spinal needle is walked off the cornu anteriorly toward the thyrohyoid ligament. Resistance is felt as the needle is advanced through the ligament, usually at a depth of 1 to 2 cm. After negative aspiration for blood and air, 1.5 to 2 mL of 2% lidocaine is injected and then repeated on the opposite side.<sup>146</sup> The third landmark for the superior laryngeal nerve block is particularly useful in patients who are obese, in whom palpation of the hyoid or the superior cornu of the thyroid cartilage may be difficult or uncomfortable for the patient. In this approach, the needle is inserted 2 cm lateral to the superior notch of the thyroid cartilage and directed in a posterior and cephalad direction to 1 to 1.5 cm depth, where 2 mL of 2% lidocaine is infiltrated and, again, repeated on the contralateral side.<sup>150</sup>

Translaryngeal (or transtracheal) block provides anesthesia of the trachea and vocal cords. This block may be particularly useful in situations where a neurologic examination is needed after intubation; it makes the presence of the ETT in the trachea more comfortable. The CTM is identified, and a 20- to 22-gauge needle attached to 5-mL syringe is directly advanced posteriorly and slightly caudally until air is aspirated, at which point 4 mL of either 2% or 4% lidocaine is quickly injected. This causes the patient to cough,

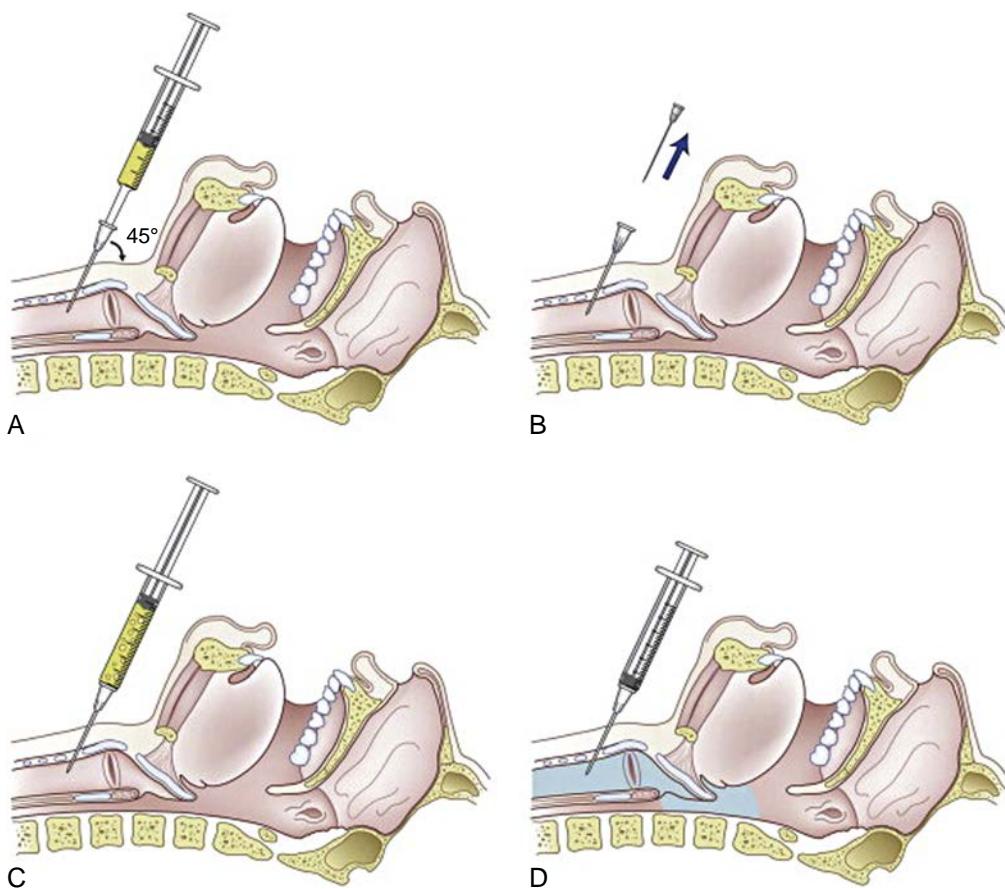


**Fig. 44.10** Superior laryngeal nerve block, external approach using as a landmark the greater cornu of the hyoid bone (A), the superior cornu of the thyroid cartilage (B), or the thyroid notch (C). (Reprinted from Artine CA, Sanchez A. Preparation of the patient for awake intubation. In: Hagberg CA, Artine CA, Aziz M, eds. *Hagberg and Benumof's Airway Management*. 4th ed. Philadelphia: Elsevier; 2018. From Difficult airway teaching aids, Irvine, University of California, Department of Anesthesia.)

anesthetizing the vocal cords and the trachea. To minimize the risk of trauma, a catheter may first be placed over the needle and the local anesthetic then injected through the catheter (Fig. 44.11 and Video 44.2).<sup>146</sup>

These techniques may be used in various different combinations as long as the maximum dose of local anesthetic is not exceeded. The maximum dose of lidocaine for application to the airway is not well established; different sources suggest total doses in the range of 4 to 9 mg/kg.<sup>146,151,152</sup> Monitoring for signs and symptoms of lidocaine toxicity, including tinnitus, perioral tingling, metallic taste, lightheadedness, dizziness, and sedation is important. Severe lidocaine overdose can cause hypertension, tachycardia, seizures, and cardiovascular collapse.<sup>153</sup>

Depending on the clinical circumstance, IV sedation may facilitate airway management in an awake patient by providing anxiolysis, amnesia, and analgesia. Benzodiazepines, opioids, IV hypnotics,  $\alpha_2$  agonists, and neuroleptics can be used alone or in combination. A summary of common medications used for sedation can be found in Table 44.1. These drugs should be carefully titrated to effect; oversedation can render a patient uncooperative and make awake intubation more difficult. Spontaneous ventilation should always be maintained. Care should be taken in situations with critical airway obstruction since awake muscle tone is sometimes necessary in these patients to maintain airway patency.



**Fig. 44.11** Translaryngeal anesthesia, angiocatheter technique (midsagittal view of the head and neck). (A) The angiocatheter is inserted at the cricothyroid membrane, aimed caudally. An aspiration test is performed to verify the position of the tip of the needle in the tracheal lumen. (B) The needle is removed from the angiocatheter. (C) The syringe containing local anesthetic is attached, and the aspiration test is repeated. (D) Local anesthetic is injected, resulting in coughing and nebulization of the local anesthetic (shaded blue area). (Reprinted from Artine CA, Sanchez A. Preparation of the patient for awake intubation. In: Hagberg CA, Artine CA, Aziz M, eds. *Hagberg and Benumof's Airway Management*. 4th ed. Philadelphia: Elsevier; 2018. From Difficult airway teaching aids, Irvine, University of California, Department of Anesthesia.)

**TABLE 44.1** Sedative Drugs for Awake Airway Management

Drug	Class	Sedative Dose	Notes
Midazolam	Benzodiazepine	1-2 mg IV, repeated prn (0.025-0.1 mg/kg)	Frequently used in combination with fentanyl.
Fentanyl	Opioid	25-200 $\mu$ g IV (0.5-2 $\mu$ g/kg)	Usually used in combination with other agents (e.g., midazolam, propofol).
Alfentanil	Opioid	500-1500 $\mu$ g IV (10-30 $\mu$ g/kg)	Has a faster onset, shorter duration than fentanyl.
Remifentanil	Opioid	Bolus 0.5 $\mu$ g/kg IV, followed by an infusion of 0.1 $\mu$ g/kg/min	Infusion can be subsequently titrated by 0.025-0.05 $\mu$ g/kg/min in 5-minute intervals to achieve adequate sedation.
Propofol	Hypnotic	0.25 mg/kg IV in intermittent boluses or Continuous IV infusion of 25-75 $\mu$ g/kg/min, titrated to effect	Can also be used in combination with remifentanil (decrease dose of both drugs).
Ketamine	Hypnotic	0.2-0.8 mg/kg IV	Pretreat with an antisialagogue. Consider administration of midazolam to attenuate undesirable psychologic effects.
Dexmedetomidine	$\alpha_2$ Agonist	Bolus 1 $\mu$ g/kg IV over 10 minutes, followed by an infusion of 0.3-0.7 $\mu$ g/kg/hr	Reduce dose in older adults and in patients with depressed cardiac function.

IV, Intravenous; prn, as needed, *pro re nata* (Latin).

Avoiding oversedation is also important in the patient at increased risk for aspiration of gastric contents, because an awake patient can protect his or her own airway if regurgitation should occur.<sup>80</sup>

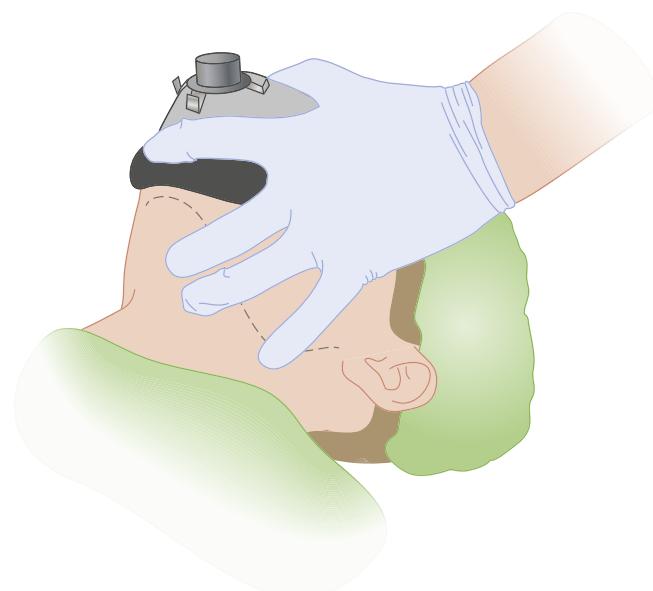
## Mask Ventilation

Mask ventilation is a straightforward, noninvasive technique for airway management that can be used as a primary mode of ventilation for an anesthetic of short duration or as a bridge to establish a more definitive airway. The use of a face mask is common for preoxygenation, inhalational induction of anesthesia, and as a means to provide oxygen and anesthetic gases to both a spontaneous ventilating patient and an anesthetized, apneic patient via PPV. Mask ventilation is not only used to ventilate and oxygenate before conditions for tracheal intubation have been achieved, but it is also a valuable rescue technique when tracheal intubation proves difficult. For this reason, mask ventilation is an important part of the ASA DAA and an essential skill for the anesthesia practitioner.<sup>7</sup>

Mask ventilation is relatively contraindicated when the risk for regurgitation is increased; no protection from pulmonary aspiration of gastric contents exists. Mask ventilation should also be performed with caution in patients with severe facial trauma and in patients in whom head and neck manipulation must be avoided (e.g., those with an unstable cervical spine fracture).

Anesthesia face masks are designed to form a seal around the patient's nose and mouth, allowing for PPV and the administration of anesthetic gases; they should not be confused with oxygen face masks, which are designed only to administer supplemental oxygen. Early anesthesia face masks were reusable and composed of black rubber. These have been almost entirely replaced in clinical use by disposable, clear plastic masks, which are less frightening for patients and have the added benefit of allowing for better visualization of cyanosis or the need for oral suctioning. Face masks are available in various styles and sizes but share a basic design: a main body, seal, and connector. The seal is the portion of the mask that comes in contact with the face, and in clear plastic masks is comprised of a plastic, air-filled, high-volume, low-pressure cushion that conforms to the facial anatomy while minimizing the chance for pressure ischemia; some models have a valve on the cushion to allow changing the volume of the air within. The connector is a standard 22-mm female adapter that allows a connection to a standard anesthesia circuit or a bag-valve device; pediatric masks usually have a 15-mm male adapter that allows the same connections.

The technique for mask ventilation is dependent on two key elements: (1) maintenance of a seal between the face mask and the patient's face, and (2) an unobstructed upper airway.<sup>22</sup> The mask is usually held with the left hand, with the thumb and index finger forming a "C" around the collar of the connector, the third and fourth digits on the ramus of the mandible, and the fifth digit on the angle of the mandible (Fig. 44.12). The thumb and index finger are used to produce downward pressure to ensure a tight mask seal, while the remaining digits provide upward displacement of the mandible (jaw thrust) to aid with airway patency. The right

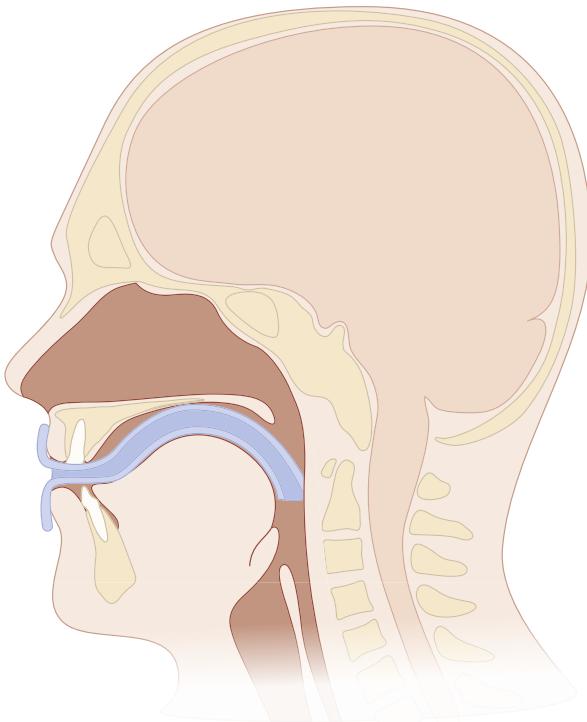


**Fig. 44.12** Standard one-handed face-mask ventilation technique. The position of the fifth digit is at the angle of the jaw. (From Maticic AA. The adult ergonomic face mask: historical and theoretical perspectives. *J Clin Anesth.* 2009;21:300–304.)

hand is free to provide manual ventilation. Ensuring that pressure from the digits is placed on the bony ridge of the mandible and not the soft tissue is important—compression of the submandibular space can cause obstruction of the airway and difficulty with mask ventilation. Many face masks have hooks around the collar for use with mask straps that can facilitate formation of a seal.

The one-handed technique is occasionally ineffective, especially in patients who are obese or edentulous, attributable to the failure to maintain a seal and/or a patent upper airway. In these situations, a two-handed technique can be more successful. Two-handed techniques depend on either an assistant or the use of pressure-control ventilation (PCV) with the anesthesia machine to provide PPV. The use of PCV for mask ventilation results in lower peak airway pressures and reduced inspiratory flow rates when compared with manual ventilation, providing an additional measure of safety against gastric insufflation.<sup>154</sup> In one approach to the two-handed technique, the left hand is positioned as in the one-handed technique and the right hand is placed on the other side of the mask in an identical conformation. A more effective approach involves using the second and third digits to perform a jaw thrust while the mask is held in place with the thumbs (Video 44.3). A study in anesthetized patients showed that this technique improved upper airway patency, compared with the traditional one-handed technique, as measured by greater tidal volumes during PCV.<sup>155</sup> Additional techniques to improve the mask seal in difficult scenarios include leaving dentures in place in edentulous patients and placing an adhesive plastic dressing over facial hair.

Once a seal is established between the face mask and the patient's face, ventilation is achieved by either spontaneous ventilation or PPV. The effectiveness of mask ventilation should be ascertained by observing for chest rise, exhaled tidal volumes, pulse oximetry, and capnography. During controlled ventilation in patients with normal lungs and a

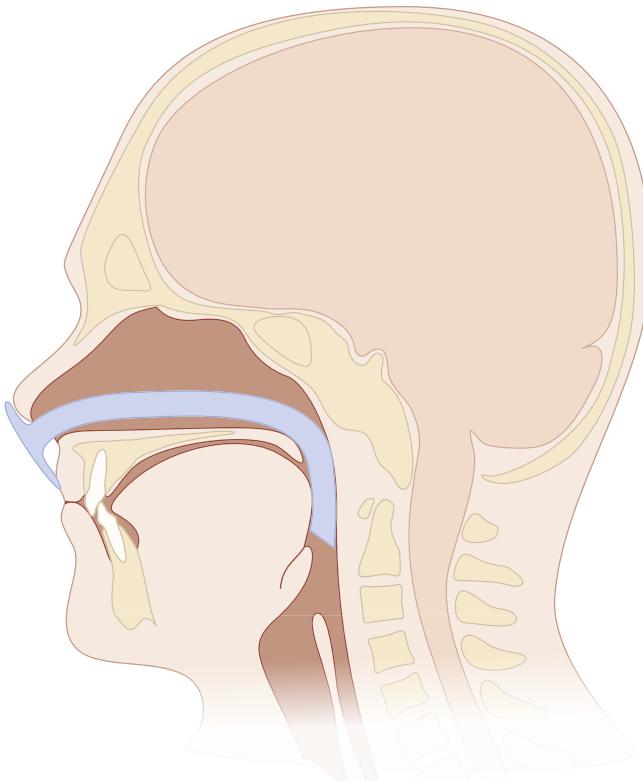


**Fig. 44.13** Oropharyngeal airway in place. The airway follows the curvature of the tongue. It pulls the tongue and the epiglottis away from the posterior pharyngeal wall and provides a channel for the passage of air. (Modified from Dorsch JA, Dorsch SE. *Understanding Anesthesia Equipment*. 4th ed. Baltimore: Williams & Wilkins; 1999.)

patent airway, adequate tidal volumes should be achieved with peak inspiratory pressures less than 20 cm H<sub>2</sub>O; higher pressures should be avoided to prevent gastric insufflation.<sup>156</sup> If PPV is inadequate at acceptable inspiratory pressures, then airway patency and pulmonary compliance should be assessed.

Because of a reduction in muscle tone as a result of general anesthesia, tissues fall backward under the influence of gravity in a supine patient and can obstruct the upper airway. Upper airway obstruction most commonly takes place at the level of the soft palate (velopharynx), epiglottis, and tongue.<sup>22,26</sup> To maximize airway patency, mask ventilation can be performed with maximal atlantooccipital extension in combination with the forward displacement of the mandible (jaw thrust) involved in the mask-holding techniques.<sup>157</sup> The addition of cervical flexion to head extension (i.e., placing the patient in the sniffing position) improves pharyngeal patency.<sup>158</sup> If the sniffing position and jaw thrust fail to relieve airway obstruction, then oropharyngeal or nasopharyngeal airways may be used to facilitate airway patency.

Oropharyngeal airways are the most commonly used. They follow the curvature of the tongue, pulling it away from the posterior pharynx (Fig. 44.13). Because they place pressure on the base of the tongue and may come in contact with the epiglottis, oropharyngeal airways can precipitate coughing, retching, or laryngospasm if laryngeal and pharyngeal reflexes are not sufficiently blunted; therefore they are not appropriate for use in conscious patients who have not had local anesthetic applied to the airway. The oropharyngeal airway is sized by measuring from the corner



**Fig. 44.14** Nasopharyngeal airway in place. The airway passes through the nose and ends at a point just above the epiglottis. (Modified from Dorsch JA, Dorsch SE. *Understanding Anesthesia Equipment*. 4th ed. Baltimore: Williams & Wilkins; 1999.)

of a patient's mouth to the angle of the jaw or the earlobe. Inappropriately sized oropharyngeal airways can actually worsen airway obstruction; therefore correct size selection is important. Proper placement is accomplished by inserting the oropharyngeal airway with the curvature facing posteriorly and then rotating 180 degrees; alternatively, a tongue depressor can be used to displace the tongue anteriorly as the oropharyngeal airway is inserted with the curvature facing anteriorly. Complications from oropharyngeal airways include lingual nerve palsy and damage to the teeth.<sup>159,160</sup> Nasopharyngeal airways are less stimulating than oropharyngeal airways once in place and thus are more appropriate for conscious patients (Fig. 44.14). They should be well lubricated before insertion and inserted perpendicularly to the longitudinal axis of the body with the bevel facing the nasal septum. To avoid epistaxis, force should never be used during insertion of a nasopharyngeal airway.

Difficult mask ventilation occurs when ventilating via the face mask is not possible because of an inadequate mask seal, excessive gas leak, and/or excessive resistance to the ingress or egress of gas.<sup>7</sup> Predictors for difficult mask ventilation that can be identified during the preoperative airway assessment are listed in **Box 44.2**.

## Supraglottic Airways

The term *supraglottic airway* or *extraglottic airway* refers to a diverse family of medical devices that are blindly inserted into the pharynx to provide a patent conduit for ventilation,

## BOX 44.2 Predictors of Difficult Mask Ventilation

- Obstructive sleep apnea or history of snoring
- Age older than 55 years
- Male gender
- Body mass index of  $30 \text{ kg/m}^2$  or greater
- Mallampati classification III or IV
- Presence of a beard
- Edentulousness

oxygenation, and delivery of anesthetic gases without the need for tracheal intubation. SGAs have the advantage of being less invasive than tracheal intubation while providing a more definitive airway than a face mask and can be used for either spontaneous ventilation or PPV. One of the first SGAs, the LMA, was described in 1983 by Dr. Archie Brain and introduced into clinical practice in 1988.<sup>161</sup> Since that time, the LMA has proved to be one of the single most important developments in both routine and difficult airway management and is a pivotal component of the ASA DAA. Various different designs of SGAs are now available and are widely used in current anesthesia practice as a primary airway management device, a rescue airway device, and a conduit for tracheal intubation.

The specific advantages of SGAs include the ease and speed of placement, improved hemodynamic stability, reduced anesthetic requirements, lack of a need for muscle relaxation, and an avoidance of some of the risks of tracheal intubation (e.g., trauma to the teeth and airway structures, sore throat, coughing on emergence, or bronchospasm).<sup>162,163</sup> The primary disadvantages are that SGAs have comparatively smaller seal pressures than ETTs, which can lead to ineffective ventilation when higher airway pressures are required, and they provide no protection from laryngospasm. First-generation SGAs also provide little protection from gastric regurgitation and aspiration, although newer devices have incorporated design elements to minimize this risk.

SGAs have many applications. They are considered the first choice for airway management for diagnostic and minor surgical procedures.<sup>164</sup> No standardized classification system exists for the different designs of SGAs, although several have been proposed. This chapter uses the terminology described by Donald Miller: perilaryngeal sealers; cuffless, anatomically preshaped sealers; and cuffed pharyngeal sealers.<sup>165</sup> Second-generation SGAs are differentiated from first-generation SGAs in that they incorporate features designed to reduce the incidence of aspiration.<sup>166</sup>

## LARYNGEAL MASK AIRWAY

### LMA Classic

The LMA (LMA North America, San Diego, CA) is the most widely used, well-studied SGA and is the archetype of the perilaryngeal sealer. The original version, the LMA Classic (cLMA), consists of an oval-shaped, silicone mask with an inflatable cuff that sits in the hypopharynx and forms a seal around the periglottic tissues (Fig. 44.15). An airway tube attached to the mask exits the mouth and has a standard 15-mm connector for attachment to an anesthesia circuit

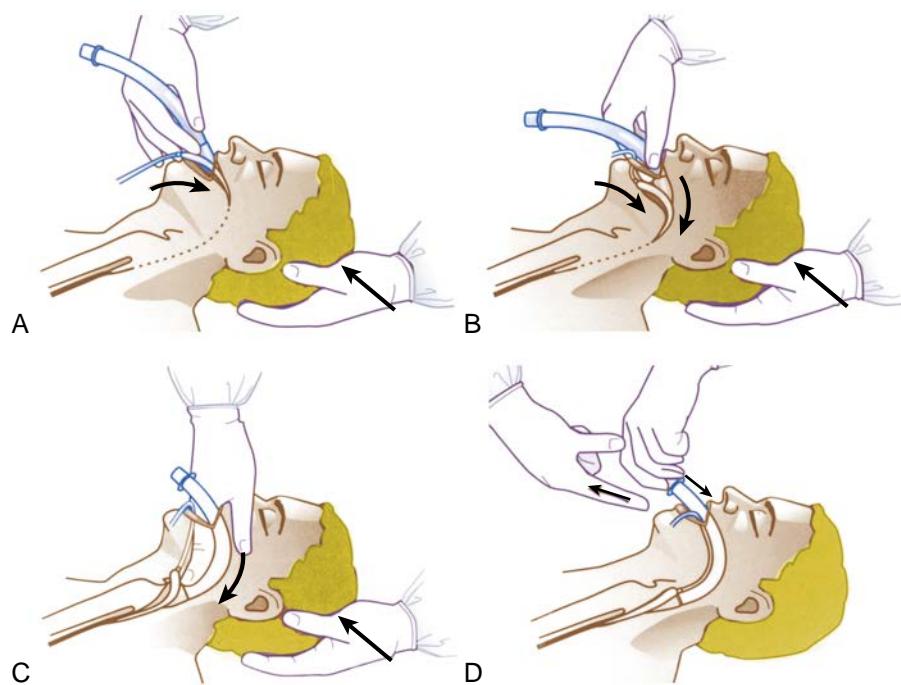


**Fig. 44.15** LMA Classic. (Image provided courtesy LMA North America, San Diego, CA.)

or to a bag-valve device. The seal around the laryngeal inlet allows for the delivery of oxygen and inhaled anesthetics during spontaneous ventilation and permits PPV at pressures up to  $20 \text{ cm H}_2\text{O}$ . The cLMA is reusable up to 40 times and is available in a variety of sizes from size 1 (neonate) to size 6 (large adult,  $>100 \text{ kg}$ ).

The LMA Classic Excel is an updated version that incorporates design features to facilitate tracheal intubation through the device, including an epiglottic-elevating bar, a wider-bore airway tube, and a removable connector. A disposable, single-use version of the cLMA, the LMA Unique, is available with either a polyvinyl chloride (PVC) or silicone cuff and has gained popularity because of its lower cost and maintenance, as well as concerns over the perceived risk of cross-contamination and the transmission of infection with reusable medical devices. The LMA Flexible, available in reusable and single-use models, has a flexible, kink-resistant airway tube that can be positioned away from the surgical field for head and neck procedures.

To achieve a proper fit, the manufacturer of the LMA suggests placing the largest size LMA possible; an airtight seal is achieved more frequently with a size 5 LMA in the average adult man and a size 4 LMA in the average adult woman.<sup>167</sup> Using an undersized LMA can result in overinflation of the cuff to achieve a seal, which can predispose the patient to oropharyngolaryngeal morbidity and nerve damage.<sup>168</sup> Smaller LMA sizes have also been shown to be associated with placement failure.<sup>169</sup> Larger sizes, however, may be



**Fig. 44.16** Insertion of a laryngeal mask airway (LMA). (A) The tip of the cuff is pressed upward against the hard palate by the index finger while the middle finger opens the mouth. (B) The LMA is pressed backward in a smooth movement. The nondominant hand is used to extend the head. (C) The LMA is advanced until definite resistance is felt. (D) Before the index finger is removed, the nondominant hand presses down on the LMA to prevent dislodgment during removal of the index finger. The cuff is subsequently inflated. (Courtesy LMA North America, San Diego, CA.)

associated with a more frequent incidence of sore throat; therefore a smaller size may be appropriate when spontaneous ventilation through the LMA is planned.<sup>170</sup>

The manufacturer's instructions for the placement of the cLMA are summarized in Fig. 44.16. Adequate depth of anesthesia for LMA insertion can be achieved with propofol or sevoflurane<sup>171</sup>; short-acting opioids such as fentanyl, alfentanil, and remifentanil may be coadministered to facilitate placement and to decrease the incidence of coughing, gagging, and laryngospasm.<sup>172,173</sup> Before insertion, the LMA cuff should be deflated and the posterior aspect of the mask should be lubricated with a water-based lubricant. Once positioned (see Fig. 44.16), the cuff should be inflated with the minimum effective volume of air, with a target cuff pressure of 40 to 60 cm H<sub>2</sub>O.<sup>167</sup> To allow the LMA to position itself correctly, the device should not be secured or attached to the anesthesia circuit until the cuff has been inflated. Confirmation of proper placement is performed by attempting gentle PPV while checking capnography and auscultation and by quantifying the inspiratory pressure at which a leak is audible, which should be 18 to 20 cm H<sub>2</sub>O. Once proper positioning is confirmed, a roll of gauze is inserted as a bite block and the LMA is secured in place with tape. Several modifications to the recommended insertion technique have been described, including a *thumb insertion method* by the manufacturer (Video 44.4).<sup>174,175</sup> Cuff pressure should be periodically monitored if N<sub>2</sub>O is being used; cuff pressures may increase above the recommended threshold of 60 cm H<sub>2</sub>O as a result of diffusion of N<sub>2</sub>O into the cuff.

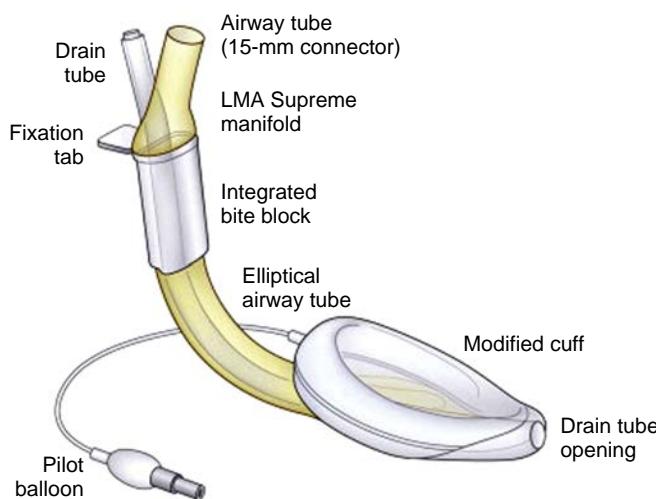
Initial difficulty with ventilation after the placement of an LMA may be due to a down-folded epiglottis. The *up-down maneuver* described by Dr. Brain may help correct this

problem; the LMA is withdrawn 2 to 4 cm and reinserted without deflating the cuff. Head extension and LMA repositioning may also improve ineffective ventilation. If these actions do not correct the problem, then a different size may be needed. Insufficient depth of anesthesia, resulting in laryngospasm or bronchospasm, may make ventilation through an LMA impossible; the administration of topical, inhaled, or IV anesthesia can help to correct this. Although not necessary, DL can also facilitate proper LMA placement.

Serious complications from LMA use are relatively rare. More commonly, minor oral, pharyngeal, or laryngeal injury occurs, expressed as complaints of a dry or sore throat.<sup>176</sup> The incidence of sore throat is approximately 10% to 20%,<sup>163,177</sup> and has been linked to higher cuff pressures and larger LMA sizes.<sup>170,178</sup> More serious cases of oropharyngolaryngeal injury have been described, such as trauma to the uvula and pharyngeal necrosis.<sup>179,180</sup> Injury to the lingual, hypoglossal, and recurrent laryngeal nerves has also been reported; these usually spontaneously resolve over a period of weeks to months.<sup>168</sup> Predisposing factors include high cuff pressures (often attributable to the use of N<sub>2</sub>O), using too small of an LMA, and nonsupine positions.<sup>168</sup>

#### LMA ProSeal

The LMA ProSeal (PLMA, LMA North America, San Diego, CA) is a reusable second-generation SGA that incorporates a posterior cuff, improving the perilyngeal seal and allowing for PPV at pressures up to 30 cm H<sub>2</sub>O. It also incorporates a gastric drainage tube that allows for gastric access with an orogastric tube and channels any regurgitated gastric contents away from the airway, effectively isolating the respiratory and gastrointestinal tracts.<sup>181</sup> Additional features include an incorporated bite block and a softer cuff.



**Fig. 44.17** The LMA Supreme has a modified cuff design, a drainage tube that allows for gastric access, and an integrated bite block. (From Vergheze C, Mena G, Ferson DZ, Brain AJ. Laryngeal mask airway. In: Hagberg CA, ed. *Benumof and Hagberg's Airway Management*. 3rd ed. Philadelphia: Saunders; 2013.)

The insertion technique is similar to the cLMA but requires deeper anesthetic levels.<sup>181,182</sup> An optional introducer can be used to facilitate insertion. As with the cLMA, cuff pressure should not exceed 60 cm H<sub>2</sub>O. Once inserted, assessment of proper placement is accomplished by providing PPV; adequate tidal volumes should be accomplished with reasonable peak inspiratory pressures, leak pressure should be above 20 cm H<sub>2</sub>O, and the capnography waveform should appear normal.<sup>22</sup> An additional test to confirm proper placement and separation of the airway and gastrointestinal tract is performed by placing a small layer (<5 mm) of water-based lubricant over the drainage tube orifice; PPV and suprasternal notch palpation should result in a small up-down movement of the gel meniscus. Easy passage of an orogastric tube through the gastric drainage tube confirms proper positioning.

### LMA Supreme

The LMA Supreme (SLMA) is a single-use, second-generation SGA based on the PLMA design. Similar to the PLMA, the SLMA has an improved cuff design that produces higher airway leak pressures, a drainage tube that allows for gastric access, and an integrated bite block (Fig. 44.17). A fixation tab allows for determination of proper sizing (the tab should rest 1 to 2.5 cm above the upper lip) and provides an improved perilyngeal seal when inward pressure is maintained by securing the mask into position by taping cheek to cheek across the fixation tab.

Although not clinically proven, evidence suggests that second-generation SGAs, such as the PLMA and the SLMA, reduce the risk of aspiration of gastric contents. This property, along with the improved airway seal and higher leak pressures, have enabled SGA devices to be used in various applications where the cLMA is potentially unsuitable, such as in nonsupine positions (e.g., lateral, prone),<sup>183</sup> in laparoscopic surgery (e.g., cholecystectomy, gynecologic surgery),<sup>184,185</sup> and in patients who are obese.<sup>186</sup> The successful, routine use of the SLMA in fasted, nonobese patients for cesarean section has also been reported.<sup>187</sup>

### NEWER LMA MODELS

The LMA Protector is an all-silicone second-generation SGA with integrated Cuff Pilot Technology, which allows constant cuff pressure monitoring. Color-coded indicator bands alert the clinician to changes in cuff pressure attributable to temperature, N<sub>2</sub>O, and movement within the airway, allowing the clinician to maintain the recommended cuff pressure of 40 to 60 cm H<sub>2</sub>O. The LMA Protector is designed to channel fluids away from the airway in the unlikely event of regurgitation and allows for gastric suctioning. The airway channel is wide enough to allow intubation with a standard-sized ETT (see Tracheal Intubation Through a Supraglottic Airway Device). The LMA Gastro is a single-use silicone LMA designed for upper gastrointestinal endoscopy procedures, simultaneously protecting the airway and facilitating passage of an endoscope.

### OTHER PERILARYNGEAL SEALERS

Over the past 15 years, a multitude of manufacturers have produced SGAs that incorporate the basic perilyngeal sealing design of the cLMA. Because the term *LMA* is a protected trademark, these devices are referred to as *laryngeal masks* (LMs). Each has its own unique characteristics that may afford it specific advantages over other designs. Although an exhaustive description of every available LM is outside the scope of this chapter, some unique features merit mentioning.

Some design features address the issue of high cuff pressures, which can lead to oropharyngolaryngeal morbidity, nerve palsies, and improper device positioning. The line of LMs manufactured by AES, Inc. (Black Diamond, WA) incorporates a cuff pilot valve (CPV) that allows constant cuff pressure monitoring. The air-Q SP (Cookgas LLC, St. Louis, MO; distributed by Mercury Medical, Clearwater, FL) has a self-pressurizing cuff that uses the positive pressure that ventilates the patient to also pressurize the cuff, obviating the need for an inflation line and eliminating the possibility of cuff overinflation. On exhalation, the mask cuff deflates to the level of positive end-expiratory pressure (PEEP), decreasing the total mucosal pressure over the course of an anesthetic, thereby potentially reducing the incidence of cuff pressure-related complications.

### CUFFLESS ANATOMICALLY PRESHAPED SEALERS

Cuffless anatomically preshaped sealers do not have a cuff; rather, they provide an airway seal by their anatomically preshaped design. Advantages include simplicity of insertion and positioning and the lack of a need to inflate a cuff. The first of these devices, the SLIPA (Curveair, London, UK), contains a hollow chamber that can trap regurgitated liquid and prevent aspiration. Other cuffless devices such as the i-gel (Intersurgical Inc., Wokingham, Berkshire, UK) and the Baska Mask (Strathfield, NSW, Australia) can also be included in this classification.

### CUFFED PHARYNGEAL SEALERS

Cuffed pharyngeal sealers have an airway with a pharyngeal cuff that seals at the level of the base of the tongue and can be subclassified as to whether they also possess an

esophageal sealing cuff.<sup>165</sup> SGAs with only a pharyngeal cuff include the Cobra Perilaryngeal Airway (CobraPLA; Engineered Medical Systems, Indianapolis, IN) and the Tulip Airway (Marshall Medical, Bath, UK); they are not detailed in this chapter. The following devices all have an esophageal sealing cuff.

The esophageal-tracheal combitube (ETC) (Covidien, Mansfield, MA) is a uniquely designed SGA with both a pharyngeal and esophageal sealing cuff and two lumina. The ETC is primarily designed for emergency intubation and is mostly used in the prehospital setting, although it has occasionally been used during general anesthesia as both a primary airway and as a rescue airway device.<sup>188,189</sup> It is inserted blindly through the mouth in a curved, downward motion until the printed ring marks lie between the teeth. Both the proximal, oropharyngeal cuff and the distal esophageal-tracheal cuff are inflated. Greater than 90% of the time, esophageal placement of the device occurs, in which ventilation should be performed via the longer, blue, #1 (esophageal) lumen.<sup>190</sup> This lumen has a closed distal end with eight small perforations located between the two cuffs, which allow oxygenation and ventilation. When the device is placed into the trachea, ventilation should occur via the shorter, clear, #2 (tracheal) lumen, which is open at its distal end. When the ETC is placed in the esophagus, an orogastric tube may be passed through the tracheal lumen to empty the stomach. Use of the ETC as a primary airway is limited by a higher risk of complications, compared with the LMA or tracheal intubation, including hoarseness, dysphagia, and bleeding.<sup>191</sup> Because the oropharyngeal cuff of the ETC contains latex, this device should not be used in latex-sensitive individuals.

The Rüsch EasyTube (Teleflex Medical, Research Triangle Park, NC) is a double-lumen SGA that is similar to the ETC. The primary differences are its nonlatex construction and a proximal lumen that ends just below the oropharyngeal balloon, allowing for the passage of a tube exchanger or FIS. The insertion technique and risks are similar to the ETC; a comparative study showed shorter insertion times with the EasyTube.<sup>192</sup>

The King LT series of SGAs (King Systems Corporation, Noblesville, IN) are similar in design to the ETC and EasyTube, with a ventilation port between the pharyngeal and esophageal cuffs. The King LT and the King LT-D (reusable and disposable, respectively) are single-lumen devices with a tapered distal tip that allows easy passage into the esophagus. The distal (esophageal) portion of the tube is occluded. The King LTS and the disposable King LTS-D, on the other hand, have an open distal tip with a secondary channel to allow suctioning of gastric contents. Although tracheal placement of a King LT device has not been reported, if it should occur, then the device should be removed and reinserted.

## Tracheal Intubation

Tracheal intubation is the gold standard for airway management. It establishes a definitive airway, provides maximal protection against the aspiration of gastric contents, and allows for PPV with higher airway pressures than with a face mask or an SGA. Tracheal intubation is usually

facilitated by DL; however, a wide variety of alternative intubation devices and techniques have been developed to circumvent the problems encountered when conventional DL is difficult.

In the fasted patient undergoing elective surgery with general anesthesia, an SGA is often suitable. Certain conditions or clinical situations, however, favor tracheal intubation, although the advent of second-generation SGAs has somewhat narrowed this list. Absolute indications for tracheal intubation include patients with a full stomach or who are otherwise at increased risk for aspiration of gastric secretions or blood, patients who are critically ill, patients with significant lung abnormalities (e.g., low lung compliance, high airway resistance, impaired oxygenation), patients requiring lung isolation, patients undergoing otolaryngologic surgery during which an SGA would interfere with surgical access, patients who will likely need postoperative ventilatory support, and patients in whom SGA placement has failed. Other indications for intubation include a surgical requirement for NMBDs, patient positioning that would preclude rapid tracheal intubation (e.g., prone or turned away from the anesthesia provider), a predicted difficult airway, and prolonged procedures.<sup>22</sup>

## ENDOTRACHEAL TUBES

The modern, standard ETT is a disposable, single-use, cuffed, plastic tube that is designed to be inserted through the nose or mouth and sit with its distal end in the mid-trachea, providing a patent airway to allow for ventilation of the lungs. A variety of different types of ETTs are available for use in specialized situations. Several features are commonplace among the different styles, however, including a universal 15-mm adapter that allows the attachment of the proximal end to different ventilating circuits and devices; a high-volume, low-pressure cuff; a beveled tip to facilitate passage through the vocal cords; and an additional distal opening in the side wall of the ETT known as a *Murphy eye*, which serves to provide an additional portal for ventilation should the distal end of the lumen become obstructed by either soft tissue or secretions.

Cuffed ETTs are routinely used for tracheal intubation in most patients; cuffless ETTs are used in neonates and infants. The high-volume, low-pressure cuff is inflated with air to provide a seal against the tracheal wall to protect the lungs from pulmonary aspiration and to ensure that the tidal volume delivered ventilates the lungs rather than escapes into the upper airway.<sup>22</sup> A pilot balloon with a one-way valve allows for the inflation of the cuff and an assessment of the cuff pressure. The cuff should be inflated to the minimum volume at which no air leak is present with positive pressure inspiration; the cuff pressure should be less than 25 cm H<sub>2</sub>O.<sup>193</sup> Excessive cuff pressure may result in tracheal mucosal injury, vocal cord dysfunction from recurrent laryngeal nerve palsy, and sore throat. Monitoring the cuff pressure with a pressure gauge is recommended. When N<sub>2</sub>O is used as part of the anesthetic, cuff pressure should be periodically measured throughout the surgery; N<sub>2</sub>O diffusion into the cuff can result in increases in cuff pressure to potentially dangerous levels.

ETT size is normally described in terms of its internal diameter (ID); the relationship of the ID to the external

diameter varies between different designs and manufacturers. Selection of the ETT size depends on the reason for placement and patient-specific factors such as gender and airway pathologic conditions. Smaller ETTs result in increased airway resistance and work of breathing, and ETTs with a smaller ID may preclude therapeutic fiberoptic bronchoscopy. Larger ETTs are more likely to be associated with laryngeal or tracheal mucosal trauma and have a higher incidence of sore throat after general anesthesia. Generally, in patients intubated only for the purposes of a general anesthetic, a smaller ETT may be used than on the patient who will remain intubated in the medium to long term as a result of respiratory failure; typically a 7-mm ETT is used for women and a 7.5- or 8-mm ETT is used for men.

A variety of specialized tracheal tubes are available for use in specific clinical situations. Preformed tubes, such as the nasal and oral Ring-Adair-Elwin (RAE) tubes, have a specific contour to maintain a low profile and to avoid surgical interference. Armored (reinforced) tubes have an embedded coil that minimizes kinking of the tube when it is subjected to angulation. Microlaryngeal tubes, which have small IDs with a longer length tube, are useful in laryngeal surgery or for specific applications, such as intubation through a cLMA. The VivaSight ETT (Ambu, Inc., Ballerup, Denmark) has an integrated video camera at the tip, useful during intubation and for confirming ETT position throughout the procedure. Other specialized tubes include laser-resistant tubes and both single- and double-lumen tubes that allow for one-lung ventilation.

## ENDOTRACHEAL TUBE INTRODUCERS

ETT introducers are long, slender devices used to assist in guiding an ETT through the glottis. They are particularly useful for performing a blind intubation when the glottic opening cannot be visualized during laryngoscopy.

The original ETT guide was the Eschmann introducer, developed by Venn in 1973.<sup>194</sup> This device, also known as the *gum elastic bougie*, is long enough to allow advancement of an ETT over its distal end after being placed through the vocal cords. It also possesses an anterior angulation at the distal end (coudé tip) to facilitate maneuvering underneath the epiglottis toward the glottic opening, even when the glottic structures are not visualized. A variety of similar introducers with different sizes and features are available; some are hollow to allow for ventilation if the need arises.

Coudé-tip introducers are particularly useful when only a portion of the laryngeal structures, such as only the tip of the epiglottis, can be visualized. Proper placement of the stylet is indicated by the perception of *tracheal clicks* as the coudé tip passes along the tracheal rings and by a *distal hold-up* as it reaches the small bronchi. An ETT is subsequently advanced over the introducer into the correct position (Video 44.5).<sup>195</sup>

## OROTRACHEAL VERSUS NASOTRACHEAL INTUBATION

Tracheal intubation can proceed via the orotracheal or nasotracheal route—this decision should be made before deciding which airway management technique will be used. Nasotracheal intubation is generally indicated when the orotracheal route is not possible (e.g., when the mouth

opening is severely limited) or when the need for surgical access precludes an orotracheal route. In addition, certain intubation techniques, such as blind intubation, awake intubation, and FSI, are significantly easier when performed through the nose.

When the nasotracheal route is not specifically indicated, however, the orotracheal route is usually preferred for several reasons. The orotracheal route is potentially less traumatic and presents a lower risk of bleeding, it usually allows for the placement of a larger ETT, and it provides for more options in terms of airway management techniques. The major disadvantages include the potential for damage to the teeth and stimulation of the gag reflex during awake intubation, requiring denser airway anesthesia and potentially being less comfortable for the patient. Nasotracheal intubation, on the other hand, bypasses the gag reflex and is usually more easily tolerated by the awake patient. However, the risks of epistaxis, trauma to the nasal turbinates, and submucosal tunneling in the nasopharynx must be taken into account.<sup>138</sup> Nasotracheal intubation is relatively contraindicated in the setting of maxillary or skull base fractures.

## DIRECT LARYNGOSCOPY

The most commonly used technique for tracheal intubation is DL, which involves direct visualization of the glottis with the assistance of a laryngoscope. The ETT is inserted through the glottic opening into the trachea under continuous observation.

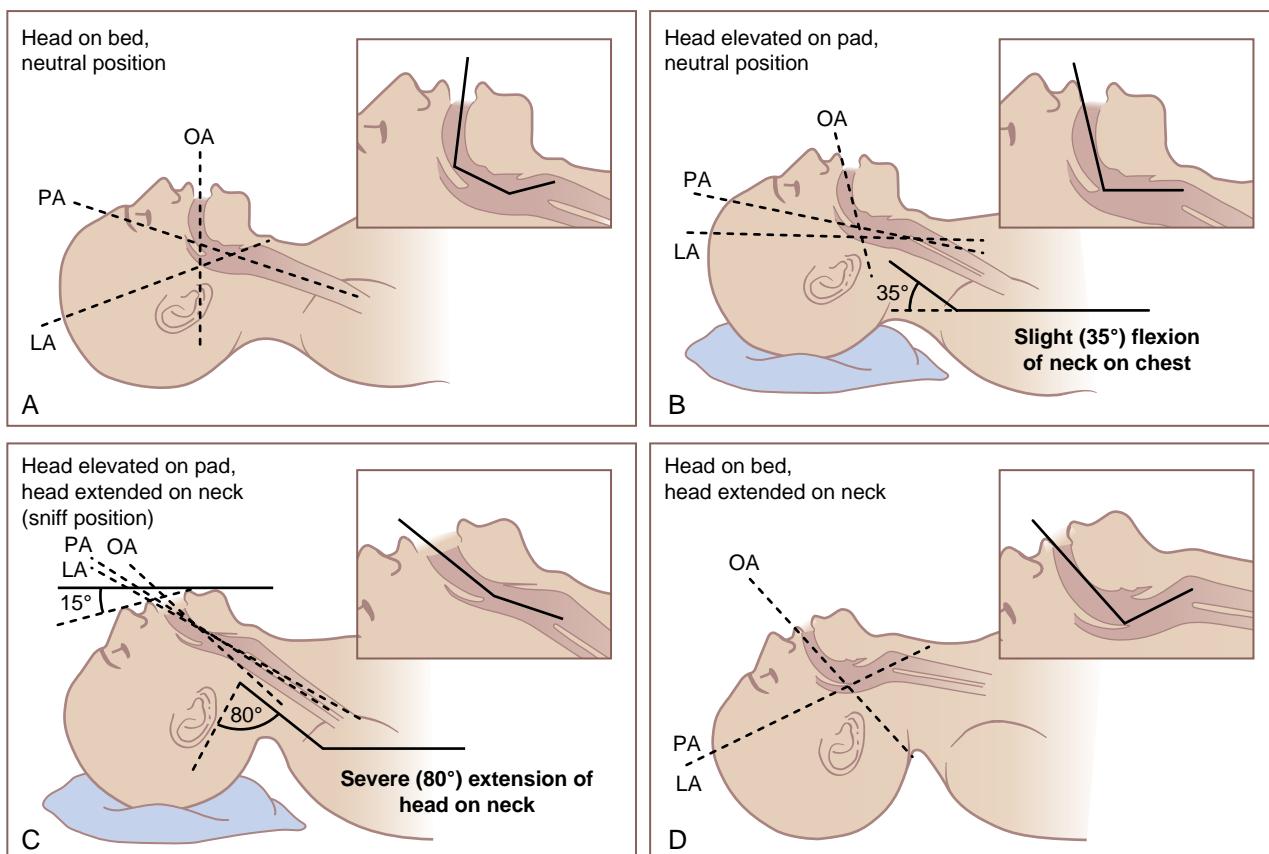
### Preparation and Positioning

Preparation for DL includes proper patient positioning, adequate preoxygenation, and ensuring the availability and proper functioning of all necessary equipment—laryngoscopes, tracheal tubes, tube stylets, an empty syringe for inflating the tracheal tube cuff, a suction apparatus, and the essential equipment for mask ventilation, including an oxygen source. A skilled assistant should be present to help with external laryngeal manipulation and stylet removal, among other tasks. Adequate preparation is of the utmost importance; as with any airway procedure, the first attempt should be the best attempt.

For DL to be successful, a line of sight from the mouth to the larynx must be achieved. The classical model used to describe the anatomic relationships necessary to achieve this was proposed in 1944 by Bannister and Macbeth and involves the alignment of three anatomic axes—oral, pharyngeal, and laryngeal.<sup>196</sup> Positioning the patient in the sniffing position approximates this alignment. Cervical flexion aligns the pharyngeal and laryngeal axes, and maximal head extension at the atlantooccipital joint brings the oral axis closer into alignment (Fig. 44.18). The accuracy of this model has been questioned,<sup>197</sup> and various alternative models to explain the anatomic advantage of the sniffing position have been proposed.<sup>198,199</sup> Regardless of the explanatory model, the evidence in the literature supports the assertion that the sniffing position is the optimal position for DL.<sup>47,200</sup>

Proper positioning in the sniffing position involves approximately 35 degrees of cervical flexion, which is accomplished by a 7- to 9-cm elevation of the head on a firm

### Head and neck position and the axes of the head and neck upper airway



**Fig. 44.18** Schematic diagrams show the alignment of the oral axis (OA), pharyngeal axis (PA), and laryngeal axis (LA) in four different head positions. Each head position is accompanied by an inset that magnifies the upper airway (oral cavity, pharynx, and larynx) and superimposes (bold line) the continuity of these three axes within the upper airway. (A) The head is in the neutral position with a marked degree of nonalignment of the LA, PA, and OA. (B) The head is resting on a large pad that flexes the neck on the chest and aligns the LA with the PA. (C) The head is resting on a pad (which flexes the neck on the chest). Concomitant extension of the head on the neck brings all three axes into alignment (sniffing position). (D) Extension of the head on the neck without concomitant elevation of the head on a pad, which results in nonalignment of the PA and LA with the OA. (From Baker PA, Timmermann A. Laryngoscopic tracheal intubation. In: Hagberg CA, Artine CA, Aziz M, eds. *Hagberg and Benumof's Airway Management*. 4th ed. Philadelphia: Elsevier; 2018.)

pillow; patients with shorter necks may require less head elevation.<sup>47,201</sup> Patients who are obese often require elevation of the shoulders and upper back to achieve adequate cervical flexion, which can be accomplished by placing the patient in the *ramped* position using either a specialized device, such as the Troop Elevation Pillow (Mercury Medical, Clearwater, FL), or folded blankets. Confirming horizontal alignment of the external auditory meatus with the sternal notch is useful for ensuring optimal head elevation in both obese and nonobese patients.<sup>202</sup> Adequate cervical flexion also facilitates maximal atlantooccipital extension, which provides optimal alignment of the oral and pharyngeal axes (the primary determinant for quality of laryngeal view) and enhanced mouth opening.<sup>203</sup>

#### Technique

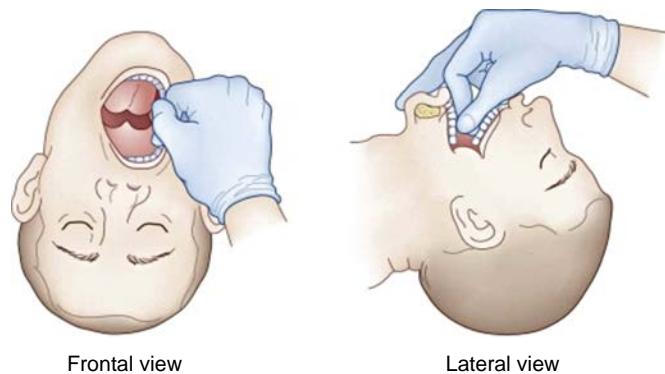
The laryngoscope is a handheld instrument consisting of a blade attached to a handle containing a light source. Most are reusable and made of steel, although disposable, plastic versions are available. The curved blade and the straight blade are the two basic types of laryngoscope blades available for DL; multiple variations of both styles exist. The Macintosh is the most commonly used curved blade, whereas the Miller is the most commonly used straight

blade. Both are designed to be held in the left hand, and both have a flange on the left side that is used to retract the tongue laterally. Each type of blade has its benefits and drawbacks and is associated with its own technique for use.

The technique for laryngoscopy consists of the opening of the mouth, inserting the laryngoscope blade, positioning of the laryngoscope blade tip, applying a lifting force exposing the glottis, and inserting a tracheal tube through the vocal cords into the trachea. Mouth opening is best achieved using the *scissors* technique; the right thumb pushes caudally on the right lower molars while the index or third finger of the right hand pushes on the right upper molars in the opposite direction (Fig. 44.19).

The decision of whether to use a Macintosh or a Miller blade is multifactorial; however, the personal preferences and experience of the laryngoscopist is a significant consideration. In general, the Macintosh is most commonly used for adults, whereas the straight blades are typically used in pediatric patients.<sup>204</sup> Curved blades provide greater room for passage of an ETT through the oropharynx, attributable to their larger flange, and are generally considered less likely to cause dental damage.<sup>205</sup> Straight blades are preferred in patients with a short thyromental distance or prominent incisors, and usually provide a better view of the glottis in

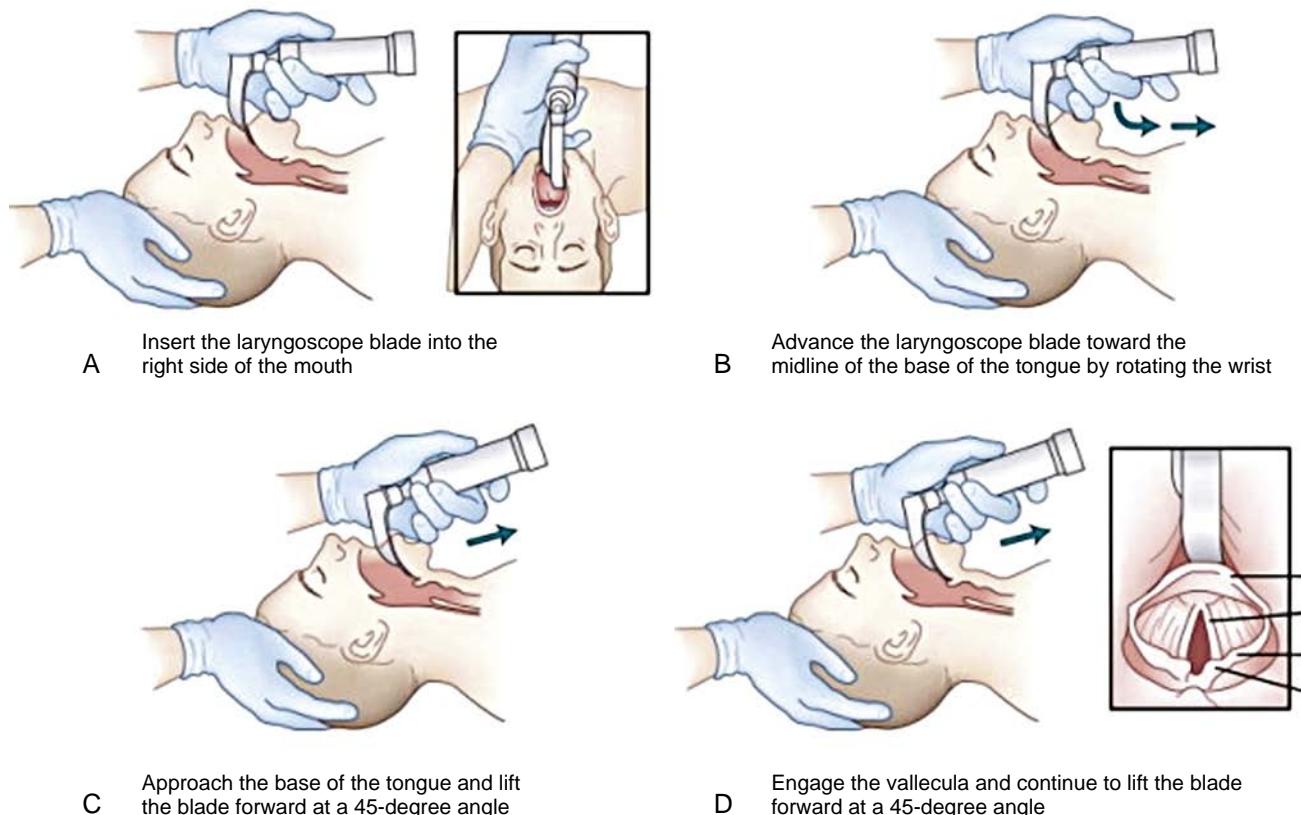
patients with a long, floppy epiglottis. Often, when one style of laryngoscope does not provide an adequate view of the glottis, the other may be more effective. For most adults, a Macintosh size 3 or a Miller size 2 blade is usually the proper size; in larger patients or patients with a very long thyromental distance, a larger blade may be more appropriate.



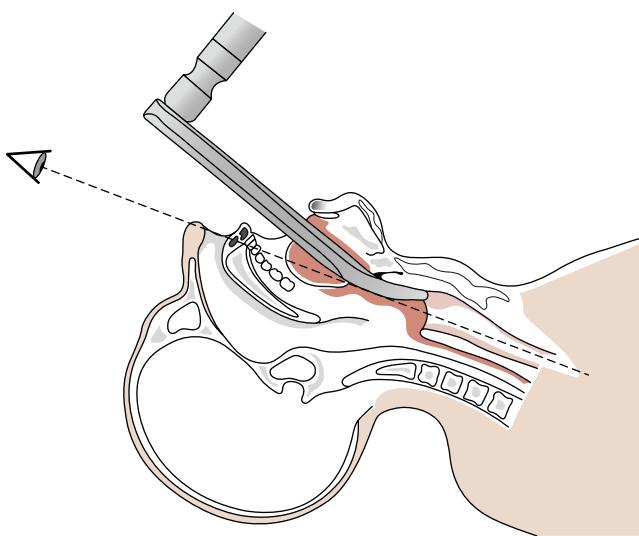
**Fig. 44.19** The scissors technique for mouth opening. The thumb of the right hand is pressed on the right lower molars in a caudad direction while the index or third finger of the right hand presses on the right upper molars in a cephalad direction. (From Baker PA, Timmermann A. Laryngoscopic tracheal intubation. In: Hagberg CA, Artime CA, Aziz M, eds. *Hagberg and Benumof's Airway Management*. 4th ed. Philadelphia: Elsevier; 2018.)

The Macintosh blade is inserted in the right side of the mouth, and the flange is used to sweep the tongue to the left. Once the laryngoscope has been inserted in the mouth, the right hand can be used to ensure that the upper lip is not impinged between the laryngoscope and the upper incisors. The blade is advanced along the base of the tongue until the epiglottis is visualized; the tip of the blade is then advanced further and positioned in the vallecula. A force oriented at a 45-degree angle up and away from the laryngoscopist indirectly lifts the epiglottis by placing tension on the hyoepiglottic ligament, exposing the glottic structures (Fig. 44.20). The tip of the blade should not be lifted by using the laryngoscope as a lever, rocking back on the upper incisors, which can damage the teeth and provides an inferior view of the glottis. A properly oriented vector of force is achieved by using the anterior deltoid and triceps, not by radial flexion of the wrist. Once a complete view of the glottis is achieved, the ETT is grasped similar to a pencil with the right hand and guided through the vocal cords into the trachea. Passage of the ETT may be facilitated by an anterior angulation of the tip, which can be accomplished by shaping the ETT with a malleable stylet into a *hockey stick* shape, with approximately a 60-degree angle formed 4 to 5 cm from the distal end, or by accentuating the natural anterior curvature of the ETT by inserting the tip into the 15-mm connector, forming a circle, for several minutes before performing DL.

#### Conventional Laryngoscopy with a Curved Blade



**Fig. 44.20** Laryngoscopy technique with a Macintosh (curved) blade. (A) The laryngoscope blade is inserted into the right side of the mouth, sweeping the tongue to the left of the flange. (B) The blade is advanced toward the midline of the base of the tongue by rotating the wrist so that the laryngoscope handle becomes more vertical (arrows). (C) The laryngoscope is lifted at a 45-degree angle (arrow) as the tip of the blade is placed in the vallecula. (D) Continued lifting of the laryngoscope handle at a 45-degree angle results in exposure of the laryngeal aperture. The epiglottis (1), vocal cords (2), cuneiform cartilage (3), and corniculate cartilage (4) are identified. (From Baker PA, Timmermann A. Laryngoscopic tracheal intubation. In: Hagberg CA, Artime CA, Aziz M, eds. *Hagberg and Benumof's Airway Management*. 4th ed. Philadelphia: Elsevier; 2018.)

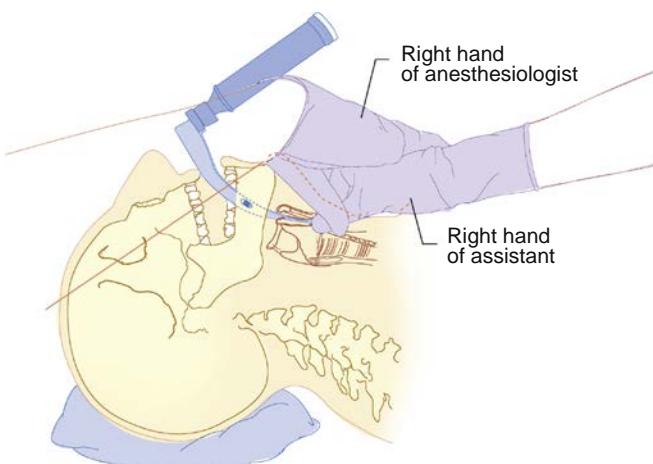


**Fig. 44.21** Paraglossal laryngoscopy technique with a Miller (straight) blade. The blade is at the right side of the tongue. The line of sight over the molars is achieved by rotating the head to the left and moving the heel of the laryngoscope to the right. The tip of the blade is placed beneath the epiglottis and a 45-degree lifting force applied to expose the glottic aperture. (From Baker PA, Timmermann A. Laryngoscopic tracheal intubation. In: Hagberg CA, Artine CA, Aziz M, eds. *Hagberg and Benumof's Airway Management*. 4th ed. Philadelphia: Elsevier; 2018.)

The Miller laryngoscope blade is inserted using the paraglossal technique described by Henderson.<sup>22</sup> This method provides maximal tongue control and avoids contact of the laryngoscope with the maxillary incisors. The laryngoscope is inserted lateral to the tongue and carefully advanced along the paraglossal gutter between the tongue and tonsil. Application of continued moderate lifting force to the laryngoscope handle helps maintain lateral displacement of the tongue and reduces contact with the maxillary teeth. As the laryngoscope is advanced, the epiglottis comes into view and the tip of the laryngoscope is passed posterior to the epiglottis. The optimal position of the tip of the straight laryngoscope is in the midline of the posterior surface of the epiglottis, close to the anterior commissure of the vocal cords (Fig. 44.21).<sup>22</sup> This position achieves good control of the epiglottis and facilitates the passage of the tracheal tube. The direction of force applied to the handle is the same as when using the Macintosh blade.

The use of external laryngeal manipulation can improve the laryngeal view. Backward, upward, rightward pressure (the BURP maneuver) on the thyroid cartilage is most commonly used. Optimal external laryngeal manipulation (OELM) is achieved when the laryngoscopist uses his or her right hand to guide the position and pressure is exerted by an assistant's hand on the larynx (Fig. 44.22).

Difficulty with tracheal intubation by DL is primarily a function of an inadequate view of the glottis. Predictors for difficult laryngoscopy that can be identified during the preoperative airway assessment are listed in **Box 44.3**. Cormack and Lehane developed a grading scale in 1984 to describe laryngoscopic views.<sup>206</sup> The grades range from I to IV, beginning with grade I (the best view), in which the epiglottis and vocal cords are in complete view, and culminating with grade IV (the most difficult view), in which the epiglottis or larynx is not visualized (Fig. 44.23). A



**Fig. 44.22** Optimal external laryngeal manipulation. The laryngoscopist guides the position, and pressure is exerted by the assistant's hand on the larynx to maximize the view of the vocal cords. The left hand of the laryngoscopist, which holds the laryngoscope handle, is omitted. (From Henderson J. Airway management. In: Miller RJ, ed. *Anesthesia*. 7th ed. Philadelphia: Churchill Livingstone; 2009.)

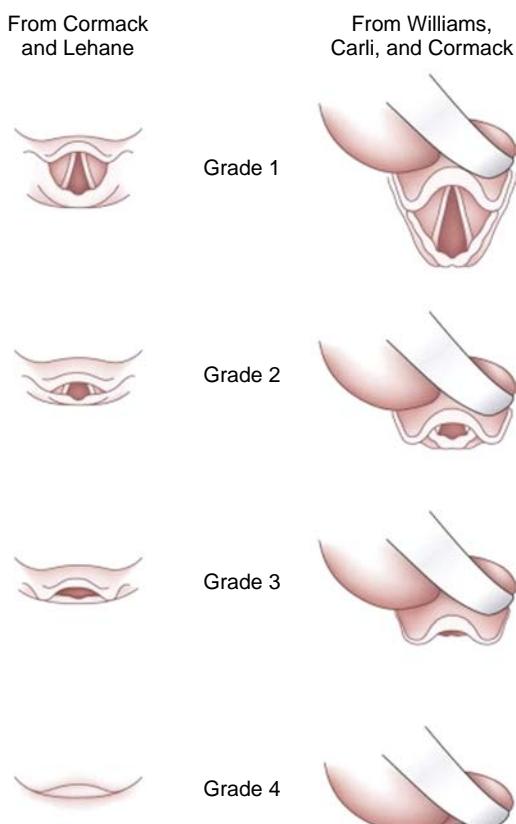
### BOX 44.3 Predictors of Difficult Laryngoscopy

- Long upper incisors
- Prominent overbite
- Inability to protrude mandible
- Small mouth opening
- Mallampati classification III or IV
- High, arched palate
- Short thyromental distance
- Short, thick neck
- Limited cervical mobility

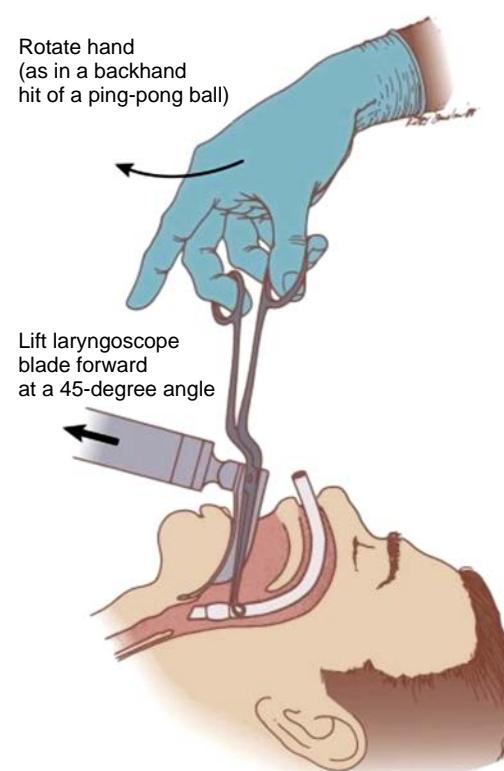
Modified from Apfelbaum JL, Hagberg CA, Caplan RA, et al. Practice guidelines for management of the difficult airway: an updated report by the American Society of Anesthesiologists Task Force on Management of the Difficult Airway. *Anesthesiology*. 2013;118:251–270.

modified classification scheme with five different grades based on the Cormack-Lehane scoring system is described by Yentis, who proposed that grade II be differentiated into IIA (partial view of the glottis) and IIB (arytenoids or posterior vocal cords only are visible).<sup>207</sup> Intubation is rarely difficult when a grade I or IIA view is achieved; grades IIB and III are associated with a significantly higher incidence of failed intubation. A grade IV laryngoscopic view requires an alternate method of intubation. An alternate method of rating laryngoscopic view is the percentage of glottic opening (POGO) scale, which is determined by the percentage of the vocal cords from the anterior commissure to the arytenoid notch that can be visualized during laryngoscopy. This scale has been shown to have a higher interobserver reliability than the Cormack-Lehane scoring system and is potentially more useful for research studies in direct and indirect laryngoscopy.<sup>208</sup>

When the laryngeal view is inadequate, the laryngoscopist should verify that the patient is in an optimal position, that OELM is being provided, and that the laryngoscope has not been inserted too deeply. Whether a larger laryngoscope or an alternate style of blade would be beneficial should be



**Fig. 44.23** The Cormack-Lehane grading system for laryngoscopic view. Grade 1 is visualization of the entire laryngeal aperture; grade 2 is visualization of only the posterior portion of the laryngeal aperture; grade 3 is visualization of only the epiglottis; and grade 4 is no visualization of the epiglottis or larynx. (Modified from Cormack RS, Lehane J. Difficult tracheal intubation in obstetrics. *Anaesthesia*. 1984;39:1105; and Williams KN, Carli F, Cormack RS. Unexpected difficult laryngoscopy: a prospective survey in routine general surgery. *Br J Anaesth*. 1991;66:38.)



**Fig. 44.24** Guiding a nasal endotracheal tube into the larynx with Magill forceps. (From Berry JM, Harvey S. Laryngoscopic orotracheal and nasotracheal intubation. In: Hagberg CA, ed. *Benumof and Hagberg's Airway Management*. 3rd ed. Philadelphia: Saunders; 2013, p. 357.)

considered. When the ETT cannot be passed into the trachea under direct visualization, the options include the following: (1) attempts at blind passage of the ETT, which risks laryngeal trauma, bleeding, and airway obstruction; (2) the use of an ETT introducer; and (3) alternative approaches to intubation as per the ASA DAA.

When the glottic view is adequate, the ETT should be inserted into the right corner of the mouth and advanced such that it intercepts the long axis of the laryngoscope blade at the glottis, rather than inserted midline and parallel to the long axis of the laryngoscope blade, ensuring that the view of the glottis is not obscured. The tip of the ETT is passed through the glottic inlet and advanced until the proximal portion of the cuff is approximately 2 cm past the vocal cords. If a stylet is being used, then the stylet should be removed when the tip of the ETT is at the level of the vocal cords while the ETT is firmly held stationary; this technique helps limit trauma to the tracheal mucosa from the semi-rigid stylet.

### Nasotracheal Intubation Technique

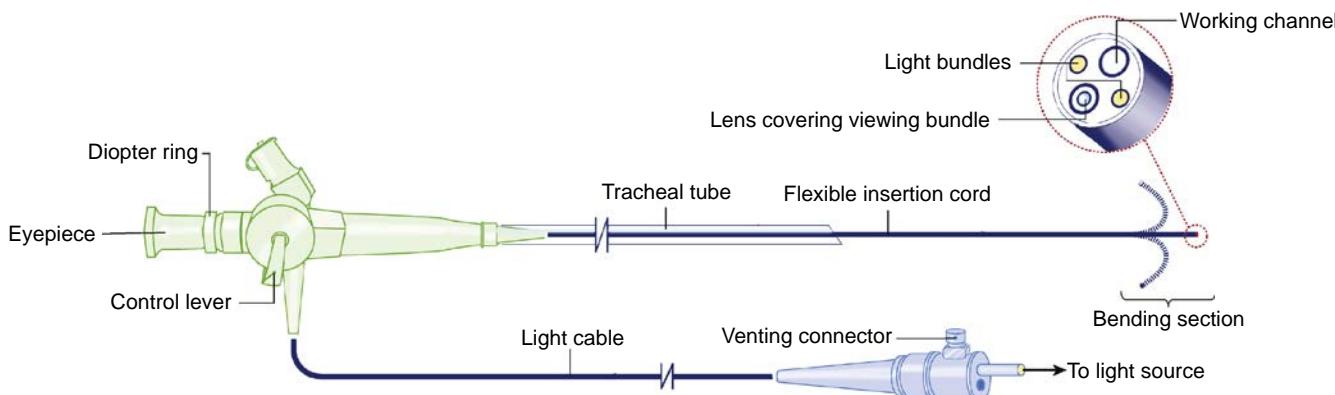
Before nasotracheal intubation, the more patent nostril should be selected. This selection can be accomplished by separately occluding each nostril and having the patient inhale—the patient will usually be able to inhale more

effectively through one of the nares. To reduce the risk of epistaxis, a nasal mucosal vasoconstrictor (e.g., cocaine, phenylephrine, oxymetazoline) should be administered. The nasal ETT should be lubricated and inserted into the naris with the bevel facing away from the midline, which decreases the risk of avulsion of a turbinate. Cephalad traction should be applied as the ETT is advanced through the nasal passage to ensure a trajectory along the floor of the nose, beneath the inferior turbinate.

Once the ETT enters the oropharynx (typically at a depth of 14 to 16 cm), standard DL is performed. The ETT can be guided into the laryngeal inlet by repositioning the head as the ETT is advanced or with the aid of Magill forceps (Fig. 44.24). Care should be taken to grasp the ETT proximal to the cuff to prevent cuff damage. Other techniques for nasotracheal intubation include blind nasal intubation, VAL, and FSI.

### Confirmation of Endotracheal Tube Placement

Once the ETT is in place, the laryngoscope is removed from the mouth, the ETT cuff is appropriately inflated, and the patient is manually ventilated while the ETT is manually held in place. Immediate verification of endotracheal placement of the ETT is necessary; esophageal or endobronchial intubation is a significant source of avoidable anesthetic-related morbidity and mortality. Endotracheal placement can be determined by confirmation of chest rise, visible condensation in the ETT, equal breath sounds bilaterally over the chest wall, lack of breath sounds over the epigastrium, large exhaled tidal volumes, and appropriate compliance of



**Fig. 44.25** Flexible fiberoptic bronchoscope. (From Henderson J. Airway management. In: Miller RJ, ed. *Anesthesia*. 7th ed. Philadelphia: Churchill Livingstone; 2009.)

the reservoir bag during manual ventilation.<sup>209</sup> The most important and objective indicator of tracheal intubation, however, is the presence of a normal capnogram (carbon dioxide [CO<sub>2</sub>] waveform) for the presence of at least three breaths. Severe bronchospasm, equipment malfunction, cardiac arrest, or hemodynamic collapse may prevent the appearance of a capnogram tracing despite proper ETT placement. If doubt remains, then flexible bronchoscopy, although not routinely used, is very reliable at confirming ETT placement.

Hypoxemia, increased airway pressures, asymmetric chest expansion, and the absence of breath sounds over one lung, generally the left, are indicative of endobronchial intubation; pneumothorax can also produce this picture. Flexible bronchoscopy or chest radiography can be used if the clinical picture is unclear.

### Securing the Endotracheal Tube

Once the proper depth of the ETT has been determined, the tube should be secured in place to prevent movement and inadvertent endobronchial intubation or extubation. The most common method is to tape the ETT to the skin of the face. Because it is less mobile, the skin of the maxilla is preferred. When tape cannot be used, such as in the case of a severe tape allergy, extensive facial burns, or epidermolysis bullosa, a surgical mask may be tied around the back of the head to secure the ETT. Other methods that may be used for intraoral or facial surgery include wire fixation to a tooth or suturing the ETT to the skin of the cheek.

### INDIRECT LARYNGOSCOPY

Conventional DL requires wide mouth opening, cervical flexion, and atlantooccipital extension to create a direct line of vision from the mouth to the larynx. In certain conditions, this positioning is impossible or contraindicated. Other times, attributable to anatomic variations in the airway (e.g., redundant soft tissue, protruding incisors, anterior larynx), DL cannot be achieved, despite optimal positioning and technique. Indirect laryngoscopy entails the indirect visualization of the glottis by way of optical aids, such as fiberoptic bundles, video cameras, mirrors, prisms, or lenses. Various different devices that use indirect laryngoscopy are available, including FISs, video laryngoscopes (VLs), and intubating optical styles. They are indispensable tools for the management of the

known or predicted difficult airway. Because no direct line of sight is needed, visualization of the larynx can occur without tissue distortion; consequently, these techniques can be readily used with topical anesthesia in an awake patient.<sup>22</sup>

### Flexible Intubation Scopes

The FIS is the most widely used, versatile, indirect laryngoscopy device. Since the first use of fiberoptics for airway management in 1967, FISs, including the flexible fiberoptic bronchoscope (FOB), have become invaluable tools for tracheal intubation in both awake and anesthetized patients. There are various clinical scenarios within which FSI provides a superior technique for airway management, as compared with DL or alternative airway devices. FSI of the awake and cooperative, spontaneously ventilating patient is considered the *gold standard* for the management of the difficult airway.<sup>195</sup>

The standard FOB (Fig. 44.25) consists of thousands of flexible glass fibers approximately 8 to 10  $\mu\text{m}$  in diameter that are capable of transmitting reflected light along their length. Light is transmitted from an external light source to the distal end of the FOB; the light reflecting off the object to be viewed is transmitted back along the length of the FOB to an eyepiece or video camera at the proximal end of the scope. In recent years, FOBs have been replaced by modern FISs that use video chip and light-emitting diode (LED) technology instead of fiberoptics.

Indications for FSI essentially include any indication for tracheal intubation. However, FSI may be the airway management technique of choice in any one of the following clinical scenarios<sup>195</sup>:

- Known or anticipated difficult airway (i.e., cannot intubate or cannot ventilate [CICV])
- Contraindication to extension of the neck (e.g., unstable cervical fracture, severe cervical stenosis, vertebral artery insufficiency, Chiari malformation)
- Increased risk of dental damage (e.g., poor dentition, fragile dental work)
- Limited mouth opening (e.g., TMJ disease, mandibular-maxillary fixation, severe facial burns)

No specific contraindications exist for FSI; however, in certain clinical situations, successful FSI is unlikely. Severe airway bleeding can obscure anatomic landmarks and soil the tip of the FIS with blood, making visualization of the

larynx extremely difficult. Obstruction or severe stenosis of the airway, resulting in the inability to pass an FIS, can also make FSI impossible.

FSI provides several advantages over DL<sup>195</sup>:

- Allows for a more complete visual examination of the airway before intubation.
- Provides confirmation of tube placement, avoiding esophageal and endobronchial intubation.
- Eliminates the need for three-axis alignment; therefore FSI is among the techniques least likely to result in cervical spine movement.
- Is well-tolerated in awake patients; results in less tachycardia and hypertension.
- Has less of a potential for airway and dental trauma.
- Can be performed in multiple positions.

FSI can be performed in the awake or anesthetized patient. Indications for an awake FSI are generally those situations in which ventilation via a mask is anticipated to be difficult, when a postintubation neurologic examination is needed, or when induction of general anesthesia could cause adverse hemodynamic or respiratory consequences. The major technical disadvantage to performing FSI under general anesthesia is the loss of pharyngeal muscle tone, which can lead to upper airway collapse and difficult fiberoptic laryngoscopy.<sup>195</sup>

Before its use, the anesthesia practitioner or skilled assistant must ensure that the FIS, light source, and video monitor are in proper working condition and that all components have been fully prepared for use. This preparation includes focusing the image if using a FOB, ensuring proper view orientation if using a video camera, lubricating the distal third of the flexible insertion cord, applying antifogging solution to the tip of the scope, and connecting a suction line or oxygen source to the suction port. The ETT should be prepared by placing it in a warm water bath, which softens the plastic, easing passage into the trachea and minimizing airway trauma.

FSI is usually performed in the supine or sitting (i.e., beach-chair) position, although emergency FSI in the lateral decubitus or even prone position has also been described.<sup>210</sup> When performing FSI in the supine position, the anesthesia provider stands at the head of the patient. Advantages to this position are that the laryngeal view through the FIS is in the same orientation as during DL, and the patient and physician are already in the optimal position to perform mask ventilation or other airway maneuvers, if necessary. When performing FSI with the patient in the sitting or beach-chair position, the practitioner should stand facing the patient at the patient's side. This position may be the position of choice in awake FSI because of improved ventilation and greater patient comfort. In addition, the sitting position optimizes airway anatomy and prevents airway collapse in patients who are obese, in patients with obstructive sleep apnea, and in patients with anterior extrinsic airway obstruction.<sup>211</sup>

Before FSI, unless contraindicated, an anti-sialagogue, such as glycopyrrolate 0.2–0.4 mg IV, may be administered to dry airway secretions. Both the orotracheal and nasotracheal routes can be used for FSI. While weighing the advantages and disadvantages, the clinician should determine which approach is best-suited for the clinical situation.

Whichever route is chosen, however, essentially two steps to FSI must be taken<sup>195</sup>:

1. Indirect laryngoscopy and endoscopy are performed, obtaining a view of the glottis with the FIS and maneuvering the FIS through the vocal cords into the trachea.
2. The ETT is advanced over the FIS into its proper position in the trachea, and the FIS is removed.

When performing orotracheal FSI, navigating the FIS around the base of the tongue to achieve a satisfactory view of the larynx is one of the major challenges. The FIS has a tendency to stray off the midline, and, frequently, little to no airspace is found between the tongue and the palate through which to navigate the FIS. To mitigate this issue, several devices or techniques can be used. Specialized intubating oral airways can be used to protect the FIS from damage by biting, to prevent the tongue from falling back into the pharynx and obstructing the airspace, and to keep the FIS midline while it is guided to the larynx. Several types of intubating oral airways are available, each with unique design differences, and include the Ovassapian, Berman, and Williams airways. A disadvantage of these devices is that they place pressure on the base of the tongue, potentially causing gagging in awake patients. In both awake patients and those under general anesthesia, gentle traction on the tongue anteriorly is helpful in preventing the tongue from falling back into the pharynx if an intubating airway is not used. This traction can be easily accomplished by hand with the help of 4- × 4-inch gauze pads for traction or with Magill forceps. Care should be taken to not injure the tongue on the bottom teeth. As previously described, LMAs and intubating LMAs can also be used as conduits for oral FSI. Obtaining a laryngeal view during nasal FSI is often easier, as compared with the oral approach, as a result of the fact that the FIS stays midline and the tip of the FIS is usually directed at the glottis as it enters the oropharynx.

Once the FIS has been successfully positioned in the oropharynx, the epiglottis and vocal cords can usually be visualized with a slight anterior deflection of the tip of the FIS. The FIS is aimed toward the anterior commissure of the vocal cords and posteriorly flexed to enter into the trachea. The trachea is easily identifiable by the presence of the cartilaginous tracheal rings. The FIS is advanced distally until a point just above the carina, and the ETT is advanced over the FIS while continually visualizing the trachea through the FIS, providing confirmation that the FIS and ETT have not been accidentally dislodged into the oropharynx or esophagus (Video 44.6). Frequently, especially with orotracheal intubation, resistance is met as the tip of ETT reaches the glottic inlet. Often, this resistance has been shown to be attributable to the bevel of the ETT impinging on the right arytenoid.<sup>212</sup> A slight withdrawal of the ETT and a counterclockwise 90-degree turn, orienting the bevel posteriorly, usually resolves this issue. For nasotracheal intubation, a clockwise 90-degree turn, ensuring that the bevel is oriented anteriorly, can prevent the tip of the ETT from impinging on the epiglottis. Alternatively, the Parker Flex-Tip ETT (Parker Medical, Englewood, CO), which has a bull-nosed tip directed toward the center of the distal lumen, can be used. This ETT has been shown to have a high first-pass success rate when being advanced over an FIS.<sup>213</sup>

After successful passage of the ETT, proper depth (2 to 3 cm from the carina) is confirmed during the withdrawal of the FIS. On rare occasions, the FIS may prove difficult to remove from the ETT, which may be attributable to the FIS having passed through the Murphy eye rather than the distal lumen or a result of inadequate lubrication of the FIS. In these situations, forceful removal may damage the device; therefore the FIS and ETT should be removed as a unit and the procedure repeated.

### Rigid Indirect Laryngoscopes

The first indirect laryngoscopes for intubation were based on modifications of the standard direct laryngoscope and used mirrors or prisms to project an image at an angle from the horizontal, facilitating visualization of the larynx. Modern indirect laryngoscopes based on the direct laryngoscope design that use optical lenses to project a refracted image of the glottis include the Viewmax (Rüsch, Duluth, GA) and the TruView EVO2 (Truphatek, Netanya, Israel).

The Airtraq SP (Prodol Meditec S.A., Guecho, Spain) is a disposable, portable, anatomically shaped, optical laryngoscope that provides a magnified view of the glottis without alignment of the oral, pharyngeal, and laryngeal axes. It includes a guiding channel to hold the ETT and direct it toward the vocal cords. It can be used for a variety of applications, including the known or predicted difficult airway, as well as for awake intubation. The Airtraq laryngoscope has been shown to result in more rapid tracheal intubation with a reduced incidence of esophageal intubation when compared to DL, especially when used by novices.<sup>214</sup> It is available in two adult and two pediatric sizes, as well as in specific designs for nasotracheal intubation and double-lumen tube placement. The Airtraq Avant is a newer model that features a reusable optic piece that is used in combination with disposable blades.

### Lighted Optical Stylets

Lighted optical stylets are rigid or semirigid fiberoptic devices that incorporate the optical and light-transmitting components into a tubular, stainless steel sheath over which the ETT is loaded. A substantial body of evidence supports the use of these optical stylets in patients with limited neck mobility,<sup>215</sup> small mouth opening,<sup>216</sup> abnormal airway anatomy,<sup>217</sup> or anticipated difficult laryngoscopy.

The Bonfils retromolar intubation fiberscope (Karl Storz Endoscopy, Tuttlingen, Germany) is a 40-cm long, rigid optical stylet with a fixed anterior tip curvature of 40 degrees (Video 44.7).<sup>218</sup> The proximal eyepiece can be used with the naked eye or connected to a video monitor. It is available with a working channel that can be used for suction, SAYGO local anesthesia,<sup>219</sup> or oxygen insufflation (oxygen flow rates should be limited to 3 L/min to avoid barotrauma).<sup>220</sup> The Shikani optical stylet (Clarus Medical, Minneapolis, MN) is a similar device to the Bonfils fiberscope but with a malleable shaft. The Levitan FPS stylet (Clarus Medical, Minneapolis, MN) is a shorter version of the Shikani stylet intended for use in combination with DL, although usable on its own.<sup>221</sup> The Clarus Video System (Clarus Medical, Minneapolis, MN) is a newer version of the Shikani stylet that incorporates a liquid crystal display (LCD) screen (Video 44.8).

These optical stylets can be used on their own or in combination with DL or VAL.<sup>222</sup> The ETT is mounted on the optical stylet and advanced under direct vision via a midline or right paraglossal route until it passes under the tongue. After indirect visualization of the tip of the stylet passing through the vocal cords (via the eyepiece or video monitor), the ETT is advanced over the stylet into the trachea. When these are not used in conjunction with DL or VAL, the left hand of the operator should lift the patient's jaw by gently grasping the mandible and displacing it anteriorly. This maneuver helps create more airspace in the oropharynx and lifts the epiglottis. Optical stylets can be used for awake intubation and have also been used for the transillumination technique (see Lighted Stylets).<sup>218,223</sup>

The SensaScope (Acutronic, Hirzel, Switzerland) is a hybrid rigid optical stylet that uses video chip technology. It has an S-shaped curvature and a 3-cm long steerable tip.<sup>224</sup> Visualization is achieved by a connection to a video monitor. The SensaScope is designed to be used in combination with DL and has been successfully used for awake intubation in patients with a predicted difficult airway.<sup>225</sup> The Video RIFL (AI Medical Devices, Williamston, MI) is a similar device with a rigid shaft and a flexible, steerable tip. This device features an LCD monitor attached to the handle that displays the video image.

### Video Laryngoscopes

As with flexible bronchoscopes, video chip technology has begun to largely replace fiberoptic technology in rigid indirect laryngoscopes because of the advantages of a higher quality image, increased durability, and reduced maintenance costs. Over the past 15 years, VLs have revolutionized the practice of airway management, and their use may become standard not only for difficult airways, but also for routine airways as well. In fact, VAL is now included in the ASA DAA as an alternative approach to intubation and should be considered for patients with a known or predicted difficult airway.<sup>7</sup> A VL is also listed as a suggested piece of equipment on a portable difficult airway cart.<sup>7</sup>

VAL has been shown to result in improved glottic visualization, compared with DL, in both routine airway management and in the predicted difficult airway.<sup>7,226</sup> Although this improved visualization does not necessarily translate into increased success with intubation (particularly in the normal airway), studies have shown improved intubation success with VAL in patients with predicted difficult airways.<sup>227,228</sup> VLs are also useful in the unexpected difficult airway; intubation success rates of 94% and 99% have been reported for VAL as a rescue modality after failed DL.<sup>229,230</sup> These devices have also been successfully used for awake intubation.<sup>231,232</sup>

Various different VLs have been introduced, each with its own design and specific features. Generally, VLs can be divided into three groups: (1) those whose design is based on the Macintosh blade, (2) those that incorporate highly curved or distally angulated blades, and (3) those that incorporate an ETT-guiding channel.<sup>233</sup> Although no single design has been shown to be superior, there are certain clinical circumstances where one style may be preferable to another. Other features that vary among different VLs include the degree of portability and the size of the video monitor. Many VLs are available in both reusable and single-use models.

VLs based on the Macintosh blade design include the C-MAC laryngoscope (Karl Storz, Tuttlingen, Germany), the McGrath MAC laryngoscope (Aircraft Medical, Edinburgh, UK), and the GlideScope Titanium MAC (Verathon, Bothell, WA). These devices can be used for both DL and VAL, making them particularly useful for teaching the DL technique. The C-MAC laryngoscope is the most extensively studied of these and is associated with shorter intubation times and greater ease of use, compared with other VLs,<sup>234,235</sup> which is possibly due to laryngoscopists' familiarity with the use of a Macintosh-style blade (Fig. 44.26). The technique for using the C-MAC laryngoscope is identical to that of DL with a Macintosh blade; alternatively, the tip of the VL can be used to lift the epiglottis directly.<sup>236</sup> In contrast to other VLs, most intubations with the C-MAC laryngoscope can be performed without

the use of a stylet<sup>237,238</sup>; the use of an oral RAE ETT can facilitate tracheal intubation.<sup>239</sup>

VLs with a distally angulated or highly curved blade permit a "look around the corner," providing an improved laryngoscopic view without requiring manipulation of the cervical spine. These devices are therefore of particular utility in patients with cervical immobilization, micrognathia, or limited mouth opening.<sup>233</sup> The GlideScope Titanium LoPro (Verathon, Bothell, WA) is the updated version of the archetype for this subset of devices. It possesses a 60-degree blade angulation, an antifogging mechanism, a 6.4-inch video monitor, and is available in reusable and single-use models (Fig. 44.27). The McGrath Series 5 laryngoscope (Aircraft Medical, Edinburgh, UK) is a similar device in that it possesses a distally angulated blade; its primary difference is its greater portability and a disarticulating handle that can be useful in patients with limited mouth opening and limited movement of the head and neck. The X-Blade is a hyperangulated blade for the McGrath MAC, while the D-Blade (Karl Storz, Tuttlingen, Germany) is a highly curved VL blade for use with the C-MAC system. These devices are typically inserted in the mouth midline, without sweeping the tongue from right to left as in DL. Because of the high degree of angulation of the blade, an ETT stylet is almost always necessary; malleable stylets with a 60- to 90-degree bend, articulating stylets, and the GlideRite stylet (a rigid stylet with a 90-degree curve specifically designed for use with the GlideScope) have all been successfully used with these VLs.<sup>240,241</sup> The VL and the styletted ETT should be inserted into the oral cavity under direct vision to avoid oropharyngeal trauma (Video 44.9).<sup>242</sup>

Some VLs with highly curved blades have integrated tube-guiding channels to facilitate intubation without the use of a stylet, similar to the Airtraq. The King Vision (King Systems, Noblesville, IN) and the Pentax Airway Scope (AWS; Pentax Medical, distributed by Ambu Inc., Ballerup, Denmark) fall into this category. This type of VL has been shown to be useful in patients with cervical immobilization and has been successfully used for awake intubation.<sup>243,244</sup>



**Fig. 44.26** The Storz C-MAC videolaryngoscope. (From Aziz M, Brambrink A. Video-assisted laryngoscopy. In: Hagberg CA, Artine CA, Aziz M, eds. *Hagberg and Benumof's Airway Management*. 4th ed. Philadelphia: Elsevier; 2018.)



**Fig. 44.27** The GlideScope AVL videolaryngoscope system with titanium blades. (From Aziz M, Brambrink A. Video-assisted laryngoscopy. In: Hagberg CA, Artine CA, Aziz M, eds. *Hagberg and Benumof's Airway Management*. 4th ed. Philadelphia: Elsevier; 2018.)



**Fig. 44.28** When the tip of a lighted stylet is placed at the glottic opening, a well-circumscribed glow can be seen in the anterior neck just below the thyroid prominence.

The VividTrac (Vivid Medical, Palo Alto, CA) is a single-use, channeled VL with a Universal Serial Bus (USB) interface that works with any monitor.

### Lighted Stylets

Lighted stylets make use of the transillumination technique to blindly intubate the trachea and have been described in the literature as an alternative or aid to DL, particularly in the predicted difficult airway. Lighted stylets may be particularly helpful when the presence of blood or heavy secretions limits visualization of the airway. However, because lighted stylet insertion is a blind technique, it is contraindicated in certain clinical situations, such as neoplasm of the airway or airway trauma. Because increased soft tissue leads to difficulty with transillumination, this technique is less useful in the patient who is morbidly obese.<sup>245</sup>

To perform the transillumination technique, an ETT is preloaded onto the stylet. The left hand of the operator lifts the supine patient's jaw by gently grasping the mandible and displacing it anteriorly to facilitate the insertion of the stylet under the tongue. The stylet should be inserted using a retromolar approach. Once inserted, the stylet should be kept midline and advanced under the tongue. A well-circumscribed glow (approximately the size of a quarter) should appear in the midline of the patient's neck at the level of the cricoid cartilage (Fig. 44.28), indicating correct positioning of the stylet within the trachea. Subsequently, the ETT can be advanced over the stylet into proper position (Video 44.10).<sup>245</sup>

### RETROGRADE INTUBATION

RI is a well-described technique for orotracheal or nasotracheal intubation that involves guiding an ETT into the trachea with a narrow, flexible guide that has been percutaneously placed through the CTM into the trachea and passed retrograde through the larynx and pharynx, exiting the mouth or nose. The guide is typically a steel guidewire, although an epidural catheter can be used. This technique has several modifications, each with its own benefits and disadvantages, and can be successfully used in awake, sedated, obtunded, or apneic patients who have either an

anticipated or unanticipated difficult airway.<sup>246</sup> Indications include failure of DL; obstruction of the view of the vocal cords by blood, secretions, or anatomic derangement; and difficult intubation scenarios such as unstable cervical spine, ankylosing spondylitis, maxillofacial trauma, or trismus. RI is also an alternative to FSI in developing countries where the availability of FISs is limited.<sup>246</sup>

The ASA DAA describes RI as an alternative approach to difficult intubation in the nonemergent pathway, when intubation is unsuccessful but mask ventilation is adequate. It is suggested that equipment for RI be included in a portable storage unit for difficult airway management. RI can take several minutes to accomplish; therefore this technique is contraindicated in an emergent CICV scenario.<sup>246</sup> Other contraindications are generally relative and include anatomic abnormalities (e.g., malignancy, goiter) that preclude access to the CTM, tracheal stenosis at the level of the CTM, coagulopathy, and local infection.

The ideal position for RI is supine with the neck in extension, allowing easy palpation of the cricoid cartilage and surrounding structures. If this position is not possible, then RI can also be performed with the patient in the sitting position or with the neck in a neutral position. If landmarks are difficult to identify, then ultrasound guidance may be used. The anterior neck should be cleansed before puncture, and aseptic technique should be used. The translaryngeal puncture site can be performed superior or inferior to the cricoid cartilage. The CTM (superior to the cricoid cartilage) has the advantage of being relatively avascular; however, a puncture at this site allows only 1 cm of space below the level of the vocal cords for the tip of the ETT. A puncture site inferior to the cricoid cartilage, at the cricotracheal ligament, allows the ETT to travel in a straight path with a long length of the ETT below the vocal cords; however, this site is associated with a greater potential for bleeding.<sup>246</sup>

The classic technique for RI involves using a Tuohy needle to puncture the CTM and an epidural catheter as the guide. More commonly, an IV catheter and a steel guidewire are used. The diameter of the guidewire should be small enough to fit through the IV catheter and should be at least twice as long as the ETT to be used; a guidewire with a .038-inch diameter (which passes through an 18-gauge IV catheter) and a length of 110 cm is commonly used. Commercial kits are available that include all necessary equipment. Performing a RI with a J-tip, steel guidewire rather than an epidural catheter provides the following advantages: the J-tip of a guidewire is less traumatic to airway, the guidewire has a lower tendency to coil or kink, retrieval of the guidewire from the oral or nasal cavity is easier, and the technique is quicker.<sup>246</sup>

Once the patient has been positioned, the operator's non-dominant hand stabilizes the trachea by placing the thumb and third digit on either side of the cricoid cartilage. The index finger is used to identify the midline of the CTM and the upper border of the cricoid cartilage. A syringe half-filled with saline is attached to an 18-gauge angiocatheter and advanced at a 90-degree angle to the CTM with the bevel facing cephalad, aspirating for air bubbles to confirm the position inside the trachea. The angle of insertion is slightly lowered, and the needle is removed. At this stage, reconfirmation of a position within the trachea and instillation of a local anesthetic can be performed with a second syringe filled with 2 to 4 mL of 2% or 4% lidocaine. This

transtracheal block can provide additional comfort to a patient who is awake or sedated and undergoing RI, or it can reduce the incidence of sympathetic stimulation and laryngospasm in a patient under general anesthesia.

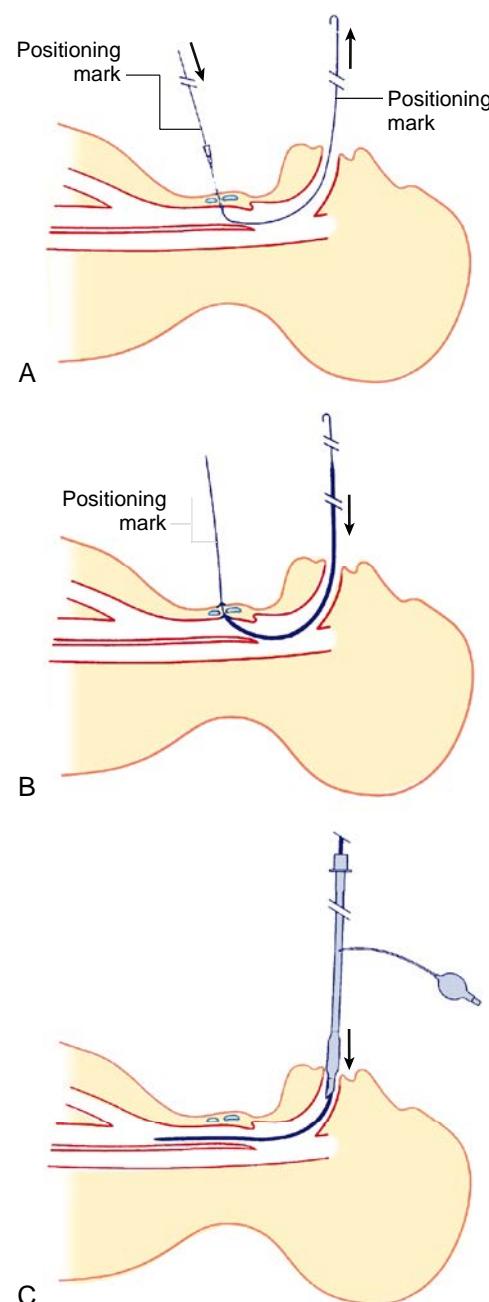
The guidewire is then advanced through the angiocatheter until it exits the mouth or nose. DL can be used to facilitate the wire exiting the mouth, if necessary. The guidewire is clamped with a hemostat at the level of the skin of the neck to prevent migration. Although the ETT can then be directly advanced over the guidewire, a tapered guide catheter (e.g., Arndt airway exchange catheter) is useful to reduce the discrepancy in diameter between the guide-wire and the ETT, which can predispose the ETT to catch on the arytenoids or vocal cords rather than smoothly slide into the trachea. The guide catheter is placed over the portion of the wire exiting the mouth or nose and advanced until it contacts the CTM. The wire is then removed, and an ETT is advanced over the guide catheter (Fig. 44.29 and Video 44.11). Potential complications include bleeding (usually minimal), subcutaneous emphysema, pneumomediastinum, pneumothorax, and injury to the posterior trachea or esophagus.<sup>246</sup>

## DOUBLE-LUMEN TUBES AND BRONCHIAL BLOCKERS

Single-lung ventilation is required for certain clinical circumstances, including protective lung isolation from infection or hemorrhage, attaining adequate exposure for surgical procedures (e.g., video-assisted thoracoscopy), and for controlling the distribution of ventilation in the setting of major bronchial surgery, trauma, or fistula. Double-lumen tubes (DLTs) and bronchial blockers are two options that allow for ventilation of only one lung (also see Chapter 53).

DLTs have a bronchial lumen and a tracheal lumen. They are designated as left-sided or right-sided, depending on whether the bronchial lumen goes to the left or right main bronchus. Most commonly, a left-sided DLT is used to avoid blockage of the right upper lobe bronchus. DLTs are placed in a similar fashion to the standard ETT, although placement is usually more difficult because of their size and stiffness. Video laryngoscopy can facilitate DLT placement.<sup>247</sup> After placing the DLT into the trachea, verification of the location of the bronchial port with an FIS should be determined. The blue bronchial cuff should be positioned just below the carina in the appropriate bronchus. Inflation of the blue bronchial balloon under direct visualization helps verify proper placement. Care should be taken to ensure that the bronchial cuff does not herniate over the carina. The VivaSight-DL (Ambu Inc., Ballerup, Denmark) is a single-use left-sided DLT with an integrated camera located at the tip of the tracheal lumen and allows for accurate positioning of the DLT without the use of an FIS. Once a DLT is properly placed, isolating a lung is possible by inflating the bronchial cuff and clamping either the tracheal or bronchial connector.

Bronchial blockers are essentially hollow, balloon-tipped catheters that are endobronchially placed to isolate and deflate one lung. In some clinical situations, lung isolation is required, but the use of a DLT is not practical because of a difficult airway, decreased size of the tracheal lumen, or the need for postoperative mechanical ventilation. In these instances, the use of a modified single-lumen tube with an integrated bronchial blocker (e.g., the Univent [Fuji



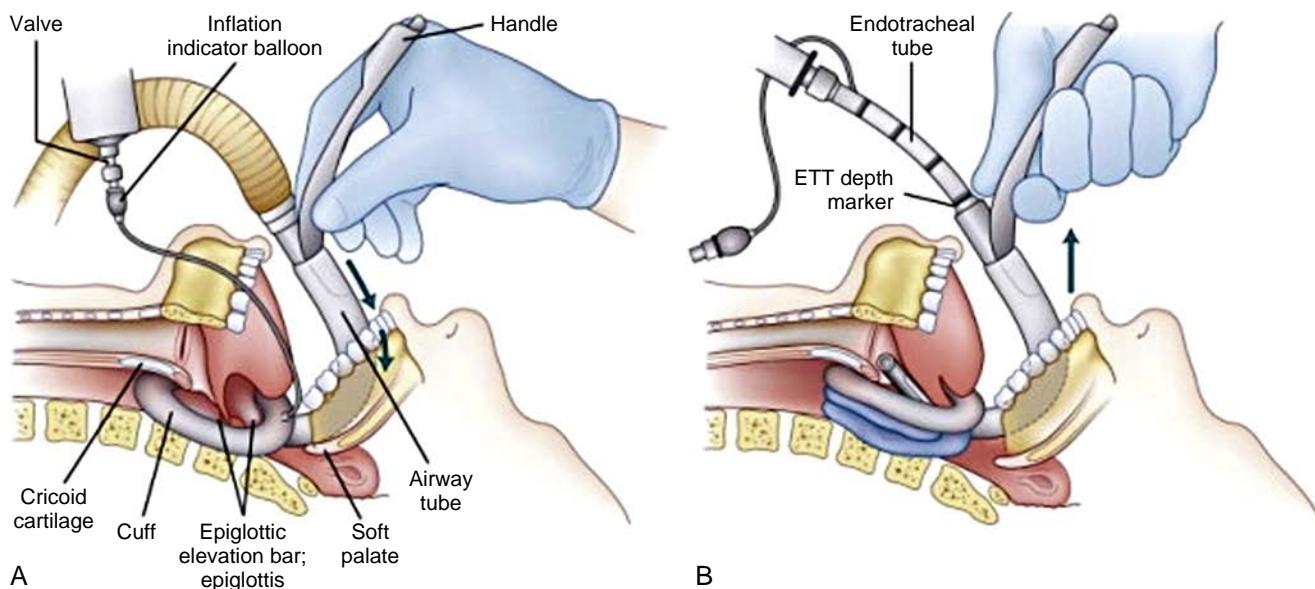
**Fig. 44.29** The guidewire technique for retrograde intubation. (A) After the placement of an 18-gauge angiocatheter through the cricothyroid membrane, the J-tip of the guidewire is inserted in a cephalad direction until it exits the mouth or nose. (B) The guide catheter is threaded over the guidewire until it contacts the laryngeal access site. The guidewire is then removed from above. (C) After advancing the guide catheter 2 to 3 cm, the endotracheal tube is advanced into the trachea. (Courtesy Cook Critical Care, Bloomington, IN.)

Systems, Tokyo, Japan]) or the use of a bronchial blocker in conjunction with a standard ETT is appropriate.

## COMBINATION TECHNIQUES

### Tracheal Intubation Through a Supraglottic Airway Device

The intubating LMA (ILMA), known as the LMA Fastrach (LMA North America, San Diego, CA), was first described



**Fig. 44.30** The Chandy maneuver consists of two steps. (A) The first step is important for establishing optimal ventilation. The intubating laryngeal mask airway (ILMA) is slightly rotated in the sagittal plane using the handle until the least resistance to bag ventilation is achieved. (B) The second step is performed just before blind intubation. The handle is used to lift (but not tilt) the ILMA slightly away from the posterior pharyngeal wall, which facilitates the smooth passage of the endotracheal tube into the trachea. (From Lindsay HA, Cook TM, Russo SG, Hagberg CA. Supraglottic airway techniques: laryngeal mask airways. In: Hagberg CA, Artine CA, Aziz M, eds. *Hagberg and Benumof's Airway Management*. 4th ed. Philadelphia: Elsevier; 2018.)

by Dr. Archie Brain in 1997; it became available for commercial use in the United States shortly thereafter. The ILMA was designed as a conduit for tracheal intubation to facilitate ventilation between attempts at tracheal intubation. The rigid handle and airway tube enable a rapid and precise control of mask position. An epiglottic elevating bar is designed to elevate the epiglottis as the tube is advanced into the bowl. A disposable, single-use version is available in addition to the original reusable model. Specialized reusable or single-use tracheal tubes are designed to facilitate atraumatic blind intubation through the ILMA. The tubes are straight, wire-reinforced, and have a soft molded tip designed to prevent impingement on laryngeal structures.

The technique of inserting the ILMA differs in many respects from the insertion of the cLMA, and the learning curve is significant. A neutral head position (nonextended head on a support) is recommended. The ILMA handle is used to rotate the mask into the pharynx. Oxygenation, ventilation, and anesthesia are stabilized after insertion. If resistance to ventilation is encountered, then the position of the ILMA is adjusted. The *Chandy maneuver* consists of two separate maneuvers: (1) the ILMA is rotated in the sagittal plane until resistance to bag ventilation is minimal; and then (2) the ILMA is gently lifted from the posterior pharyngeal wall just before passage of the tracheal tube (Fig. 44.30). The original, reusable ILMA should be removed soon after tracheal intubation has been verified because its rigidity results in high pressure on adjacent tissues. Although the blind technique has a high rate of success, intubation under vision with an FIS through the ILMA achieves higher first-attempt and overall success rates.

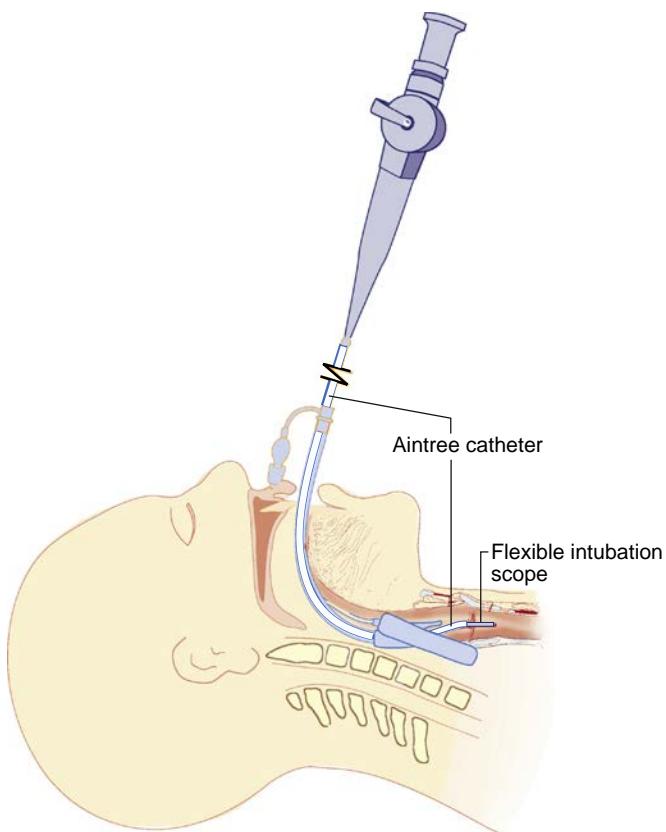
Other SGAs can be used to facilitate tracheal intubation. The cLMA, although not designed for intubation, can be an effective conduit if used in conjunction with an FIS. Because of the long and narrow airway shaft, a microlaryngeal tube must be used. Alternatively, a cLMA can be exchanged for an ETT by using an FIS in conjunction with the Aintree intubation catheter (Cook Critical Care, Bloomington, IN), which is a hollow airway exchange catheter designed to fit over a standard FIS (Fig. 44.31 and Video 44.12). Most newer SGAs have airway shafts that are wide enough to allow intubation through the device with a standard-sized ETT (Video 44.13).

### Combined Direct Laryngoscopy Techniques

DL can be used to expand the space available in the oral cavity to manipulate an FIS by displacing pharyngeal tissue, and the epiglottis can be elevated allowing the scope to be more easily directed underneath the epiglottis toward the glottic opening. This may be especially helpful in the morbidly obese patient or patients with soiled airways (e.g., with blood, secretions, or vomitus).<sup>248</sup>

When a Cormack-Lehane grade III view is encountered during DL, the coudé tip of an ETT introducer can be passed underneath the epiglottis, and tracheal positioning confirmed by the sensation of clicks as the bougie tip passes the tracheal rings.

While using an optical stylet as an adjunct to DL, the tip of the stylet can be guided just beneath the tip of the epiglottis under direct vision. While holding the ETT/fiberoptic stylet securely, the clinician transfers his/her vision to the eyepiece or monitor where the glottic opening can be visualized, and the ETT can be advanced through the vocal cords and into the trachea.<sup>248</sup>



**Fig. 44.31** Aintree intubating catheter within a flexible intubation scope, inserted through a laryngeal mask airway. (From Henderson J. Airway management. In: Miller RJ, ed. *Anesthesia*. 7th ed. Philadelphia: Churchill Livingstone; 2009.)

### Combined Video-Assisted Laryngoscopy Techniques

Just as the bougie has been demonstrated to be an invaluable adjunct to DL, it may be used in combination with VAL in order to improve the success of tracheal intubation, and may offer additional advantages. In a trial featuring a simulated airway with vomitus, the use of a bougie improved intubation success rate and decreased the time to intubation with the Pentax-AWS and the McGrath MAC compared to DL.<sup>249</sup> A bougie may also facilitate advancement of the ETT into the trachea when an adequate view is obtained with VAL, but difficulty is encountered with intubation (Video 44.14).<sup>250</sup>

Optical stylets can also be used in combination with VAL. A study examining the use of the C-MAC VL and the Bonfils Intubation Scope in patients with a history of difficult intubation found that the combination of the two devices was superior in terms of glottic view than either device by itself.<sup>251</sup>

Certain circumstances may arise in which a combination of VAL and FSI may be beneficial. A patient with severely limited mouth opening and/or unstable cervical spine injury may preclude the use of DL in order to assist in FSI; using VAL in this situation may provide the ability to view the glottic opening and better guide the FIS into position. VAL can also diagnose difficulties with the passage of the ETT over the FIS into the glottis (Video 44.15).<sup>248</sup>

### Combined Retrograde Intubation Techniques

To improve the success of retrograde intubation, it can be combined with DL or an FIS. DL can be used as an adjunct in order to improve success during retrograde guided intubation. During the classic technique of retrograde intubation, after a catheter is placed in the inferior cricothyroid membrane, the J-tip of a guidewire is directed upward until it can be retrieved from the mouth or nares. If orotracheal intubation is desired, DL can aid the clinician in opening the oropharynx and visualizing the wire so that it may be retrieved more easily through the mouth prior to entering the nasopharynx. In addition, after the guiding catheter is advanced anterograde over the wire until tenting is noted at the cricothyroid access point, DL may be used in order to lift the epiglottis and pharyngeal tissue, facilitating the passage of an ETT through the vocal cords.<sup>248</sup>

Alternatively, an FIS can be used to facilitate retrograde intubation. After the guidewire is retrieved from the mouth or nares, it is passed through the working channel of the FIS from distal to proximal. The FIS is then passed over the guidewire and into the glottis until resistance is met at the cricothyroid membrane. The hemostat that held the guidewire in place internally may now be released and the guidewire removed. The FIS may then be advanced until the carina is visualized and the ETT is passed into the trachea. In this fashion, the FOB reduces the likelihood that the ETT will become dislodged and the airway can be visualized throughout the procedure. There are several advantages to passing a FOB anterograde over a retrograde placed wire.<sup>248</sup>

- The outer diameter of the guidewire and the internal diameter of the fiberoptic suction port form a tight fit that allows the FOB to follow a straight path through vocal cords without impinging on anatomic structures.
- The FIS acts as large anterograde guide catheter and allows easy passage of the ETT.
- It allows placement of the ETT under direct visualization.
- The FIS may be advanced to the carina freely (past the puncture site) which eliminates the problem of distance between vocal cords and puncture site.

### Emergency Front of Neck Access

Emergency FONA refers to rescue techniques used in a CICO situation when attempts at establishing a noninvasive airway have failed. These techniques may also be used as a primary airway in some difficult airway situations when attempts at securing a noninvasive airway are likely to fail, such as a patient with a laryngeal neoplasm and critical airway obstruction. Options for FONA include transtracheal jet ventilation (TTJV), cricothyrotomy, and tracheostomy. Whereas tracheostomy is usually performed by a surgeon, the anesthesia practitioner should become proficient with the techniques for TTJV and cricothyrotomy; the situation will inevitably arise in which an invasive airway will become necessary. An emergent situation is not the time to become familiar with a new technique.

## TRANSTRACHEAL JET VENTILATION

Percutaneous TTJV is a relatively quick and effective but invasive method of oxygenation and ventilation in the CICV scenario when more conservative measures fail. The ASA DAA lists TTJV as an emergent invasive technique to be used in patients who cannot be conventionally ventilated or intubated.<sup>7</sup> TTJV is widely regarded as a life-saving procedure that can provide adequate, temporary oxygenation and ventilation with less training and complications than a surgical airway, the last resort for obtaining an airway in the algorithm.<sup>252</sup> Nonetheless, TTJV is an invasive technique, and its primary use is as an emergency airway. Occasionally, it is used on an elective basis for laryngeal surgery.

Inpiration during TTJV is achieved by insufflation of pressurized oxygen through a cannula placed by needle cricothyrotomy. Expiration is passive as a result of the elastic recoil of the lungs and the chest wall. Allowing sufficient time for passive expiration to avoid barotrauma from breath stacking is essential. Expiration occurs through the glottis and depends on a nonobstructed upper airway, which is imperative to avoid barotrauma and resulting pneumothorax. The egress of air through the glottic aperture can also provide bubbles to facilitate the placement of an ETT. In fact, several case reports have demonstrated that after the initiation of TTJV in an airway with little or no visualization of the glottis, successful intubation occurred because of the opening of the glottis and guidance from the bubbles with jet ventilation.

TTJV should not be performed in patients who have sustained direct damage to the cricoid cartilage or larynx or in patients with complete upper airway obstruction. Other relative contraindications to TTJV include coagulopathy, obstructive pulmonary disease, or distorted anatomy in which catheter placement might be difficult.

Typically, a 12- to 16-gauge kink-resistant catheter is used for TTJV. A coil-reinforced 6Fr catheter (Cook Critical Care, Bloomington, IN) is specifically designed for TTJV to prevent kinking, and its Teflon coating facilitates its passage through the CTM into the trachea. The technique for placement is similar to the technique for RI, with the exception that the needle is inserted with the bevel facing caudally. Confirmation of proper intratracheal placement of the catheter by testing for aspiration of air is imperative before initiating jet ventilation.

The minimum pressure required to drive a jet ventilator is 15 psi. The pipeline pressure for oxygen in hospitals in the United States is approximately 55 psi. Commercially available jet ventilators generally contain pressure regulators to lower the pipeline pressure to provide successful jet ventilation while avoiding higher pressures that might result in barotrauma. In most instances in the operating room, adequate pressure for jet ventilation can be achieved by connecting straight to the pipeline supply. Difficulty usually arises in locations outside of the surgical unit where TTJV may be needed but adequate driving pressure is not available.<sup>252</sup>

A major complication of TTJV is barotrauma with resulting pneumothorax from the use of high-pressure oxygen. To prevent this complication, ensuring that a path for air egress exists and that adequate time for passive expiration

is available is an absolute necessity. The lowest possible pressure that will provide adequate oxygenation and ventilation should be used. Other complications associated with TTJV include subcutaneous or mediastinal emphysema, hemorrhage, aspiration, and perforation of the posterior wall of the trachea or esophagus.<sup>252</sup>

The Ventrain is a single-use, manually operated oxygen insufflation device designed to decrease the risk of barotrauma when compared to TTJV through a small-bore percutaneous catheter.<sup>253</sup> It uses the Bernoulli principle to provide expiratory ventilation assistance, meaning that negative pressure is generated that facilitates the egress of gas, and therefore can even be used when the upper airway is obstructed.<sup>254</sup> It is driven by oxygen from a high-pressure source with a controllable flow, e.g., a wall-mounted flowmeter or an oxygen cylinder with a flow regulator.

## CRICOHYROTOMY

Cricothyrotomy is an invasive technique that provides access to the airway in situations when either noninvasive maneuvers have failed or when it is clinically indicated as a primary plan to secure the airway.<sup>255</sup> Cricothyrotomy is included in the ASA DAA as an emergent invasive technique after other rescue maneuvers have failed or are not feasible. Cricothyrotomy equipment should be included in all emergency airway storage units and readily available. Cricothyrotomy is not considered a permanent airway, and, after placement, plans should be made for either the removal of the cricothyrotomy catheter or conversion to a formal tracheostomy.<sup>255</sup>

In children younger than 6 years of age (also see [Chapter 77](#)), the cricoid cartilage is the narrowest portion of the airway and the isthmus of the thyroid gland typically reaches the level of the CTM; therefore cricothyrotomy is contraindicated. Needle cricothyrotomy with TTJV is indicated in this pediatric population. Other contraindications to cricothyrotomy include laryngeal fractures, laryngeal neoplasm, subglottic stenosis, coagulopathy, and distorted or unidentifiable neck anatomy.

The two most common techniques for performing a cricothyrotomy are the percutaneous dilational cricothyrotomy and the surgical cricothyrotomy. For the anesthesiologist, the percutaneous technique has historically been preferred because of the familiarity of using the Seldinger technique for other procedures (e.g., central venous catheterization). Recently, however, surgical cricothyrotomy has been advocated as the preferred technique due to its faster speed and higher reliability.<sup>8</sup>

A number of surgical methods for cricothyrotomy have been described; however, the scalpel-bougie technique is the preferred technique in the Difficult Airway Society guidelines for management of the difficult airway. The process is outlined in [Box 44.4](#) and [Fig. 44.32](#). It is recommended that all anesthesiologists learn this technique and receive regular training to avoid fading of skill.<sup>8</sup>

A number of commercially available cricothyrotomy kits use the percutaneous dilational technique. The basis for this procedure is the insertion of an airway catheter over a dilator that has been inserted over a guidewire. The patient's neck is extended, and the cricothyroid groove is identified. If landmarks are difficult to identify, then

#### BOX 44.4 Surgical Cricothyrotomy

##### Equipment

- No. 10 scalpel
- Bougie with a coudé (angled) tip
- Cuffed endotracheal tube (ETT) with a 6-mm internal diameter

##### Technique

1. Stand on the patient's left-hand side if you are right handed (reverse if left handed).
2. Stabilize the larynx using the left hand.
3. Use the left index finger to identify the cricothyroid membrane (CTM). If the CTM is not palpable, make a 8-10 cm vertical incision in the midline and use blunt dissection with the fingers of both hands to separate tissues and identify and stabilize the larynx with the left hand.
4. Holding the scalpel in your right hand, make a transverse stab incision through the skin and cricothyroid membrane with the cutting edge of the blade facing toward you.
5. Keep the scalpel perpendicular to the skin and turn it through 90° so that the sharp edge points caudally (toward the feet).
6. Swap hands; hold the scalpel with your left hand.
7. Maintain gentle traction, pulling the scalpel toward you (laterally) with the left hand, keeping the scalpel handle vertical to the skin (not slanted).
8. Pick the bougie up with your right hand.
9. Holding the bougie at a right angle to the trachea, slide the coudé tip of the bougie down the side of the scalpel blade furthest from you into the trachea.
10. Rotate and align the bougie with the patient's trachea and advance gently up to 10-15 cm.
11. Remove the scalpel.
12. Stabilize trachea and tension skin with left hand.
13. Railroad a lubricated size 6.0 mm cuffed tracheal tube over the bougie.
14. Rotate the tube over the bougie as it is advanced. Avoid excessive advancement and endobronchial intubation.
15. Remove the bougie.
16. Inflate the cuff and confirm ventilation with capnography.

Modified from Frerk C, Mitchell VS, McNarry AF, et al. Difficult Airway Society 2015 guidelines for management of unanticipated difficult intubation in adults. *Br J Anaesth.* 2015;115(6):827-848.

ultrasound guidance may be used. A 1- to 1.5-cm vertical incision is made through the skin overlying the CTM. An 18-gauge needle-catheter attached to a fluid-filled syringe is passed through the incision at a 45-degree angle in the caudal direction with continuous aspiration. Because of the location of the cricothyroid artery and the proximity of the CTM to the vocal folds, puncture of the CTM should be made in the lower third of the membrane and directed inferiorly (Fig. 44.33).<sup>255</sup> Aspiration of free air confirms passage through the CTM. The catheter is advanced over the needle into the trachea. The needle is removed, and the catheter is left in place. The guidewire is inserted caudally to a depth of approximately 2 to 3 cm. The catheter is removed, and the curved dilator with the airway cannula is threaded over the guidewire. The dilator and cannula unit is advanced through the CTM while maintaining control of the guidewire. The dilator and guidewire are removed together while the cannula remains in place. The cuff is inflated, and ventilation is attempted. Proper placement is confirmed by capnography, and the airway cannula is secured in place (Video 44.16).<sup>255</sup>

Complications include hemorrhage, injury to the posterior tracheal wall or esophagus, vocal cord injury, laceration of the thyroid gland, and improper insertion of the cannula. Placement of the airway cannula in the subcutaneous tissue can result in subcutaneous or mediastinal emphysema. Late complications from cricothyrotomy include swallowing dysfunction, infection, voice changes, and tracheal stenosis. Tracheal stenosis has an incidence of approximately 2% to 8% in adults and is more likely if pre-existing trauma or infection is present.

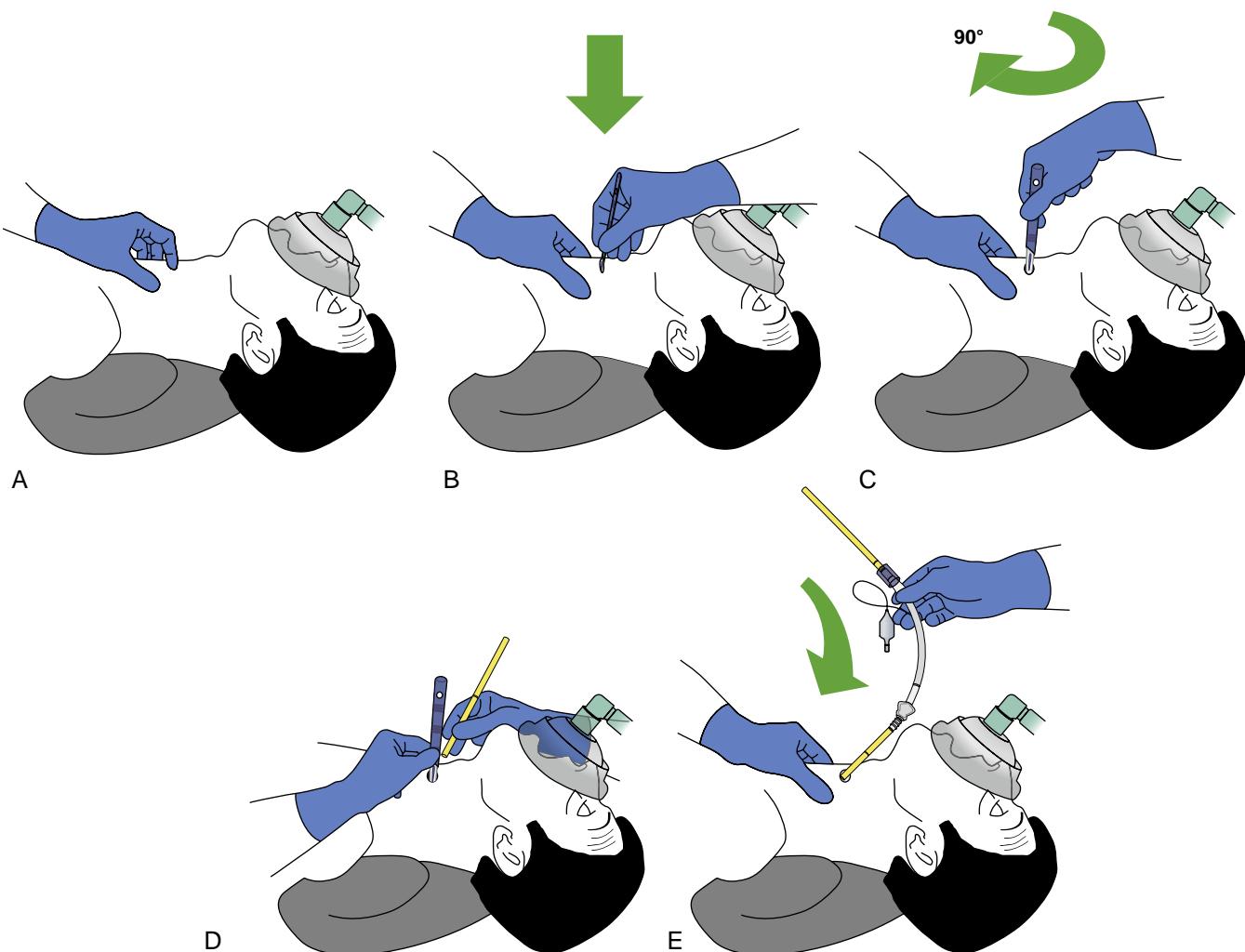
## Extubation of the Trachea

A critical component of airway management is the process of extubation. Although considerable emphasis is placed on the problems that can arise during induction and intubation, the risk of complications can potentially be higher during extubation of the trachea.<sup>256</sup> Analysis of the ASA Closed Claims database has shown that although the number of claims for death and brain damage during intubation have decreased since the adoption of the ASA *Practice Guidelines for Management of the Difficult Airway*, the number of claims arising from injury at extubation and during recovery have not decreased.<sup>1</sup> In response to these trends and in the absence of any well-established strategies for the management of tracheal extubation, the DAS established a set of guidelines in 2012 to "discuss the problems arising during extubation and recovery" and to "promote a strategic, stepwise approach to extubation."<sup>257</sup>

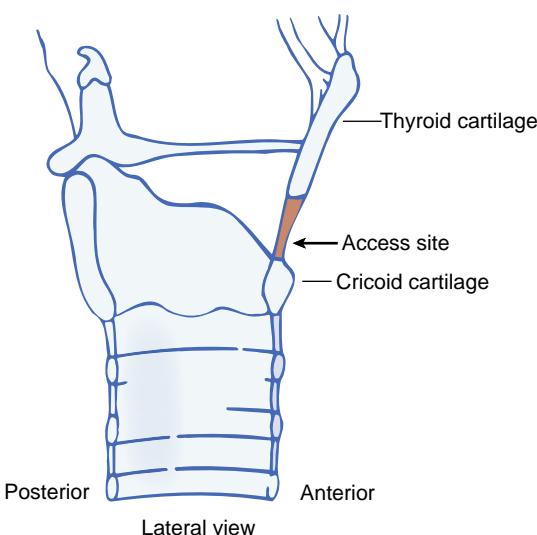
A number of complications can arise during extubation (Box 44.5); although some of these complications are minor with no long-term sequelae, others can lead to a failed extubation. Failed extubation can result from the failure of oxygenation, failure of ventilation, inadequate clearance of pulmonary secretions, or loss of airway patency.<sup>84</sup> If an airway is not quickly reestablished, then serious complications, including death, may result. As such, the anesthesia practitioner needs to stratify extubation risk preemptively and establish an extubation plan before attempting extubation. Per the DAS guidelines, risk stratification can be accomplished by considering the following: (1) whether the airway was normal and uncomplicated at induction; (2) whether the airway has become difficult to manage as a result of surgical changes, trauma, or nonsurgical factors; and (3) whether the patient has general risk factors for an unsuccessful extubation.<sup>257</sup>

### GENERAL CONSIDERATIONS FOR EXTUBATION OF THE TRACHEA

For both routine and difficult extubation scenarios, an extubation plan must be preemptively formulated, including a plan for reintubation that can be implemented should the patient be unable to maintain an adequate airway after extubation.<sup>7</sup> The decision of whether to extubate the trachea when the patient is fully awake versus a deep extubation before the return of consciousness should be made based on the risks and benefits of each technique. The awake patient can more easily maintain a patent airway, attributable to the recovery of awake pharyngeal muscle tone and airway reflexes. Deep extubation avoids coughing



**Fig. 44.32** Scalpel-bougie technique—“stab, twist, bougie, tube.” (A) Identify the cricothyroid membrane (CTM). (B) Make a transverse stab incision through the CTM. (C) Rotate the scalpel so that the sharp edge points caudally. (D) Pulling the scalpel toward you to open up the incision, slide the coudé tip of the bougie down the scalpel blade into the trachea. (E) Advance the endotracheal tube into trachea. (From Frerk C, Mitchell VS, McNarry AF, et al. Difficult Airway Society 2015 guidelines for management of unanticipated difficult intubation in adults. *Br J Anaesth*. 2015;115(6):827–848.)



**Fig. 44.33** Midsagittal anatomy of the larynx and trachea. The access point for percutaneous cricothyrotomy is in the lower third of the cricothyroid membrane. (Courtesy Cook Critical Care; Bloomington, IN.)

and adverse hemodynamic effects but risks upper airway obstruction and hypoventilation. An alternative extubation technique, known as the Bailey maneuver, involves exchanging an ETT for an SGA while the patient is under deep anesthesia.<sup>258</sup> Extubation during a light plane of anesthesia (stage II) can increase the risk for laryngospasm and other airway complications and should be avoided.

General preparations for extubation should include ensuring adequate reversal or recovery from neuromuscular blockade, hemodynamic stability, normothermia, and adequate analgesia. Patients should be preoxygenated with a 100% fraction of inspired oxygen concentration (FIO<sub>2</sub>), and alveolar recruitment maneuvers should be considered if appropriate. Suctioning of the pharynx (and the trachea, if indicated), the removal of throat packs, and the placement of a bite block should be performed while the patient is under deep anesthesia.<sup>22</sup> Bite blocks are essential for an awake intubation to prevent biting of the tube during emergence, which can result in airway obstruction and the development of negative-pressure pulmonary edema. Oropharyngeal airways are not recommended for use as a

### Box 44.5 Complications Associated with Extubation

- Laryngospasm and bronchospasm
- Upper airway obstruction
- Hypoventilation
- Hemodynamic changes (hypertension, tachycardia)
- Coughing and straining, leading to surgical wound dehiscence
- Laryngeal or airway edema
- Negative-pressure pulmonary edema
- Paradoxical vocal cord motion
- Arytenoid dislocation
- Aspiration

bite block because they can result in dental damage; rather, taped, rolled gauze securely inserted between the molars should be used.<sup>259</sup>

Gastric insufflation with air can increase the risk of pulmonary aspiration after extubation and can impede ventilation. Patients in whom mask ventilation with high pressures is necessary should have an orogastric tube placed and suctioned before extubation.

The sniffing position is the standard position for extubation; its major advantage is that the patient is optimally positioned for airway management, if necessary. Patients who are morbidly obese and other patients at risk for hypoventilation and airway obstruction can benefit from extubation in the head-up position. The lateral decubitus position may be the preferred option when the risk for pulmonary aspiration is high.<sup>22</sup>

Application of positive pressure immediately before cuff deflation may help expel secretions that have collected above the ETT cuff. Inspection of the pilot balloon to ensure complete cuff deflation before extubation is essential; extubation with an inflated cuff can cause vocal cord injury or arytenoid dislocation.

### EXTUBATION AND REINTUBATION OF THE DIFFICULT AIRWAY

Many surgical and anesthetic factors can increase extubation risk. A summary of the most pertinent factors is listed in **Box 44.6**. Although several techniques can be used to manage extubation of the difficult airway, including the Bailey maneuver and remifentanil infusion,<sup>257</sup> the use of an airway exchange catheter (AEC) is most common and recommended by the ASA's Task Force on Management of the Difficult Airway. This hollow reintubation guide is passed through the ETT before extubation and kept in situ until the possible need for reintubation has passed. AECs have the additional capability of maintaining oxygenation or monitoring respiration by connection to a capnograph. Smaller AECs (11Fr) are generally well-tolerated by awake patients, who can breathe, talk, and cough around them. They should be secured with tape in place to prevent accidental dislodgement and labeled to distinguish them from traditional feeding tubes, which can have a similar appearance. Reintubation over an AEC, if necessary, can be facilitated by gentle DL to retract the tongue and oropharyngeal soft tissue.

### Box 44.6 Factors Associated with Increased Extubation Risk

#### Airway Risk Factors

- Known difficult airway
- Airway deterioration (bleeding, edema, trauma)
- Restricted airway access
- Obesity and obstructive sleep apnea
- Aspiration risk

#### General Risk Factors

- Cardiovascular disease
- Respiratory disease
- Neuromuscular disease
- Metabolic derangements
- Special surgical requirements

Modified from Popat M, Mitchell V, Dravid R, et al. Difficult Airway Society guidelines for the management of tracheal extubation. *Anaesthesia*. 2012;67:318–340.

### Dissemination of Critical Airway Information

As stated earlier, one of the most predictive factors for difficult intubation is a history of previous difficulty with intubation. Therefore it is crucial that critical airway information be documented and disseminated in such a way that clinicians who subsequently care for a patient with a difficult airway be alerted to the history and obtain the necessary information to safely manage the patient's airway. The ASA Practice Guidelines for Management of the Difficult Airway recommend that clinicians document the difficulty with airway management and inform the patient or responsible person of the difficulty encountered.<sup>7</sup> Consideration of notification systems, such as a written report or letter to the patient, a written report in the medical chart, communication with the patient's surgeon or primary caregiver, a notification bracelet or equivalent identification device, and/or chart flags is recommended.

In 1992, the MedicAlert Foundation National Difficult Airway/Intubation Registry was created to standardize the documentation and dissemination of critical airway information. By 2010, more than 11,000 patients were included in the registry.<sup>260</sup> Patients with a difficult airway should be directed to the MedicAlert website.

### Summary

Airway management is at the core of safe anesthetic practice. The anesthesia practitioner must have a fundamental knowledge of airway anatomy, physiology, and pharmacology, and well-developed skills in the use of a wide variety of airway devices. Although most airways are straightforward, management of the difficult airway remains one of the most relevant and challenging tasks for anesthesia care providers. Prediction and anticipation of the difficult airway and the formulation of an airway management plan are essential. Many airway problems can be solved with relatively simple devices and techniques; however,

experience and good clinical judgment are necessary for their successful application. Newer airway devices with the potential to improve patient outcomes are continually being developed. Anesthesia providers must concurrently develop their skills and learn new techniques to be prepared when difficulty presents itself. Competency-based training with routine assessment of clinical ability with airway techniques is likely in the future for all practitioners involved in airway management. Expertise comes from dedicated practice and a commitment from the practitioner for career-long learning.

Complete references available online at [expertconsult.com](http://expertconsult.com).

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**Video 44.1** Noninvasive Glossopharyngeal Nerve Block. (From Artine CA, Sanchez A. Preparation of the patient for awake intubation. In: Hagberg CA, Artine CA, Aziz M, eds. *Hagberg and Benumof's Airway Management*. 4th ed. Philadelphia: Elsevier; 2018.)

**Video 44.2** Transtracheal Anesthesia. (From Hagberg CA, Artine CA, Daily WH, eds. *The Difficult Airway: A Practical Guide*. Oxford: Oxford University Press; 2013.)

**Video 44.3** Mask Ventilation Techniques. (From Hagberg CA, Artine CA, Daily WH, eds. *The Difficult Airway: A Practical Guide*. Oxford: Oxford University Press; 2013.)

**Video 44.4** LMA Insertion Techniques. (From Hagberg CA, Artine CA, Daily WH, eds. *The Difficult Airway: A Practical Guide*. Oxford: Oxford University Press; 2013.)

**Video 44.5** Tracheal Intubation Using Direct Laryngoscopy and an Intubating Stylet. (From Hagberg CA, Artine CA, Daily WH, eds. *The Difficult Airway: A Practical Guide*. Oxford: Oxford University Press; 2013.)

**Video 44.6** Transoral Flexible Scope Intubation. (Modified from Hagberg CA, Artine CA, Daily WH, eds. *The Difficult Airway: A Practical Guide*. Oxford: Oxford University Press; 2013.)

**Video 44.7** Tracheal Intubation with the Bonfils Retromolar Intubation Fiberscope. (From Hagberg CA, Artine CA, Daily WH, eds. *The Difficult Airway: A Practical Guide*. Oxford: Oxford University Press; 2013.)

**Video 44.8** Tracheal Intubation with the Clarus Video System. (From Hagberg CA, Artine CA, Daily WH, eds. *The Difficult Airway: A Practical Guide*. Oxford: Oxford University Press; 2013.)

**Video 44.9** Tracheal Intubation Using the GlideScope. (From Hagberg CA, Artine CA, Daily WH, eds. *The Difficult Airway: A Practical Guide*. Oxford: Oxford University Press; 2013.)

**Video 44.10** Tracheal Intubation with a Lighted Stylet. (From Hagberg CA, Artine CA, Daily WH, eds. *The Difficult Airway: A Practical Guide*. Oxford: Oxford University Press; 2013.)

**Video 44.11** Guidewire-Assisted Retrograde Intubation. (From Hagberg CA, Artine CA, Daily WH, eds. *The Difficult Airway: A Practical Guide*. Oxford: Oxford University Press; 2013.)

**Video 44.12** Combination Techniques: LMA/Aintree/Flexible Scope Intubation. (From Hagberg CA, Artine CA, Daily WH, eds. *The Difficult Airway: A Practical Guide*. Oxford: Oxford University Press; 2013.)

**Video 44.13** Combination Techniques: Supraglottic Airway Device/Flexible Scope Intubation. (From Hagberg CA, Artine CA, Daily WH, eds. *The Difficult Airway: A Practical Guide*. Oxford: Oxford University Press; 2013.)

**Video 44.14** Combination Techniques: Videolaryngoscopy/Intubation Stylet. (From Hagberg CA, Artine CA, Daily WH, eds. *The Difficult Airway: A Practical Guide*. Oxford: Oxford University Press; 2013.)

**Video 44.15** Combination Techniques: Videolaryngoscopy/Flexible Intubating Scope. (From Hagberg CA, Artine CA, Daily WH, eds. *The Difficult Airway: A Practical Guide*. Oxford: Oxford University Press; 2013.)

**Video 44.16** Percutaneous Dilational Cricothyrotomy (Seldinger Technique). (From Hagberg CA, Artine CA, Daily WH, eds. *The Difficult Airway: A Practical Guide*. Oxford: Oxford University Press; 2013.)

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## KEY POINTS

- The distal termination of the spinal cord varies from L3 in infants to the lower border of L1 in adults.
- The speed of neural blockade depends on the size, surface area, and degree of myelination of the nerve fibers exposed to the local anesthetic.
- Blockade of the peripheral (T1-L2) and cardiac (T1-T4) sympathetic fibers is responsible for the decrease in arterial blood pressure (cardiac output and systemic vascular resistance) associated with neuraxial techniques.
- Cerebrospinal fluid volume and local anesthetic baricity are the most important determinants for the spread (i.e., block height) of spinal anesthesia.
- The use of smaller-gauge spinal needles decreases the incidence of post-dural puncture headache.
- Serious neurologic complications associated with neuraxial blockade are rare, but the risk increases in the elderly and those with preexisting spinal pathology.
- The use of low-molecular-weight heparin and potent platelet inhibitors increases the risk of epidural hematoma from neuraxial blockade.
- Epidural blood patches are greater than 90% effective in relieving post-dural puncture headache.
- Local anesthetic systemic toxicity results from unintentional administration of the drug into an epidural vein.
- Use of neuraxial blockade, particularly when used as the sole anesthetic, can reduce perioperative morbidity and may reduce mortality.

## Principles

Spinal, epidural, and caudal neuraxial blocks result in one or a combination of sympathetic blockade, sensory blockade, or motor blockade depending on the dose, concentration, or volume of local anesthetic administered. Despite these similarities, there are significant technical, physiologic, and pharmacologic differences. Spinal anesthesia requires a small mass (i.e., volume) of drug that is almost devoid of systemic pharmacologic effects to produce rapid (<5 minutes), profound, reproducible sensory analgesia. In contrast, epidural and caudal anesthesia progress more slowly (>20 minutes) after a large mass of local anesthetic that produces pharmacologically active systemic blood levels, which may be associated with side effects and complications unknown to spinal anesthesia. The introduction of combined spinal and epidural techniques blurs some of these differences, but also adds flexibility to clinical care.

## Practice

Neuraxial blockade has a wide range of clinical applications for surgery, obstetrics, acute postoperative pain management, and chronic pain relief. Single-injection spinal or epidural anesthesia with local anesthetic is most commonly

used for surgery to the lower abdomen, pelvic organs (e.g., prostate), and lower limbs, and for cesarean deliveries. Continuous catheter-based epidural infusions of dilute local anesthetics and opioids are used for obstetric labor analgesia and postoperative pain relief after major surgery (e.g., thoracic, abdominal, and less commonly lower limb) to provide analgesia for days if required. Evidence demonstrating that epidural analgesia can reduce pulmonary morbidity and mortality in high-risk patients undergoing major thoracic and abdominal surgery served to propel the practice of epidural analgesia at the beginning of the millennium.<sup>1</sup> Caudal blocks are mostly performed for surgical anesthesia and analgesia in children, and for therapeutic analgesia in adults with chronic pain. Indwelling spinal catheters can be applied long term (from months to years) for the treatment of chronic malignant and nonmalignant pain.

## Historical Perspectives

The first case of spinal anesthesia in humans was performed by August Bier in 1898 using the local anesthetic cocaine.<sup>2</sup> Subsequently, spinal anesthesia was successfully performed using procaine by Braun in 1905, tetracaine by Sise in 1935, lidocaine by Gordh in 1949, chloroprocaine by Foldes and McNall in 1952, mepivacaine by Dhunér and

Sternberg in 1961, and bupivacaine by Emblem in 1966. Spinal anesthesia using ropivacaine and levobupivacaine was introduced in the 1980s. The year 1901 marked the first reported use of intrathecal morphine described by Racoviceanu-Pitesti, as well as the first description of caudal anesthesia reported by Cathleen. Lumbar epidural anesthesia in humans was first described by Pagés in 1921, the loss-of-resistance technique by Dogliotti in the 1930s, continuous caudal for obstetrics by Hingson in 1941, and lumbar epidural catheterization for surgery by Curbelo in 1947.<sup>3</sup> The use of epidural morphine analgesia was first reported by Behar in 1979.

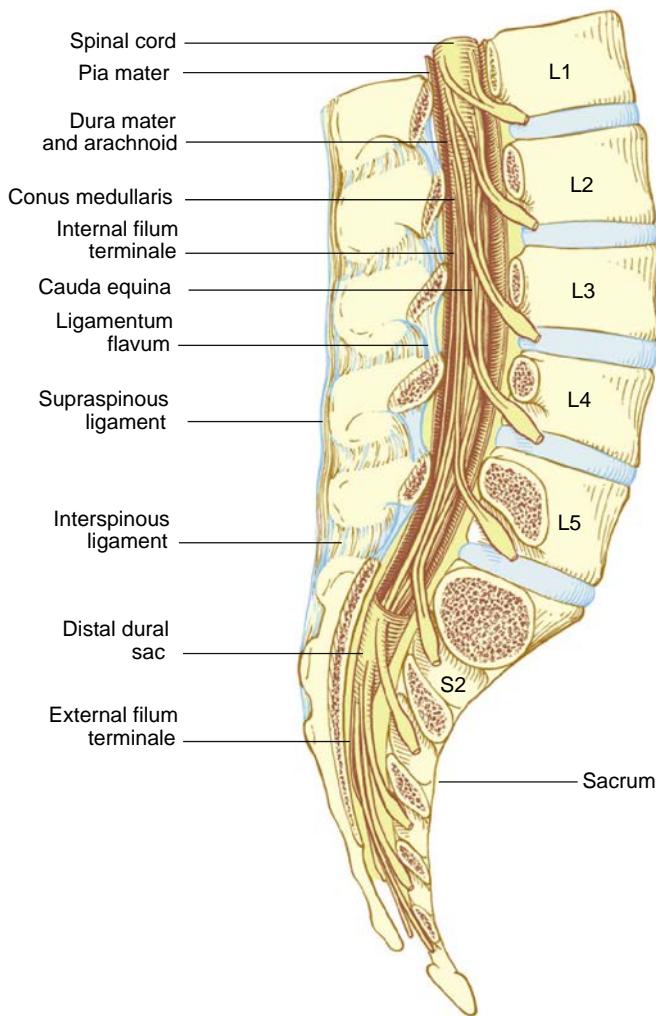
Despite the extensive experience using neuraxial techniques throughout the past century, several events caused major setbacks along the way, including the Woolley and Roe case detailing paraplegia after spinal anesthesia in 1954,<sup>4</sup> the reports of persistent neurologic deficits and adhesive arachnoiditis with spinal chloroprocaine in the early 1980s, and cauda equina syndrome with continuous spinal lidocaine anesthesia in the early 1990s.<sup>5</sup> More recently, the potential for catastrophic epidural hematoma with newer potent anticoagulants (e.g., low-molecular-weight heparin [LMWH]) and antiplatelet agents (e.g., clopidogrel) has caused concern.<sup>6</sup>

## Anatomy

The spinal cord is continuous with the brainstem proximally and terminates distally in the conus medullaris as the filum terminale (fibrous extension) and the cauda equina (neural extension). This distal termination varies from L3 in infants to the lower border of L1 in adults because of differential growth rates between the bony vertebral canal and the central nervous system.

Surrounding the spinal cord in the bony vertebral column are three membranes (from innermost to outermost): the pia mater, the arachnoid mater, and the dura mater (Fig. 45.1). The cerebrospinal fluid (CSF) resides in the space between the pia mater and the arachnoid mater, termed the *subarachnoid* (or *intrathecal*) space. The pia mater is a highly vascular membrane that closely invests the spinal cord and brain. Approximately 500 mL of CSF is formed daily by the choroid plexuses of the cerebral ventricles, with 30 to 80 mL occupying the subarachnoid space from T11 to T12 downward. The arachnoid mater is a delicate, nonvascular membrane that functions as the principal barrier to drugs crossing into (and out of) the CSF and is estimated to account for 90% of the resistance to drug migration.<sup>7</sup> As Liu and McDonald<sup>8</sup> and Bernards<sup>9</sup> emphasize, the functional proof of the arachnoid's role as the primary barrier to flow is the observation that spinal CSF resides in the subarachnoid, and not the subdural, space. The outermost layer is the dura.

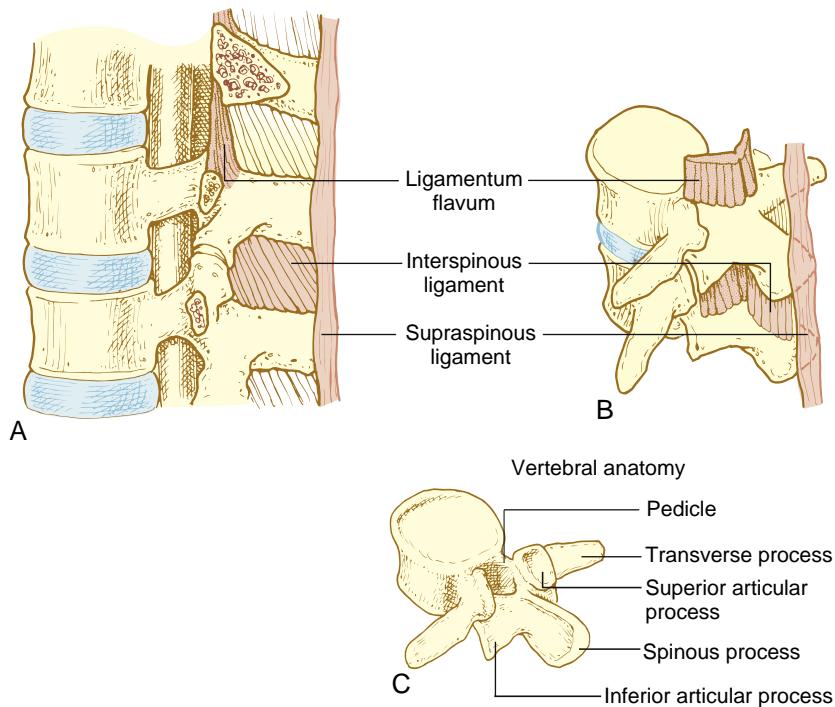
Surrounding the dura mater is the epidural space, which extends from the foramen magnum to the sacral hiatus and surrounds the dura mater anteriorly, laterally, and posteriorly. The epidural space is bound anteriorly by the posterior longitudinal ligament, laterally by the pedicles and intervertebral foramina, and posteriorly by the ligamentum flavum. Contents of the epidural space include the nerve roots and fat, areolar tissue, lymphatics, and blood vessels including the well-organized Batson venous plexus.



**Fig. 45.1** Spinal cord anatomy. Notice the termination of the spinal cord (i.e., conus medullaris) at L1-L2 and termination of the dural sac at S2.

Posterior to the epidural space is the ligamentum flavum (the so-called yellow ligament), which extends from the foramen magnum to the sacral hiatus. Although classically portrayed as a single ligament, it is actually comprised of two ligamenta flava—the right and the left—which join in the middle and form an acute angle with a ventral opening (Fig. 45.2).<sup>10,11</sup> The ligamentum flavum is not uniform from skull to sacrum, nor even within an intervertebral space. Ligament thickness, distance to the dura, and skin-to-dura distance vary with the area of the vertebral canal. The vertebral canal is triangular and largest in area at the lumbar levels, and it is circular and smallest in area at the thoracic levels. The two ligamenta flava are variably joined (fused) in the midline, and this fusion or lack of fusion of the ligamenta flava occurs at different vertebral levels in individual patients.<sup>10</sup> Immediately posterior to the ligamentum flavum are the lamina and spinous processes of vertebral bodies or the interspinous ligaments. Extending from the external occipital protuberance to the coccyx posterior to these structures is the supraspinous ligament, which joins the vertebral spines (see Fig. 45.2).

There are 7 cervical vertebrae, 12 thoracic vertebrae, 5 lumbar vertebrae, and a sacrum. The vertebral arch, spinous process, pedicles, and laminae form the posterior



**Fig. 45.2** Vertebral anatomy. (A) Sagittal view. (B) Oblique view of the lumbar vertebrae showing the ligamentum flavum thickening in the caudad extent of the intervertebral space and in the midline. (C) Oblique view of a single lumbar vertebra.

elements of the vertebra, and the vertebral body forms the anterior element. The vertebrae are joined together anteriorly by the fibrocartilaginous joints with the central disks containing the nucleus pulposus, and posteriorly by the zygapophyseal (facet) joints. The thoracic spinous process is angulated steeply caudad as opposed to the almost horizontal angulation of the lumbar spinous process. This is a clinically important distinction for needle insertion and advancement in the thoracic versus lumbar levels.

The sacral canal contains the terminal portion of the dural sac, which typically ends at S2. Variation is found in this feature as well, with the termination of the dural sac being lower in children. In addition to the dural sac, the sacral canal contains a venous plexus, which is part of the valveless internal vertebral venous plexus. The volume of the caudal canal in adults, excluding the foramina and dural sac ranges, is about 10 to 27 mL. Perhaps this wide variability in volume accounts for some of the variation in block height with caudal anesthesia (Fig. 45.3).<sup>12</sup>

### BLOOD SUPPLY

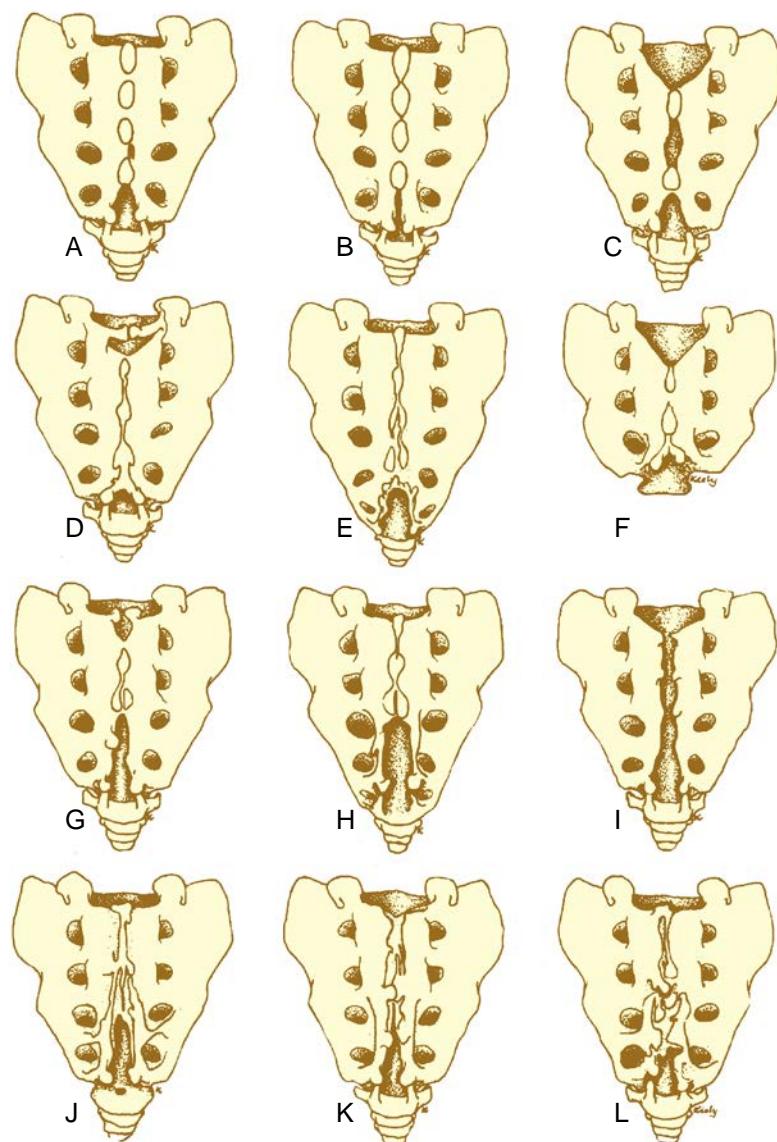
Blood is supplied to the spinal cord from one anterior spinal artery (originating from the vertebral artery), two posterior spinal arteries (originating from the inferior cerebellar artery), and the segmental spinal arteries (originating from the intercostal and lumbar arteries).<sup>13</sup> The spinal arteries enter the spinal canal at each intervertebral foramen and give off branches to both the nerve roots and the medullary branches to the spinal cord; one of the major branches is the artery of Adamkiewicz, variably entering between T7 and L4 on the left, which supplies the lower thoracic and upper lumbar regions. The anterior two thirds of the spinal cord is supplied by the anterior arterial branches and the

posterior one third by the posterior branches. The anterior and deep portion of the cord (gray matter) is most prone to ischemia (leading to anterior horn motor neuron injury, or anterior spinal syndrome) because there are fewer anterior medullary feeder vessels than posterior feeder vessels. Likewise, the midthoracic part of the spinal cord (from T3 to T9) is most at risk where segmental medullary feeder vessels are rare. Venous drainage of the spinal cord follows a similar distribution as the spinal arteries. There are three longitudinal anterior spinal veins and three posterior spinal veins that communicate with the segmental anterior and posterior radicular veins before draining into the internal vertebral venous plexus in the medial and lateral components of the epidural space. There are no veins in the posterior epidural space except those caudal to the L5-S1 disk.

## Anatomic Variations

### NERVE ROOTS

The spinal nerve roots are not uniform in size and structure. Specifically, Hogan and Toth<sup>14,15</sup> have shown that there is considerable interindividual variability in nerve root size. These differences may help to explain the interpatient differences in neuraxial block quality when equivalent techniques are used on seemingly similar patients. Another anatomic relationship may affect neuraxial blocks; although generally larger than the ventral (motor) roots, the dorsal (sensory) roots are often blocked more easily. This apparent paradox is explained by organization of the dorsal roots into component bundles, which creates a much larger surface area on which the local anesthetics act, possibly explaining why larger sensory nerves are blocked more easily than smaller motor nerves.<sup>8</sup>



**Fig. 45.3** Anatomic variants of the sacrum and sacral hiatus. (A) Normal. (B) Longitudinal slitlike hiatus. (C) Second midline hiatus. (D) Transverse hiatus. (E) Large hiatus with absent cornua. (F) Transverse hiatus with absent coccyx, two prominent cornua, and two proximal “decoy hiatuses lateral to the cornua.” (G–I) Large midline defects contiguous with the sacral hiatus. (J–L) Enlarged longitudinal hiatuses, each with an overlying decoy hiatus. (From Willis RJ. Caudal epidural block. In: Cousins MN, Bridenbaugh PO, eds. *Neural blockade in clinical anesthesia and management of pain*. 2nd ed. Philadelphia: JB Lippincott; 1988:365.)

## CEREBROSPINAL FLUID

Lumbosacral CSF has a constant pressure of approximately 15 cm H<sub>2</sub>O, but its volume varies by patient, in part because of differences in body habitus and weight.<sup>16</sup> It is estimated that CSF volume accounts for 80% of the variability in peak block height and regression of sensory and motor blockade. Nevertheless, except for body weight (less CSF in subjects with high body mass index [BMI]), the volume of CSF does not correlate with other anthropomorphic measurements available clinically.<sup>17</sup> (See section, Factors Affecting Block Height, later in the chapter.)

## EPIDURAL SPACE

Hogan's<sup>18</sup> study of frozen cryomicrotome cadaver sections suggests that the epidural space is more segmented and less uniform than previously believed from indirect anatomic

analysis. Another study by Hogan<sup>18</sup> has also shown in cadavers that the spread of solution after epidural injection into the tissues of the epidural space is nonuniform, and he postulated that this accounts for the clinical unpredictability of epidural drug spread. This lack of uniformity also extends to age-related differences. There is evidence that adipose tissue in the epidural space diminishes with age,<sup>19</sup> and this decrease in epidural space in adipose tissue may dominate the age-related changes in epidural dose requirements (see [Chapter 65](#)).

## Mechanism of Action

Local anesthetic binding to nerve tissue disrupts nerve transmission, resulting in neural blockade. For spinal and epidural anesthesia, the target binding sites are located within the spinal cord (superficial and deep portions) and on the spinal nerve roots in the subarachnoid and epidural spaces. The

spinal nerve roots and dorsal root ganglia are considered the most important sites of action. Nerves in the subarachnoid space are highly accessible and easily anesthetized, even with a small dose of local anesthetic, compared with the extradural nerves, which are often ensheathed by dura mater (the “dural sleeve”). The speed of neural blockade depends on the size, surface area, and degree of myelination of the nerve fibers exposed to the local anesthetic. Anatomic studies show that the S1 and L5 posterior roots are the largest and thus most resistant to blockade during epidural anesthesia.<sup>15</sup> Smaller nerves are more sensitive to the effects of local anesthetics because of their relatively high membrane surface area to axon unit volume ratio. For example, the small preganglionic sympathetic fibers (B fibers, 1-3  $\mu$ m, minimally myelinated) are most sensitive to local anesthetic blockade. Among the sensory nerves, the C fibers (0.3-1  $\mu$ m, unmyelinated), which conduct cold temperature sensation, are blocked more readily or earlier than the A-delta fibers (1-4  $\mu$ m, myelinated), which conduct pinprick sensation. The A-beta fibers (5-12  $\mu$ m, myelinated), which conduct touch sensation, are the last to be affected among the sensory fibers. The larger A-alpha motor fibers (12-20  $\mu$ m, myelinated) are more resistant than any of the sensory fibers. Regression of blockade (“recovery”) follows in the reverse order: motor function followed first by touch, then pinprick, and finally cold sensation.<sup>20</sup> Another manifestation of relative sensitivity or susceptibility to the effects of local anesthetics is the observed differences in the peak block height (highest or most cephalad level of anesthesia) according to each sensory modality, which is termed *differential sensory block*. For example, the level of anesthesia to cold sensation (also an approximate level of sympathetic blockade) is most cephalad and is on average one to two spinal segments higher than the level of pinprick anesthesia, which in turn is one to two segments higher than the level of touch anesthesia.<sup>21</sup>

## DRUG UPTAKE

When local anesthetic is injected directly into the subarachnoid space during spinal anesthesia, it diffuses through the pia mater and penetrates through the spaces of Virchow-Robin (extensions of the subarachnoid space accompanying the blood vessels that invaginate the spinal cord from the pia mater) to reach the deeper dorsal root ganglia.<sup>22</sup> Furthermore, a portion of the subarachnoid drug diffuses outward through the arachnoid and dura mater to enter the epidural space,<sup>23</sup> whereas some is taken up by the blood vessels of the pia and dura maters.<sup>24</sup>

Drug penetration and uptake is directly proportionate to the drug mass, CSF drug concentration, contact surface area, lipid content (high in spinal cord and myelinated nerves), and local tissue vascular supply, but is inversely related to nerve root size. The concentration of local anesthetic in the CSF is highest at the site of subarachnoid injection in the case of spinal anesthesia (generally L2-L4 levels).

For epidural anesthesia, drug uptake is more complex. Some of the injected local anesthetic will move from the epidural space through the meninges into the CSF to exert its neural blocking effect, whereas some will be lost through vascular absorption into the capillary vessels and into the systemic circulation and uptake into epidural fat. The bioavailability of local anesthetics found in the CSF after epidural administration is low (<20%).

## DRUG DISTRIBUTION

Diffusion is the primary mechanism of local anesthetic distribution in the CSF from areas of high concentration (i.e., at the site of injection) toward other segments of the spinal cord with low drug concentration.<sup>25</sup> Rostral spread after the administration of a small local anesthetic dose, often evident within 10 to 20 minutes, is related to the CSF circulation time. Longitudinal oscillations generated by the pulsations of the arteries in the skull are believed to be responsible for CSF bulk flow. This likely facilitates the cephalad distribution of local anesthetic from the lumbar subarachnoid space to the basal cisterns within 1 hour of injection.

Drug distribution in the epidural space is more complex, with possible contributions from one, some, or all of the following mechanisms: (1) crossing the dura mater into the subarachnoid space, (2) rostral and caudal (longitudinal) spread within the epidural space, (3) circumferential spread within the epidural space, (4) exit of the epidural space through the intervertebral foramina, (5) binding to epidural fat, and (6) vascular absorption into the epidural vessels. Longitudinal spread of local anesthetic by bulk flow within the epidural space may occur after the administration of a larger dose (i.e., volume). Factors that may enhance the distribution of local anesthetic within the epidural space are small caliber (greater spread in the thoracic space), increased epidural space compliance, decreased epidural fat content, decreased local anesthetic leakage through the intervertebral foramina (e.g., in the elderly and with spinal stenosis), and increased epidural pressure (e.g., pregnancy).<sup>26</sup> Drug is also preferentially distributed from areas of high to low concentration. Finally, the direction of drug spread varies with the vertebral level—that is, epidural spread is mostly cephalad in the lumbar region, caudad after a high thoracic injection, and spread mostly cephalad after a low thoracic injection.<sup>26</sup>

## DRUG ELIMINATION

Regression of neural blockade results from a decline in the CSF drug concentration, which in turn is caused by nonneuronal tissue uptake and, most importantly, vascular absorption. Time for block regression is also inversely correlated with CSF volume.<sup>27</sup> Drug is absorbed by the vessels in the pia mater or the epidural vessels through back diffusion before entering the systemic circulation. No drug metabolism takes place in the CSF. The rate of elimination is also dependent on the distribution of local anesthetic; greater spread will expose the drug to a larger area for vascular absorption and thus a shorter duration of action. Lipid-soluble local anesthetics (e.g., bupivacaine) bind to epidural fat to form a depot that can slow vascular absorption.

## Physiologic Effects

Safe conduct of spinal, epidural, and caudal anesthesia requires an appreciation of their physiologic effects. Neural-anesthetic evokes blockade of the sympathetic and somatic (sensory and motor) nervous systems, along with compensatory reflexes and unopposed parasympathetic activity.<sup>28</sup> The physiologic effects of epidural anesthesia are

similar to those of spinal anesthesia, with the exception that local anesthetic blood levels reach concentrations sufficient enough to produce systemic effects on their own.

## CARDIOVASCULAR

The effects of neuraxial blocks on blood pressure are similar in some ways to the combined use of intravenous  $\alpha_1$ - and  $\beta$ -adrenergic blockers on cardiac output: decreased stroke volume and heart rate (see [Chapter 14](#)) caused by blockade of the peripheral (T1-L2) and cardiac (T1-T4) sympathetic fibers as well as adrenal medullary secretion. The decrease in arterial blood pressure is believed to be more gradual and of less magnitude with epidural than with spinal anesthesia of comparable sensory block levels. However, when tetracaine (10 mg) spinal anesthesia was compared with lidocaine (20-25 mL of a 1.5% solution) epidural anesthesia, there was a larger decrease in arterial blood pressure (approximately 10%) with the epidural technique than with the spinal anesthetic.<sup>29</sup> Of prime importance, the extent to which arterial blood pressure decreases with either technique depends on multiple factors, including patient age and intravascular volume status.

### Stroke Volume

Sympathectomy usually decreases stroke volume. Venous and arterial vasodilation reduces preload (venous return) and afterload (systemic vascular resistance), respectively. Because of the large amount of blood that resides in the venous system (approximately 75% of the total blood volume), the venodilation effect predominates, owing to the limited amount of smooth muscle in venules; in contrast, the vascular smooth muscle on the arterial side of the circulation retains a considerable degree of autonomous tone. Cardiac output is thought to be either maintained or slightly decreased during the onset of spinal anesthesia. Yet a biphasic response, characterized by an early transient increase followed by an eventual decrease in cardiac output,<sup>30</sup> has been observed. This initial increase is caused by a greater magnitude of decline in the systemic vascular resistance than by venous return, especially in elderly patients with preexisting hypertension and high baseline systemic vascular resistance (also see [Chapter 65](#)).

The vasodilatory changes after neuraxial blockade that can affect cardiac output depend on each patient's baseline sympathetic tone (i.e., higher sympathetic tone in the elderly equates to a greater hemodynamic change) and the extent of the sympathectomy (i.e., the height of the block). The extent of the sympathectomy is typically described as extending for two to six dermatomes above the sensory block level with spinal anesthesia and at the same level with epidural anesthesia.<sup>31</sup> If normal cardiac output is maintained, systemic vascular resistance should decrease only 15% to 18% after neuraxial blockade in healthy normovolemic patients, even with nearly total sympathectomy. In elderly patients with cardiac disease, systemic vascular resistance may decrease almost 25% after spinal anesthesia, whereas cardiac output decreases only 10%.<sup>32</sup> Determination of baseline autonomic nervous system activity (e.g., blood pressure variability signaled by low-frequency band power and near-infrared spectroscopy reduction) has been found to predict the risk of hypotension in the elderly.<sup>30</sup>

### Heart Rate

Heart rate may decrease during a high neuraxial block as a result of blockade of the cardioaccelerator fibers arising from T1 to T4.

Heart rate may also decrease in the presence of extensive peripheral sympathectomy (T5-L2), with venous pooling in the lower extremity and the abdominal and pelvic viscera. Although hypotension will trigger a compensatory baroreceptor sympathetic response (vasoconstriction and increased heart rate) above the level of blockade, the reduction in venous return and right atrial filling causes a decrease in signal output from intrinsic chronotropic stretch receptors located in the right atrium and great veins,<sup>31</sup> leading to a marked increase in parasympathetic activity (vagal tone). The two opposing responses are usually in check with a minimal change in heart rate (or a slight reduction). However, when neuraxial anesthesia is extended to the T1 level, blockade of the cardioaccelerator fibers in addition to a marked reduction in venous return may result in severe bradycardia and even asystole because of unopposed parasympathetic activity. However rare, the likelihood of cardiac arrest appears to be more likely in young, healthy, and conscious patients.<sup>33</sup> The Bezold-Jarisch reflex may be a possible cause of profound bradycardia and circulatory collapse after spinal anesthesia, especially in the presence of hypovolemia, when a small end-systolic left ventricular volume may trigger a mechanoreceptor-mediated bradycardia.<sup>34</sup>

### Coronary Blood Flow

When coronary artery blood flow and myocardial metabolism were determined in humans during spinal anesthesia to T4 in hypertensive and normotensive patients, decreases in coronary blood flow (153 to 74 mL/100 g per minute) paralleled the decrease in mean arterial blood pressure (119 to 62 mm Hg), and the percent extraction of myocardial oxygen was unchanged (75% to 72%). Extraction of oxygen was unchanged because myocardial work, as expressed by myocardial use of oxygen, paralleled the decrease in mean arterial blood pressure and coronary blood flow (16 to 7.5 mL/100 g per minute).<sup>35</sup> A high thoracic block in patients with ischemic heart disease can be beneficial, with improvement in global and regional myocardial function and reversal of ischemic changes likely a result of reduced myocardial oxygen demand and left ventricular afterload.<sup>36</sup> Both infarction size and ischemia-induced arrhythmias improved in coronary occlusion experiments in animals, with no apparent vasodilatory effect on the coronary vessels.<sup>37</sup> These data support the observations by Stanley and coworkers<sup>38</sup> but still do not provide a patient-by-patient indication of the organ most at risk for flow-related ischemia.

### Treatment

The clinical question of what level of decrease in arterial blood pressure after a neuraxial block is acceptable without a significant decrease in organ perfusion (e.g., brain, liver, gut) remains to be answered, although some human and animal data are available (see respective sections). Once arterial blood pressure decreases to a level at which treatment is believed to be necessary, ephedrine, a mixed adrenergic agonist, provides more appropriate therapy for the noncardiac circulatory sequelae of neuraxial block than does a pure  $\alpha$ -adrenergic agonist (see [Chapter 14](#)), unless the patient has a specific and defined arterial blood pressure requirement.<sup>39</sup>

That the decrease in arterial blood pressure after neuraxial block can be minimized by the administration of crystalloids intravenously is probably not a valid concept. Specifically, 250- to 2000-mL preblock hydration regimens may temporarily increase preload and cardiac output but do not consistently increase arterial blood pressure or prevent hypotension.<sup>8</sup> Useful techniques to prevent hypotension include the repeated low-dose local anesthetic boluses through a continuous spinal catheter,<sup>40</sup> small-dose unilateral spinal anesthesia, and selective small-dose spinal anesthesia.

## CENTRAL NERVOUS SYSTEM

Spinal anesthesia-induced hypotension may decrease regional cerebral blood flow (CBF) in elderly patients and those with preexisting hypertension. In a study of elderly patients who had hypotension during bupivacaine spinal anesthesia, Minville and colleagues demonstrated a significant but transient decrease of middle cerebral artery blood flow velocity and an increase in cerebral vascular resistance, both of which suggest a decrease in cerebral perfusion.<sup>41</sup> There was no change in cognitive function after surgery in any of these patients. Both CBF and velocity decline as a result of changes in the cerebral vasculature, especially in the elderly. Whether cerebral autoregulation is impaired in the elderly is still debatable (see Chapter 65).

Kety and colleagues<sup>42</sup> demonstrated that producing spinal anesthesia to the midthoracic levels with procaine, even in patients with essential hypertension, results in a decrease in mean arterial blood pressure of 26% (155 to 115 mm Hg) accompanied by a 12% (52 to 46 mL/100 g per minute) decrease in CBF. When the level of spinal anesthesia was purposely increased to produce higher levels of block (T4) in normotensive and hypertensive patients, CBF was unchanged in the normotensive group (45-46 mL/100 g per minute), whereas a 19% decrease occurred in the apparently untreated hypertensive patients (46.5-37.5 mL/100 g per minute).<sup>43</sup>

## RESPIRATORY

Alterations in pulmonary variables in healthy and even in elderly patients during neuraxial block are usually of little clinical consequence.<sup>44</sup> A decrease in vital capacity follows a reduction in expiratory reserve volume related to paralysis of the abdominal muscles necessary for forced exhalation rather than a decrease in phrenic or diaphragmatic function.<sup>45</sup> Blockade of the intercostal and abdominal muscles during neuraxial anesthesia is adequately compensated by unaltered function of the diaphragm and other accessory respiratory muscles (e.g., sternomastoid, scalenes), especially for forceful inspiration and expiration.<sup>46</sup> Nonetheless, neuraxial block should be used cautiously in the setting of severe respiratory disease because paralysis of the intercostal and abdominal muscles is common. However rare, respiratory arrest associated with spinal anesthesia is often unrelated to phrenic or inspiratory dysfunction but rather to hypoperfusion of the respiratory centers in the brainstem. Supportive evidence for this concept is observed after resuscitation, when apnea almost always disappears as soon as pharmacologic and intravascular fluid therapies have restored cardiac output and arterial blood pressure.

## Pregnancy

In young healthy pregnant women undergoing cesarean delivery, spinal bupivacaine, ropivacaine, and levobupivacaine affect pulmonary function minimally (a reduction of 3% to 6% for forced vital capacity and 6% to 13% for peak expiratory flow rate), irrespective of the peak sensory block level.<sup>47</sup> However, in overweight pregnant women, vital capacity declines even more (24% vs. 11%) and recovers more slowly compared with normal-weight pregnant women after hyperbaric spinal bupivacaine administration (see also Chapter 62).<sup>48</sup>

## Obesity (also see Chapter 58)

The impact of spinal anesthesia on lung volume variables is significantly reduced compared with general anesthesia<sup>49</sup> but is significantly more in overweight patients than in normal-weight patients.<sup>48</sup> The magnitude of decline in vital capacity is proportional to the BMI value (vital capacity 19% for BMI 30–40 kg/m<sup>2</sup> vs. 33% for BMI >40 kg/m<sup>2</sup>).<sup>50</sup> Importantly, however, for obese patients undergoing laparotomy surgery, thoracic epidural anesthesia (TEA) lessens the extent of decline in postoperative vital capacity and hastens recovery when compared with parenterally administered opioids.<sup>49</sup>

## GASTROINTESTINAL

Neuraxial blockade from T6 to L1 disrupts splanchnic sympathetic innervation to the gastrointestinal tract, resulting in a contracted gut and hyperperistalsis. Nausea and vomiting may be associated with neuraxial block in as much as 20% of patients and they are primarily related to gastrointestinal hyperperistalsis caused by unopposed parasympathetic (vagal) activity.<sup>51</sup> Atropine is effective in treating nausea associated with high (T5) subarachnoid anesthesia.<sup>52</sup>

TEA has a direct blood pressure-dependent effect on intestinal perfusion.<sup>53</sup> TEA improves anastomotic mucosal blood flow in patients undergoing esophagectomy when mean arterial blood pressure is minimally altered but worsens local perfusion when arterial blood pressure is decreased by about 50%. In colorectal surgery, TEA decreases anastomotic blood flow but improves gastric and transverse colonic blood flow.<sup>54</sup> Correction of systemic hypotension by vasopressor therapy (e.g., norepinephrine) has been found to reverse impaired colonic perfusion. TEA may also reduce the rate of anastomotic leak after emergency laparotomy, esophageal surgery,<sup>55</sup> and other gastrointestinal interventions.<sup>56</sup>

A reduction in hepatic blood flow parallels the reduction in mean systemic arterial pressure in the setting of spinal anesthesia.<sup>57</sup> Although lumbar epidural anesthesia also results in a decline in hepatic perfusion despite colloid preloading in young and elderly patients, hepatic perfusion can increase, though mildly (<10%), with TEA after major abdominal surgery.<sup>57</sup>

## RENAL

Despite a predictable decrease in renal blood flow accompanying neuraxial blockade, this decrease is of little physiologic importance.<sup>58,59</sup> One aspect of genitourinary function

of clinical importance is the belief that neuraxial blocks are a frequent cause of urinary retention, which delays discharge of outpatients and necessitates bladder catheterization in inpatients (see section Complications—Urinary Retention, later in the chapter). However, this belief is questionable. For example, in orthopedic patients undergoing hip replacement, bladder catheterization was no more frequent after spinal or epidural anesthesia than it was after general anesthesia and opioid analgesics. In any case, excessive volumes of intravenous crystalloid solutions should not be given to patients undergoing spinal anesthesia. The requirement for voiding before discharge in low-risk ambulatory surgery patients after short-acting spinal or epidural anesthetics should be encouraged.<sup>60</sup>

## Indications

At the most basic level, neuraxial blockade is indicated when the surgical procedure can be accomplished with a sensory level of anesthesia that does not produce adverse patient outcomes. The level of anesthesia or analgesia required is of prime importance because the physiologic effects of a high-level block may be untenable.

### NEURAXIAL ANESTHESIA

When considering neuraxial anesthesia, the nature and duration of surgery, patient comorbidities, the ease of spinal insertion (i.e., positioning and spinal pathology), and the relative benefits and risks to the individual are important. Spinal anesthesia is most commonly used for patients who require surgical anesthesia for procedures of known duration that involve the lower extremities, perineum, pelvic girdle, or lower abdomen. Descriptions of spinal anesthesia as the primary surgical anesthetic have more recently expanded to include lumbar spine surgery,<sup>61</sup> as well as upper abdominal procedures, such as laparoscopic cholecystectomy.<sup>62</sup> Spinal anesthesia may be useful when patients wish to remain conscious or when comorbidities such as severe respiratory disease or a difficult airway increase the risks of using general anesthesia. Epidural anesthesia can also be used for the lower extremities, perineum, pelvic girdle, or lower abdomen, but by virtue of intermittent or continuous catheter-based local anesthetic delivery, the duration of surgical anesthesia is not necessarily finite as it is with single-injection spinal anesthesia. Continuous catheter-based spinal anesthesia is both less conventional and less commonly used than either single-shot spinal anesthesia or catheter-based epidural anesthesia, but may be especially useful when insertion of an epidural catheter is challenging<sup>63</sup> or in the setting of severe cardiac disease when the reliability of a single-shot spinal anesthetic must be combined with more hemodynamically stable incremental dosing.

### NEURAXIAL ANALGESIA

Local anesthetics (as well as other additives, discussed later) applied to the neuraxis in subanesthetic doses can provide potent, long-lasting analgesia for a variety of indications, including intraoperative analgesia, acute postsurgical

pain,<sup>64</sup> and severe chronic pain associated with malignancy. The use of intrathecal and/or epidural opioids either alone or in combination with local anesthetics can provide excellent quality pain relief<sup>65,66,66a</sup> and are an analgesic mainstay in labor and delivery,<sup>67,68</sup> during and after hip<sup>69</sup> or knee replacement,<sup>70</sup> in laparotomy,<sup>71</sup> in thoracotomy,<sup>72</sup> and increasingly even in cardiac surgery.<sup>73,74</sup> Some of the most important benefits of epidural analgesia are realized in patients with preexisting respiratory disease undergoing abdominal surgery.<sup>75</sup> Neuraxial analgesia may have other beneficial outcomes beyond analgesia and these are reviewed later.

## Contraindications

### ABSOLUTE

There are few absolute contraindications to neuraxial blockade. Some of the most important include patient refusal, localized sepsis, and an allergy to any of the drugs planned for administration. A patient's inability to maintain stillness during needle puncture, which can expose the neural structures to traumatic injury,<sup>76</sup> as well as raised intracranial pressure, which may theoretically predispose to brainstem herniation,<sup>77</sup> should also be considered absolute contraindications to a neuraxial technique.

### RELATIVE

Relative contraindications must be weighed against the potential benefits of neuraxial blockade. Relative contraindications can be approached by system.

#### Neurologic

**Myelopathy or Peripheral Neuropathy.** A preexisting neurologic deficit can in theory worsen the extent of any injury in this group of patients (so-called double-crush phenomenon). While many reports suggest central neuraxial techniques may be used safely, there is no definitive evidence.<sup>76,78-80</sup> Chronic low back pain without neurologic deficit is not a contraindication to neuraxial blockade. The association between neuraxial techniques and the exacerbation of back pain symptoms is not documented.

**Spinal Stenosis.** Patients with spinal stenosis appear to be at increased risk of neurologic complications after neuraxial blockade,<sup>81</sup> but the relative contribution of surgical factors and natural history of the spinal pathology itself is unknown. Using a lower mass of local anesthetic may in theory reduce the risk if spinal anesthesia is undertaken in the setting of spinal stenosis.

**Spine Surgery.** Previous spine surgery does not predispose patients to an increased risk of neurologic complications after neuraxial blockade.<sup>81,82</sup> However, depending on postsurgical anatomy and the presence of scar tissue, adhesions, hardware, and/or bone grafts, needle access to the CSF, or epidural space and/or epidural catheter insertion may be challenging or impossible. In addition, the resultant spread of local anesthetic in the CSF or epidural space can be unpredictable and incomplete.

**Multiple Sclerosis.** Patients with multiple sclerosis (MS) may be more sensitive to neuraxial local anesthetics and thus exhibit a prolonged duration of motor and sensory blockade; however, any association between neuraxial anesthesia and exacerbation of MS symptoms is not based in evidence.<sup>83,84</sup> Given that demyelinated fibers may be more prone to the toxic effects of local anesthetics, it is prudent to use a lower dose and concentration of spinal local anesthetic in this group of patients, or else consider epidural rather than spinal anesthesia.

**Spina Bifida.** Spina bifida comprises a wide spectrum of congenital spinal cord malformations. Depending on the severity of the neural tube defect, patients with spina bifida may have a tethered cord and the ligamentum flavum may be absent, thereby increasing the potential for traumatic needle injury to the spinal cord. In patients who have undergone repair of open spinal dysraphisms, the spread of local anesthetic in the CSF and epidural space (if present) can be highly variable. Neuraxial techniques have been successfully used in isolated spina bifida occulta patients, but are not advised in the setting of severe neural tube defects such as diastematomyelia or tethered cord.

If, after consideration of risks and benefits, a neuraxial technique is to be undertaken in a patient with a neural tube defect, a careful clinical and radiologic evaluation of neurologic status must first be undertaken and noted along with documentation of the discussion of the risks and benefits.

#### Cardiac (also see Chapter 54)

**Aortic Stenosis or Fixed Cardiac Output.** The unpredictable speed and extent to which systemic vascular resistance is reduced after spinal anesthesia may cause many providers to avoid spinal anesthesia in preload-dependent patients and try to prevent a dangerous decrease in coronary perfusion. This concern is borne of theoretic risk and a great deal of caution rather than evidence.<sup>85</sup> Clinical practice mandates that neuraxial anesthesia be considered individually for each patient with aortic stenosis in the context of their own disease severity, left ventricular function, and case urgency. A catheter-based neuraxial anesthetic, whether it is an epidural or intrathecal catheter, allows for the repeated administration of small doses of local anesthetic, with potentially more control over hemodynamic changes, and may be a logical alternative choice.

**Hypovolemia.** An extension of patients who are preload-dependent, hypovolemic patients may exhibit an exaggerated hypotensive response to the vasodilatory effects of neuraxial blockade.

#### Hematologic

**Thromboprophylaxis.** Borne of the catastrophic cases of spinal hematoma causing paralysis associated with the introduction and use of LMWH in the United States (US FDA public health advisory: reports of epidural or spinal hematomas with the concurrent use of low molecular weight heparin and spinal/epidural anesthesia or spinal puncture. US Department of Health and Human Resources, 1997), the American Society of Regional Anesthesia and Pain Medicine (ASRA) first published a practice

advisory to guide the provision of neuraxial techniques in patients receiving antithrombotic or thrombolytic therapy in 2004. Now in its fourth iteration and addressing a myriad of novel potent oral anticoagulants, the ASRA practice advisory<sup>6</sup> is an invaluable resource for providers performing neuraxial techniques in this challenging and ever-growing patient population. A summary of the ASRA guidelines<sup>1</sup> is reproduced in Table 45.1.

**Inherited Coagulopathy.** The safety of neuraxial techniques in patients with common bleeding diatheses is not well documented. Hemorrhagic complications after neuraxial techniques in patients with known hemophilia, von Willebrand disease, or idiopathic thrombocytopenic purpura appear infrequently when factor levels are more than 0.5 IU/mL for factor VIII, von Willebrand factor, and ristocetin cofactor activity, or when the platelet count is greater than  $50 \times 10^9/L$ <sup>1</sup> before block performance.<sup>86</sup> The minimum safe factor levels and platelet count for neuraxial blockade, however, remain undefined in both the obstetric and general populations.<sup>86</sup>

#### Infection

Theoretic concerns based on animal data and laboratory and case reports in humans<sup>87-89</sup> suggest iatrogenic seeding of the neuraxis in the setting of a systemic infection. Some providers avoid neuraxial techniques in febrile patients. A definitive causative relationship between existing systemic infection and meningitis or epidural abscess after a neuraxial technique has never been shown. In fact, a lumbar puncture is a critical component of the investigation of fever of unknown origin, yet there are no definitive data linking lumbar puncture to increased risk of neuraxial infection in this setting.<sup>90</sup> Although the profound vasodilation may be sufficient reason to avoid neuraxial techniques in patients with profound bacteremia or septic shock, the theoretic risk of seeding the intrathecal or epidural spaces by performing neuraxial techniques in patients with untreated systemic infection further supports using another technique. Yet patients with evidence of systematic infection may safely undergo neuraxial anesthesia once antibiotic therapy has been initiated and the patient has demonstrated a response to the antibiotics.<sup>90</sup>

## Spinal Anesthesia

### FACTORS AFFECTING BLOCK HEIGHT

The dermatomal level required for various surgical procedures is outlined in Table 45.2. The provider must recall that intraabdominal structures such as the peritoneum (T4), bladder (T10), and uterus (T10) have a spinal segment innervation that may be much more cephalad compared with that of the corresponding skin incision used to operate on these structures.

Drug, patient, and procedural factors can all affect the distribution of local anesthetic spread within the intrathecal space, some of which are more clinically relevant than others.<sup>25,91</sup> Many of these factors are not controllable by the anesthesiologist, leading to significant interpatient variability (Table 45.3).

**TABLE 45.1** ASRA Evidence-Based Guidelines for Neuraxial Anesthesia in the Patient Receiving Thromboprophylaxis

DRUG	NEURAXIAL NEEDLE/CATHETER PLACEMENT			NEURAXIAL CATHETER REMOVAL		COMMENTS
	Discontinuation prior to placement	Restart following needle placement	Indwelling catheter placement	Discontinuation prior to removal	Restart following removal	
<b>Antiplatelet agents</b>						
Aspirin		Safe for all categories				
NSAIDs		Safe for all categories but caution with concomitant drugs that may affect coagulation				
Clopidogrel	5-7 d			Catheters may be maintained for 1-2 days after restarting Clopidogrel or Ticlodipine		
Ticlodipine	10 d	Immediately				Immediately
Prasugrel	7-10 d	If loading dose: 6 h	Avoid catheters			If loading dose: 6 h
Ticagrelor	5-7 d					
Dipyridamole	24 h	6 h	Avoid catheters		6 h	
GP IIa/IIIb inhibitors	Avoid until platelet function returns to normal		These drugs are generally contraindicated for 4 weeks post surgery			
Abciximab						
Eptifibatide						
Tirofiban						
<b>Unfractionated Heparin</b>						
Intravenous	4-6 h and confirm normal coagulation	1 h	Safe	4-6 h and confirm normal 1 h coagulation		Check platelet count before needle placement or catheter removal if duration of LMWH > 4 d
<b>Subcutaneous</b>						
Low-dose prophylaxis	4-6 h or confirm normal coagulation		Safe	4-6 h and confirm normal coagulation		5,000 U SC bid or tid
Higher-dose prophylaxis	12 h and confirm normal coagulation	1 h		Safety of catheters not established	1 h	7,500-10,000 U SC bid or ≤20,000 U/d
Therapeutic	24 h and confirm normal coagulation			Avoid catheters		>10,000 U SC/dose or >20,000 U/d
<b>Low molecular weight heparin</b>						
Once daily prophylaxis	12 h	12 h	Safe	12 h		Check platelet count before needle placement or catheter removal if duration of LMWH > 4 d
Twice daily prophylaxis				Avoid catheters	4 h	
Therapeutic dose	24 h	24 - 72 h		Avoid catheters		
<b>Oral anticoagulants</b>						
Coumarins	Ideally 5 d and INR <1.5	No delay	Monitor INR daily and check sensory/motor function routinely	INR < 1.5	No delay	
Apixaban		6 h		Avoid catheters	6 h	Refer to ASRA guidelines if unanticipated indwelling catheter
Rivaroxaban	72 h					

Abbreviations: bid=twice a day, tid=three times a day, d=day(s), h=hour(s), SC=subcutaneous, U=unit(s). *Reg Anes Pain Med* 2018; 43: 263-309.

## Drug Factors

The adjustable factors for any given local anesthetic solution are dose, volume, concentration, temperature, and baricity. Baricity and dose are most important.

**Baricity.** Baricity is the ratio of the density of a local anesthetic solution to the density of CSF. Density is defined as the mass per unit volume of solution (g/mL) at a specific temperature. Density may be compared between different substances by calculating the specific gravity, which is the ratio of the density of a solution to the density of water. Because density varies inversely with temperature, the baricity of a local anesthetic solution is conventionally defined at 37°C. The density of CSF is 1.00059 g/L.<sup>92</sup> Local anesthetic solutions that have the same density as CSF are termed *isobaric*, those that have a higher density than CSF are termed *hyperbaric*, and those with a lower density than CSF are termed *hypobaric*. The spread of hyperbaric solutions is more predictable,<sup>93</sup> with less interpatient variability.<sup>94</sup> To make a drug hyperbaric to CSF, it must be denser than CSF, with a baricity appreciably more than 1.0000 or a density appreciably more than 1.00059. The reverse is true for making a drug hypobaric to the CSF. Dextrose and sterile water are commonly added to render local anesthetic solutions either hyperbaric or hypobaric, respectively. The clinical importance of baricity is the ability to influence the distribution of local anesthetic spread based on gravity. Hyperbaric solutions will preferentially spread to the dependent regions of the spinal canal, whereas hypobaric solutions will spread

to nondependent regions. Isobaric solutions tend not to be influenced by gravitational forces.<sup>95</sup> Anesthesiologists can capitalize on this phenomenon by altering the position of the patient. For example, the administration of hyperbaric local anesthetic to patients in the lateral decubitus position will result in a preferential anesthetic effect on the dependent side, whereas the opposite is true for the administration of a hypobaric solution. A thoughtful understanding of the natural curvatures of the vertebral column can help predict local anesthetic spread in patients placed in the horizontal supine position immediately after intrathecal administration. Hyperbaric local anesthetics injected, while sitting, at the L3-L4 or L4-L5 interspace will spread with gravity from the height of the lumbar lordosis down toward the trough of the thoracic kyphosis in the horizontal supine position, resulting in a higher level of anesthetic effect than isobaric or hypobaric solutions.<sup>91</sup> Hyperbaric solutions are also useful in small doses for a saddle block and to achieve unilateral anesthesia. CSF and local anesthetic density change with temperature. Plain bupivacaine 0.5%, for example, may be isobaric at 24°C but is slightly hypobaric at 37°C. A small volume of drug at room temperature injected intrathecally quickly equilibrates after injection and increases to the temperature of the CSF. Nevertheless, increasing temperature decreases density of a solution and warming of local anesthetic solution to body temperature, therefore making it more hypobaric, increases the block height in patients who remain seated for several minutes after injection.<sup>96</sup>

**Dose, Volume, and Concentration.** The dose, volume, and concentration are inextricably linked (Volume × Concentration = Dose), but dose is the most reliable determinant of local anesthetic spread (and thus block height) when compared with either volume or concentration for isobaric and hypobaric local anesthetic solutions.<sup>97,98</sup> Hyperbaric local anesthetic injections are primarily influenced by baricity.

The choice of local anesthetic itself does not influence spread if all other factors are controlled. Additive drugs, other than opioids, also do not affect spread. However, opioids do seem to increase mean spread,<sup>91,99</sup> possibly as a result of pharmacologic enhancement at the extremes of the spread where the local anesthetic block alone would have been subclinical.<sup>100,101</sup>

**TABLE 45.2** Dermatomal Level Required for Various Common Surgical Procedures

Type of Surgery	Dermatomal Level
Upper abdominal surgery	T4
Cesarean delivery	T4
Transurethral resection of prostate	T10
Hip surgery	T10
Foot and ankle surgery	L2

**TABLE 45.3** Factors Affecting Local Anesthetic Distribution and Block Height

	More Important	Less Important	Not Important
Drug factors	Dose Baricity	Volume Concentration Temperature of injection Viscosity	Additives other than opioids
Patient factors	CSF volume Advanced age Pregnancy	Weight Height Spinal anatomy Intraabdominal pressure	Menopause Gender
Procedure factors	Patient position Epidural injection post spinal	Level of injection (hypobaric more than hyperbaric) Fluid currents Needle orifice direction Needle type	

## Patient Factors

Patient characteristics that may influence block height include patient height, weight, age, sex, pregnancy, anatomic configuration of the spine, and the CSF properties (volume and composition). Within the range of “normal-sized” adults, patient height does not seem to affect the spread of spinal anesthesia. This is likely because the length of the lower limb bones rather than the vertebral column contributes most to adult height. A correlation has been found between the vertebral column length and local anesthetic spread<sup>102</sup> and, at extremes of height, consideration should be given to altering the dose accordingly.

The CSF volume is an important patient-related factor that significantly influences peak block height and regression of sensory and motor blockade.<sup>17</sup> Lumbosacral CSF has a fairly constant pressure of approximately 15 cm H<sub>2</sub>O but its volume varies from patient to patient, in part because of differences in body habitus and weight.<sup>16</sup> In a small sample of patients, block height varied indirectly with CSF volume.<sup>17</sup> Unfortunately, CSF volume does not correlate well with anthropomorphic measurements available clinically other than body weight.<sup>17</sup> In theory, the increased abdominal mass in obese patients, and possible increased epidural fat, may decrease the CSF volume and therefore increase the spread of local anesthetic and block height. This has indeed been demonstrated using hypobaric solutions,<sup>103,104</sup> which are characterized by more variable spread anyway, but not hyperbaric solutions (see [Chapter 58](#)).<sup>103,105</sup>

CSF density can also vary between and within individuals depending on sex, menopausal status, and pregnancy (see [Chapter 62](#)).<sup>92</sup> The density of CSF is lower in women compared with men, premenopausal compared with postmenopausal women, and pregnant compared with non-pregnant women. Although this may affect relative baricity of local anesthetics, the clinical variation in spread is probably unimportant.

Advanced age is associated with increased block height (see [Chapter 65](#)).<sup>106,107</sup> In older patients, CSF volume decreases, whereas its specific gravity increases. Further, the nerve roots appear more sensitive to local anesthetic in the aged population.

Gender can theoretically affect block height by several mechanisms. CSF density is higher in males, thereby reducing the baricity of local anesthetic solution and possibly limiting the extent of cephalad spread. In the lateral position, the broader shoulders of males relative to their hips make the lateral position slightly more head-up. The reverse is true in females who have a slightly head-down tilt in the lateral position compared with males. Despite this, there is little objective data that males have a slightly less cephalad spread than females in the lateral position.

Variations of the spine may be an important contributor to block height. Scoliosis, although it possibly makes insertion of the needle more difficult, will have little effect on local anesthetic spread if the patient is turned supine. Kyphosis, however, in a supine patient may affect the spread of a hyperbaric solution. Spread of local anesthetic is enhanced by changes in the lumbar lordosis during pregnancy, as well as by the volume and density of CSF, by twin pregnancies compared with singletons, by intraabdominal

pressure increases (possibly), and by a progesterone-mediated increase in neuronal sensitivity.

## Procedure Factors

Patient position, needle type and alignment, and the level of injection are each procedure-related factors that can affect block height. Combined with the baricity and local anesthetic dose, patient position is the most important factor in determining the block height. Position should not affect the spread of a truly isobaric solution.<sup>95</sup> Intrathecal local anesthetic appears to stop spreading 20 to 25 minutes after injection, thus positioning of the patient is most important during this time period, but particularly in the initial few minutes. However, marked changes in patient posture up to two hours after injection can still result in significant changes in the block level, probably because of bulk movement of CSF.<sup>108,109</sup> Although a 10-degree head-up tilt can reduce the spread of hyperbaric solutions without hemodynamic compromise,<sup>110</sup> a head-down tilt does not always increase the spread of hyperbaric bupivacaine.<sup>111</sup> Flexion of the hips in combination with the Trendelenburg position flattens the lumbar lordosis and has been shown to increase cephalad spread of hyperbaric solutions.<sup>112</sup> A “saddle block” where only the sacral nerve roots are anesthetized can be achieved by using a small dose of hyperbaric local anesthetic while the patient remains in the sitting position for up to 30 minutes. When larger hyperbaric doses are administered, however, the block can still extend cephalad despite maintaining the sitting position for a prolonged period of time.<sup>113</sup> The reverse holds true for hypobaric solutions, where block height is greater (than hyperbaric solutions) if they are administered in a sitting position.<sup>114</sup>

The specific needle type and orientation of the orifice may affect block quality. With hypobaric solutions, cephalad alignment of the orifice of Whitacre, but not Sprotte, needles produces greater spread.<sup>115-117</sup> The orientation of the needle orifice does not appear to affect the spread of hyperbaric solutions. When directing the needle orifice to one side (and using hyperbaric anesthetic), a more marked unilateral block is achieved again when using a Whitacre, rather than a Quincke, needle.<sup>118</sup>

The level of injection affects block height. Most studies have demonstrated that, even when the difference is only one interspace more cephalad, the block height is greater<sup>119-122</sup> when using isobaric bupivacaine. The level of injection does not appear to influence the spread of hyperbaric solutions.<sup>123,124</sup> Injection rate and barbotage (repeated aspiration and reinjection of CSF) of isobaric and hyperbaric solutions have not consistently been shown to affect block height.<sup>91</sup> A slower injection may actually increase spread, and this is perhaps also safer because forceful injection may cause the syringe to disconnect from the needle. Other maneuvers that do not appear to affect block height are coughing and straining after local anesthetic injection. This is related to the physics of injecting drugs into a closed column of CSF, which instantaneously transmits pressure changes throughout the CSF column, such as those that occur with coughing or straining.<sup>25</sup> The injection of local anesthetic or even saline into the epidural space after a spinal anesthetic increases the block height. This is discussed separately in the combined spinal-epidural (CSE) section.

## DURATION

The duration of a spinal anesthetic depends on how this variable is defined. For example, the duration of surgical anesthesia is less than the time for complete block resolution. In addition, surgical anesthesia depends on the surgical site because anesthesia is more prolonged at the lower lumbar and sacral levels than at those more cephalad from where the block regresses first. Duration is affected primarily by the dose,<sup>97,125</sup> the intrinsic properties of the local anesthetic (which affect elimination from the subarachnoid space), and the use of additives (if applicable). The latter two are described later. Hyperbaric solutions have a shorter duration of action than isobaric solutions.<sup>125</sup>

## PHARMACOLOGY

The clinical effects of intrathecal local anesthetics are mediated by drug uptake and distribution within the CSF and elimination. These in turn are dictated in part by the pKa, lipid solubility, and protein binding of the local anesthetic solution. Rather than their pharmacologic structure (i.e., amide or ester), it is the duration of action—short-acting (i.e., procaine, chloroprocaine, articaine), intermediate-acting (i.e., lidocaine, prilocaine, mepivacaine), and long-acting (i.e., tetracaine, bupivacaine, levobupivacaine, ropivacaine)—that is most often used to classify local anesthetics in the clinical setting. The choice and dose of local anesthetic depend on both the expected duration and the nature (location, ambulatory) of surgery. Table 45.4 shows a range of local anesthetics used for spinal anesthesia with corresponding doses, onset times, and durations of action.<sup>126-134</sup>

### Short- and Intermediate-Acting Local Anesthetics

**Procaine.** Procaine is a short-acting ester local anesthetic and one of the oldest spinal anesthetics, having originally replaced cocaine as the drug of choice for spinal anesthesia in the early 20th century. Procaine itself was then replaced by lidocaine, but with concerns about lidocaine

and transient neurologic symptoms (TNS), procaine has recently been reexamined as an alternative fast-acting local anesthetic. However, it is not commonly used because of a more frequent failure rate than lidocaine, significantly more nausea, and a slower time to recovery.<sup>135</sup> If used, it is often administered as a hyperbaric drug in a dose ranging between 50 and 200 mg in a 10% concentration.

**Chloroprocaine.** Chloroprocaine is an ultra-short-acting ester local anesthetic that was introduced in the 1950s. Its initial popularity stemmed from its rapid metabolism by pseudocholinesterase, which translated into minimal systemic or fetal effects in the setting of epidural labor analgesia. However, its reputation as a spinal anesthetic has been tarnished because of reports of neurologic injury associated with the preservative once used in older preparations of the drug (see Complications, discussed later).<sup>136-139</sup> Recently, interest in chloroprocaine has increased for use in spinal anesthesia for ambulatory surgery (see Chapter 72). Modern, preservative-free preparations of chloroprocaine administered in small doses (30-60 mg) produce reliable, short-duration spinal anesthesia,<sup>126</sup> with a faster recovery time than procaine, lidocaine, and bupivacaine.<sup>140-144</sup> TNS can occur with modern chloroprocaine preparations, albeit at a considerably lesser rate (0.6%) than lidocaine (14%).<sup>145-147</sup>

**Articaine.** Articaine is a relatively novel amide local anesthetic that also has an ester linkage. The ester linkage allows for metabolism by nonspecific cholinesterases. It has been widely used since 1973 for dental nerve blocks with a good safety profile. Intrathecal articaine has not been extensively investigated, but studies do suggest that doses of 50 to 80 mg with or without glucose appear to provide rapid-onset spinal anesthesia for about 1 hour, with a recovery profile faster than bupivacaine.<sup>148,149</sup>

**Lidocaine.** Lidocaine is a hydrophilic, relatively poorly protein-bound amide local anesthetic. It has a rapid onset

**TABLE 45.4** Dose, Block Height, Onset Times, and Duration of Commonly Used Spinal Anesthetics

Local Anesthetic Mixture	DOSE (MG)		DURATION (MIN)		
	To T10	To T4	Plain	Epinephrine (0.2 mg)	Onset (min)
Lidocaine 5% (with/without dextrose)*	40-75	75-100	60-150 <sup>†</sup>	20%-50%	3-5
Mepivacaine 1.5% (no dextrose)	30-45 <sup>‡</sup>	60-80 <sup>§</sup>	120-180 <sup>¶  </sup>	—	2-4
Chloroprocaine 3% (with/without dextrose)	30-40	40-60	40-90 <sup>¶</sup>	N/R	2-4
Bupivacaine 0.5%-0.75% (no dextrose)	10-15	12-20	130-230 <sup>#</sup>	20%-50%	4-8
Levobupivacaine 0.5% (no dextrose)	10-15	12-20	140-230 <sup>#</sup>	—	4-8
Ropivacaine 0.5%-1% (with/without dextrose)	12-18	18-25	80-210 <sup>**</sup>	—	3-8

\*Lidocaine is not commonly used now.

<sup>†</sup>Regression to T12.

<sup>‡</sup>Note peak with these doses was T12, and not in all cases.

<sup>§</sup>Median peak block height in this study with 60 mg was T5, not T4.

<sup>¶||</sup>Regression to S1 for block duration.

<sup>#</sup>Regression to L1.

<sup>\*\*</sup>Regression to L2.

<sup>\*\*</sup>Regression to S2.

N/R, Not recommended. Note that duration depends on how the regression of the block is measured, which varies widely between studies.

and intermediate duration and is used in doses of 50 to 100 mg for shorter procedures that can be completed in 1.5 hours or less. It was traditionally prepared as a 5% solution in 7.5% dextrose; this preparation has been associated with both permanent nerve injury and TNS (see section Complications, discussed later). Despite efforts to reduce the concentration of both the drug and dextrose,<sup>150,151</sup> the use of intrathecal lidocaine declined and has not yet recovered.

**Prilocaine.** Prilocaine is an amide local anesthetic based on the structure of lidocaine. Prilocaine was introduced in 1965 and has an intermediate duration of action that may lend itself to use in the ambulatory surgery setting.<sup>152</sup> A dose of 40 to 60 mg of 2% hyperbaric prilocaine can provide a block to T10 for 100 to 130 minutes, whereas as little as 20 mg combined with fentanyl has been successfully used for ambulatory arthroscopic knee surgery.<sup>153</sup> Prilocaine is rarely associated with TNS.<sup>152,154,155</sup> In large doses (>600 mg), prilocaine can result in methemoglobinemia. This should not be an issue with doses used for spinal anesthesia, but it has been reported after epidural infusions.<sup>156</sup>

**Mepivacaine.** Mepivacaine is another short-acting amide local anesthetic. It was first introduced for spinal anesthesia in 1962 and was initially prepared as a hyperbaric solution. The use of spinal mepivacaine has declined because the incidence of TNS after hyperbaric mepivacaine was similar to that of lidocaine,<sup>147</sup> although TNS were less frequent with the isobaric preparation of mepivacaine.<sup>157-159</sup> Doses of 30 to 80 mg with and without additives have been used (see Table 45.4) and, when compared with lidocaine, mepivacaine has a slightly longer duration of action.<sup>160</sup>

### Long-Acting Local Anesthetics

**Tetracaine.** Tetracaine is an ester local anesthetic with a rate of metabolism one tenth that of chloroprocaine. It is packaged either as Niphanoid crystals (20 mg) or as an isobaric 1% solution (2 mL, 20 mg). When Niphanoid crystals are used, a 1% solution is obtained by adding 2 mL of preservative-free sterile water to the crystals. Mixing 1% solution with 10% dextrose produces a 0.5% hyperbaric preparation that may be used for perineal and abdominal surgery in doses of 5 and 15 mg, respectively. Tetracaine is usually combined with a vasoconstrictor additive because the duration of tetracaine alone can be unreliable. Although such combinations can provide up to 5 hours of anesthesia,<sup>161-164</sup> the addition of phenylephrine in particular has been associated with TNS.<sup>165</sup>

**Bupivacaine.** Bupivacaine was introduced in 1963 and is a highly protein-bound amide local anesthetic with a slow onset because of its relatively high pKa. It is appropriate for procedures lasting up to 2.5 to 3 hours (see Table 45.4).<sup>166,167</sup> Bupivacaine is available as 0.25%, 0.5%, and 0.75% clear isobaric solutions and also as a hyperbaric 0.5% (in Europe) and 0.75% solution containing 80 mg/mL glucose. At room temperature, plain bupivacaine is actually slightly hypobaric compared with CSF. Recovery profiles using small doses appear to be similar to that of lidocaine<sup>168-170</sup> and thus low-dose bupivacaine is used in

ambulatory procedures. A recent systematic review<sup>171</sup> concluded that 4 to 5 mg of hyperbaric bupivacaine combined with unilateral positioning was adequate for short knee arthroscopy procedures. Bupivacaine is rarely associated with TNS.

**Levobupivacaine.** Levobupivacaine is the pure S (−) enantiomer of racemic bupivacaine. Although it is used in similar doses to bupivacaine and has a similar onset and duration, levobupivacaine potency appears to be slightly less than bupivacaine.<sup>129</sup> Nevertheless, the majority of clinical studies using identical doses of levobupivacaine and bupivacaine have found no significant difference in clinical efficacy for spinal anesthesia.<sup>129,172-174</sup> The main advantage of levobupivacaine is that it is less cardiotoxic than bupivacaine,<sup>175,176,178</sup> which is more of a theoretic than a real risk in the setting of spinal anesthesia.

**Ropivacaine.** Ropivacaine was introduced in 1996 and is another highly protein-bound amide local anesthetic. It is structurally related to bupivacaine, with the same pKa (8.1) and so it is also characterized by slow onset and a long duration of action. Compared to bupivacaine, the proposed advantages of spinal ropivacaine were less cardiotoxicity and greater motor-sensory block differentiation, resulting in less motor block. Subsequently, the potency of ropivacaine was found to be 0.6 that of bupivacaine.<sup>179-181</sup> When ropivacaine is given in an equivalent dose to bupivacaine, there is slightly less motor block and earlier recovery with ropivacaine.<sup>8,182-184</sup>

### Spinal Additives

Whether administered into the CSF in conjunction with a local anesthetic or alone, a variety of medications may exert a direct analgesic effect on the spinal cord and nerve roots, or prolong the duration of sensory and motor blockade. As such, the coadministration of these agents often allows for a reduction in the required dose of local anesthetic, with the advantage of motor block sparing and faster recovery while still producing the same degree of analgesia.

**Opioids.** The effects of opioids within the CSF are complex, because of a combination of direct spinal cord dorsal horn opioid receptor activation, cerebral opioid receptor activation after CSF transport, and peripheral and central systemic effects after vascular uptake. The effect at each of these sites depends on both the dose administered and the physicochemical properties of the opioid, particularly lipid solubility. Highly lipid-soluble drugs such as fentanyl and sufentanil have a more rapid onset and shorter duration of action than more hydrophilic opioids. In addition to increasing uptake into neural tissue, greater lipid solubility results in rapid uptake into both blood vessels (with a resultant systemic effect) and fatty tissue. The spread of lipophilic opioids within the CSF is therefore more limited than hydrophilic opioids such as morphine, which demonstrate greater spread as a result of slower uptake and elimination from the CSF. As a result, hydrophilic opioids have a greater risk of late respiratory depression, which is one of the rare but most serious consequences of intrathecal opioid administration. The extent of neural tissue and vascular uptake also affects the potency of intrathecal

opioids. For example, the relative intrathecal to intravenous potency of morphine is 200 to 300 to 1, whereas for fentanyl and sufentanil it is only 10 to 20 to 1.<sup>185</sup> In addition to respiratory depression, intrathecal opioids have other side effects including nausea and vomiting, pruritus, and urinary retention. These are discussed later in the Complications section.

**Hydrophilic Opioids.** Preservative-free morphine is the most widely used hydrophilic opioid in spinal anesthesia. It has a slow onset but provides analgesia for up to 24 hours.<sup>186</sup> Adequate analgesia is achieved with 100 µg, with minimal side effects for cesarean deliveries, whereas the most efficacious dose for major orthopedic surgery is less clear.<sup>187</sup> Doses as high as 1000 µg may be used for major abdominal surgery or thoracotomies, where it is becoming increasingly common to administer spinal opioids alone as a simple alternative to epidural local anesthetic-based analgesia. The magnitude of the analgesic response and the optimal dose remain unclear. Given adverse effects increase at higher doses it has been suggested that the lowest effective dose (<300 microg) should be used.<sup>66a</sup> Overall, the beneficial effects of intrathecal morphine seem most marked in abdominal surgery, and within the first 24 hours in particular.<sup>186,188</sup>

Diamorphine is available for use in the United Kingdom only. It is a lipid-soluble prodrug that crosses the dura faster than morphine and is cleared from the CSF more quickly than morphine. Once in the dorsal horn of the spinal cord, it is converted to morphine and 6-monoacetyl morphine, both of which are  $\mu$ -agonists with a relatively long duration of action. It is recommended for use in doses of 0.3 to 0.4 mg for cesarean delivery<sup>189</sup> and is widely used instead of morphine in the United Kingdom.

There are only limited data related to the use of hydromorphone for spinal analgesia. It is more commonly used epidurally, as discussed later. Limited data suggest that intrathecal hydromorphone 50 to 100 µg provides comparable analgesia with similar side effects to 100 to 200 µg of morphine, with a similar duration of action. However, it has not undergone full neurotoxicity screening and does not provide any advantage compared with morphine.<sup>190</sup>

Meperidine is an opioid of intermediate lipid solubility, but it also has some local anesthetic properties and has been used as the sole intrathecal agent (doses ranging from 0.5 to 1.8 mg/kg) in both obstetric and general surgery.<sup>191,192</sup> Smaller doses are used in combination with local anesthetics. Both 10 mg and 20 mg improve analgesia compared with placebo after cesarean delivery<sup>193</sup> although side effects were more frequent with the larger dose. However, this drug is used infrequently because of the availability of other opioids and its unknown neurotoxicity profile.

**Lipophilic Opioids.** Fentanyl and sufentanil are used frequently in obstetrics for labor analgesia and cesarean delivery as discussed elsewhere (also Chapter XX). Sufentanil 2 to 10 µg and fentanyl 25 µg provide comparable analgesia in early labor.<sup>194-197</sup> In transurethral prostatectomy surgery, when combined with low-dose bupivacaine, sufentanil 5 µg provides superior analgesia compared with fentanyl 25 µg.<sup>198</sup> Fentanyl in doses of 10 to 30 µg is commonly used in ambulatory surgery because of its rapid

onset time of 10 to 20 minutes and relatively short duration of 4 to 6 hours. Although the local anesthetic dose can be reduced and analgesia prolonged,<sup>199</sup> the addition of fentanyl to bupivacaine may increase side effects and delay discharge.<sup>171</sup>

**Vasoconstrictors.** Vasoconstrictors, such as epinephrine and phenylephrine, prolong the duration of sensory and motor blockade when added to local anesthetics. The mechanism of action is reduced systemic local anesthetic uptake caused by an  $\alpha_1$ -mediated vasoconstriction. Epinephrine may also enhance analgesia via a direct  $\alpha_2$ -mediated effect. Traditionally, epinephrine 0.1 to 0.6 mg was thought to prolong tetracaine spinal anesthesia, but not bupivacaine or lidocaine spinal anesthesia.<sup>22</sup> This theory was postulated because of differences in the vasodilatory action of the local anesthetic drugs; plain lidocaine and bupivacaine cause vasodilation, whereas plain tetracaine does not. However, lidocaine spinal anesthesia can be prolonged by epinephrine when measured by both two-dermatome regression in the lower thoracic dermatomes and by occurrence of pain at the operative site for procedures carried out at the level of the lumbosacral dermatomes.<sup>200,201</sup> Similarly, bupivacaine spinal duration may be increased, but because of the already long duration, epinephrine is not generally added to bupivacaine. There is a concern that potent vasoconstrictive action places the blood supply of the spinal cord at risk. However, there are no human data supporting this theory, and in animal studies,<sup>164,202-204</sup> administering either subarachnoid epinephrine (0.2 mg) or phenylephrine (5 mg) does not decrease spinal cord blood flow. Phenylephrine 2 to 5 mg prolongs both lidocaine and tetracaine spinal anesthesia to a similar extent as epinephrine.<sup>201,205</sup> Bupivacaine spinal anesthesia is not prolonged by phenylephrine.<sup>206,207</sup> Concepcion and co-workers<sup>208</sup> compared epinephrine (0.2 and 0.3 mg) and phenylephrine (1 and 2 mg) added to tetracaine and did not find any differences in duration between the two vasoconstrictors. Caldwell and associates<sup>163</sup> used larger doses of vasoconstrictors, epinephrine at 0.5 mg and phenylephrine at 5 mg, and showed that phenylephrine prolonged tetracaine spinal anesthesia significantly more than did epinephrine. The addition of phenylephrine has declined in popularity because of its association with TNS.<sup>165,209</sup>

**$\alpha_2$ -Agonists.** Clonidine, dexmedetomidine, and epinephrine all act on prejunctional and postjunctional  $\alpha_2$  receptors in the dorsal horn of the spinal cord. Activation of presynaptic receptors reduces neurotransmitter release, whereas postjunctional receptor activation results in hyperpolarization and reduction of pulse transmission.<sup>210</sup> In doses of 1.5 to 225 µg, clonidine prolongs the duration of sensory and motor blockade by approximately 1 hour and improves analgesia, reducing morphine consumption by up to 40%.<sup>211-215</sup> It appears to cause less urinary retention than morphine but, as with intravenous clonidine administration, spinal clonidine can also cause hypotension. A systematic review concluded that the hypotension associated with spinal clonidine was not dose-related and that the risk of bradycardia with clonidine was not increased.<sup>216</sup> Sedation can also occur with spinal clonidine, peaking within 1 to 2 hours and lasting up to 8 hours.<sup>210</sup> Dexmedetomidine

is approximately 10-fold more  $\alpha_2$ -selective than clonidine is.<sup>217</sup> As little as 3  $\mu$ g of dexmedetomidine can prolong motor and sensory block without hemodynamic compromise.<sup>218,219</sup>

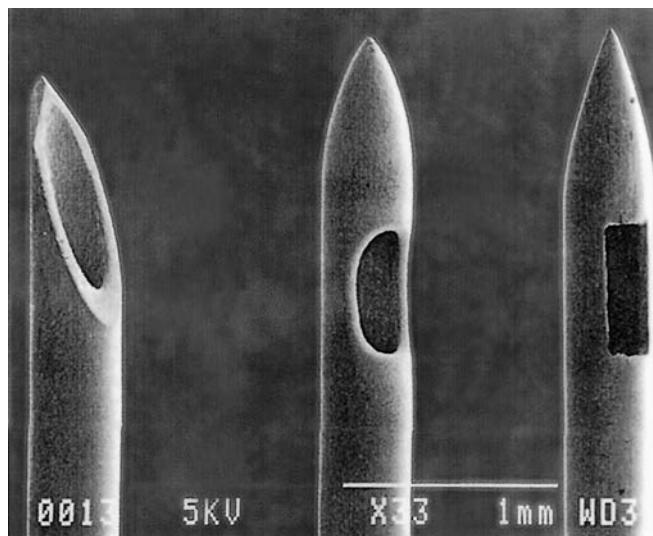
**Other Drugs.** Neostigmine in doses of 10 to 50  $\mu$ g has analgesic effects after intrathecal administration.<sup>220,221</sup> Intrathecal neostigmine has been shown to prolong motor and sensory blockade and reduce postoperative analgesic requirements. Neostigmine inhibits the breakdown of acetylcholine, therefore increasing acetylcholine concentration, which itself is antinociceptive. It also appears to stimulate the release of nitric oxide in the spinal cord. Its benefits, however, are limited by nausea, vomiting, bradycardia, and, in higher doses, lower extremity weakness,<sup>222,223</sup> and is therefore not in widespread use.<sup>224</sup> Midazolam is a  $\gamma$ -aminobutyric acid receptor agonist that in doses of 1 to 2 mg appears to increase sensory and motor block and decrease analgesic requirements postoperatively, without the adverse effects observed with  $\alpha_2$  agonists or opioids. Early work raised concerns of spinal cord toxicity, but more recent studies suggest that it is safe.<sup>225</sup> Ketamine, adenosine, tramadol, magnesium, and nonsteroidal antiinflammatory drugs have also all been administered intrathecally, but further work is required to establish safety and whether these drugs have any clinical value.

### Technique

Technique should be classified into a series of steps (i.e., the four Ps): preparation, position, projection, and puncture.

**Preparation.** Informed consent must be obtained, with adequate documentation of the discussion of risk (see Complications, discussed later). Resuscitation equipment must always be readily available whenever a spinal anesthetic procedure is performed. The patient should have adequate intravenous access and be monitored with pulse oximetry, noninvasive arterial blood pressure, and electrocardiogram. Preprepared packs are now commonly used and often contain fenestrated drapes, swabs and towels, syringes, needles, filters, spinal needles, sterilizing solution, and local anesthetic for skin infiltration. When the local anesthetic for subarachnoid injection is chosen, the duration of block should be matched with both the surgical procedure and patient variables (see Table 45.4).

The most important characteristics of a spinal needle are the shape of the tip and the needle diameter. Needle tip shapes fall into two main categories: those that cut the dura and those with a conical, pencil-point tip. The former include the Pitkin and the Quincke-Babcock needle, and the Whitacre and Sprotte needles belong to the latter group (Fig. 45.4). The orifice of the Whitacre needle is smaller. If a continuous spinal technique is chosen, use of a Tuohy or other thin-walled needle can facilitate passage of the catheter. The use of small needles reduces the incidence of post-dural puncture headache from 40% with a 22-G needle to less than 2% with a 29-G needle. The use of larger needles, however, improves the tactile sense of needle placement, and so although 29-G needles result in a very low rate of post-dural puncture headache, the failure rate is increased.<sup>226,227</sup> Pencil-point needles provide better tactile sensation of the different layers encountered during needle



**Fig. 45.4** Scanning electron micrographs of spinal needle tip designs: Quincke (left), Sprotte (middle), and Whitacre (right). (Modified from Puolakka R, Andersson LC, Rosenberg PH. Microscopic analysis of three different spinal needle tips after experimental subarachnoid puncture. *Reg Anesth Pain Med*. 2000;25:163–169.)

insertion but, more importantly, they reduce the incidence of post-dural puncture headache. Pencil-point needles of 25, 26, and 27-G probably represent the optimal needle choice. An introducer needle can assist with guidance of smaller-gauge spinal needles in particular. Special Luer-Lok needles and syringes for spinal kits are now also available. These have been designed to prevent inadvertent intrathecal injection but still rely on the correct drug being drawn up into the “special” connector syringe (see Fig. 45.4).

Sterility is an issue of utmost importance. One of the most common organisms responsible for postspinal bacterial meningitis is *Streptococcus viridans*, which is an oral commensal, emphasizing the purpose of wearing a mask as part of a full aseptic technique. Hands and forearms must be washed and all jewelry removed. A variety of solutions may be used to clean the patient’s back prior to skin puncture, such as chlorhexidine or alcohol (alone or in combination), or iodine solutions. Chlorhexidine and alcohol together have been concluded to be most effective.<sup>229–231</sup> It is important that chlorhexidine is allowed to dry completely before skin puncture because chlorhexidine is neurotoxic.

The recently published Practice Advisory for the Prevention, Diagnosis, and Management of Infectious Complications Associated with Neuraxial Techniques by the American Society of Anesthesiologists (ASA) Task Force on Infectious Complications Associated with Neuraxial Techniques and the ASRA<sup>229</sup> recommends that to prevent infection, it is important to identify patients at increased risk of infection (e.g., known bacteremia, immunocompromised) and consider alternatives, consider pre-procedure antibiotics in patients with bacteremia, ensure full asepsis including masks and use antiseptic solution such as chlorhexidine, sterile occlusive dressings, and bacterial filters. Disconnection and reconnection of neuraxial catheters should be minimized and catheters should not remain in situ longer than clinically necessary. Patients should be evaluated

daily for signs of infection and if suspected then this should be promptly investigated and treated appropriately.

**Position (also see Chapter 34).** The three primary patient positions include the lateral decubitus, sitting, and prone positions, each of which has advantages in specific situations. The superiority of any one particular position is unclear. In the obstetric population, there have been small studies demonstrating that block operator performance was faster in the sitting position, albeit this benefit was offset by a slower onset time compared with the lateral decubitus position (see Chapter 62).<sup>232</sup> Current consensus guidelines state that neuraxial blocks should not be routinely performed with the patient anesthetized or deeply sedated,<sup>76</sup> except in those circumstances where the physician and patient conclude that benefit outweighs the risk. General anesthesia or heavy sedation can prevent a patient from recognizing warning signs of pain or paresthesia if the needle is in close proximity to nervous tissue.

A patient in the lateral decubitus position facilitates the administration of sedative medication if required, is less dependent on a well-trained assistant than for a patient in the sitting position, and is arguably more comfortable. Patients are placed with their back parallel to the edge of the operating table nearest the anesthesiologist, thighs flexed onto the abdomen, with the neck flexed to allow the forehead to be as close as possible to the knees in an attempt to “open up” the vertebral spaces. The assistant may still be invaluable during this positioning by encouraging and assisting the patient in assuming the ideal lateral decubitus position. Because of the differing proportional sizes of hips and shoulders, the spine may slope down toward the head in females, with the opposite occurring in males. The patient should be positioned so that spread of hypobaric, isobaric, or hyperbaric solution to the operative site is optimized.

Identification of the midline may be easier when the patient is placed in the sitting position, especially when obesity or scoliosis renders midline anatomy difficult to examine. Ultrasound may also be used to identify the midline (see later discussion). When placing patients in this position, a stool can be provided as a footrest and a pillow placed in the lap, or a specially designed stand may be used. The assistant helps to maintain the patient in a vertical plane while flexing the patient’s neck and arms over the pillow, relaxing the shoulders, and asking the patient to “push out” the lower back to open up the lumbar vertebral spaces. Care must be taken not to oversedate a patient in this position. Hypotension may also be more common for a person in the sitting position.

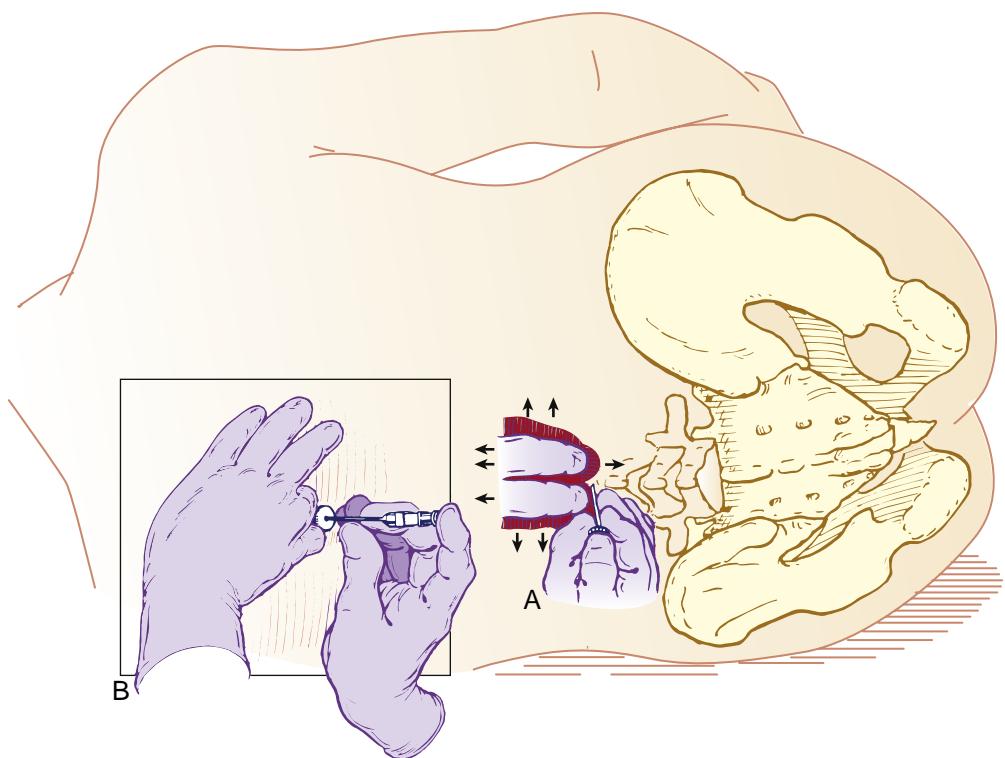
The prone position is rarely used but may be chosen when the patient is to be maintained in that position (often with the jack-knife modification) during the surgical procedure. Such cases may include rectal, perineal, or lumbar procedures. The anesthesiologist may have to aspirate for CSF because CSF pressure is minimized when insertion of the lumbar needle is carried out in this position.

**Projection and Puncture.** The midline approach relies on the ability of patients and assistants to minimize lumbar lordosis and allow access to the subarachnoid space between adjacent spinous processes, usually at the L2-L3, L3-L4, or the L4-L5 space. The spinal cord ends at the level of L1-L2 and so needle insertion above this level should be avoided.

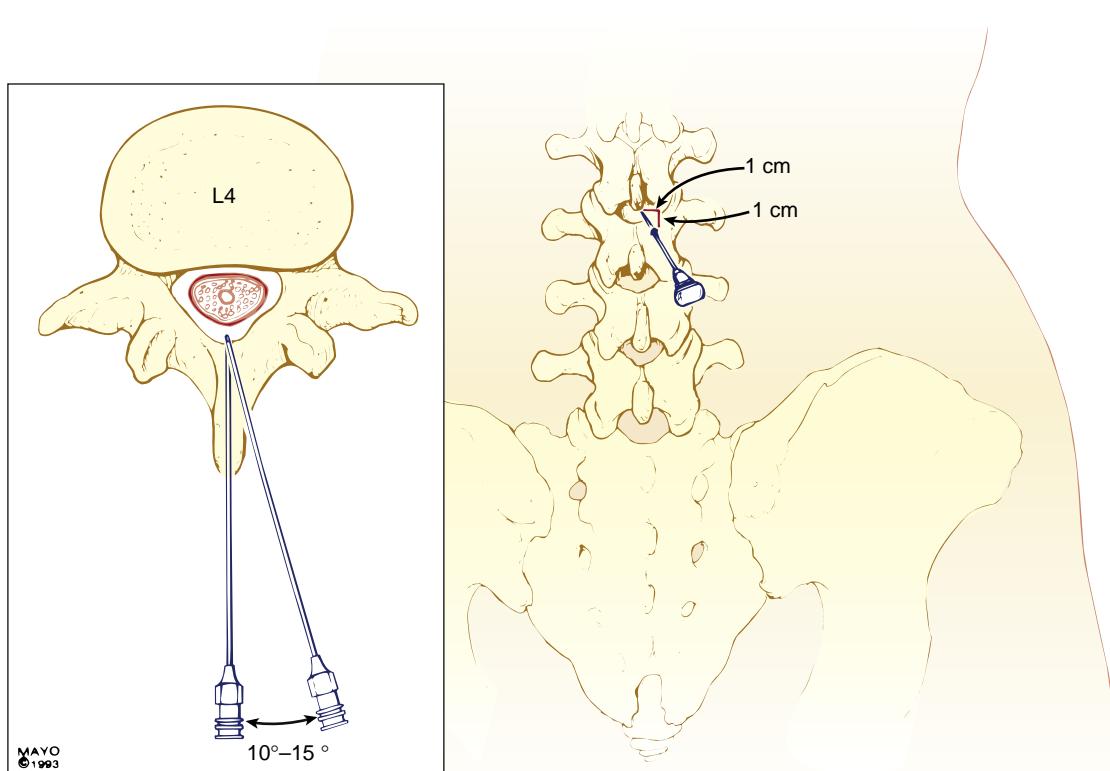
The intercrisal line is the line drawn between the two iliac crests and traditionally corresponds to the level of the L4 vertebral body or the L4-L5 interspace, but the reliability of this landmark is questionable as demonstrated by recent ultrasonography studies.<sup>233</sup> Once the appropriate space has been selected, a subcutaneous skin wheal of local anesthetic is developed over this space, and the introducer is inserted at a slight cephalad angle of 10 to 15 degrees through skin, subcutaneous tissue, and supraspinous ligament to reach the substance of the interspinous ligament. The introducer is grasped with the palpating fingers and steadied while the other hand is used to hold the spinal needle like a dart, and the fifth finger is used as a tripod against the patient’s back to prevent patient movement and unintentional insertion to a level deeper than intended. The needle, with its bevel parallel to the midline, is advanced slowly to heighten the sense of tissue planes traversed and to prevent skewing of nerve roots, until the characteristic change in resistance is noted as the needle passes through the ligamentum flavum and dura. On passing through the dura, there is often a slight “click” or “pop” sensation. The stylet is then removed, and CSF should appear at the needle hub. The smaller the needle diameter, the longer the wait for CSF flow, particularly if the patient is not in the sitting position. If the CSF does not flow, the needle might be obstructed and rotation in 90-degree increments can be undertaken until CSF appears. If CSF does not appear in any quadrant, the needle should be advanced a few millimeters and rechecked in all four quadrants. If CSF still has not appeared and the needle is at a depth appropriate for the patient, the needle and introducer should be withdrawn and the insertion steps should be repeated. A common reason for failure is insertion of the needle off the midline (Fig. 45.5).

After CSF is freely obtained, the dorsum of the anesthesiologist’s nondominant hand steadies the spinal needle against the patient’s back while the syringe containing the therapeutic dose is attached to the needle. CSF is again freely aspirated into the syringe, and the anesthetic dose is injected at a rate of approximately 0.2 mL/s. After completion of the injection, 0.2 mL of CSF can be aspirated into the syringe and reinjected into the subarachnoid space to reconfirm location and clear the needle of the remaining local anesthetic.

The paramedian approach exploits the larger “subarachnoid target” that exists if a needle is inserted slightly lateral to the midline (Fig. 45.6). The paramedian approach may be especially useful in the setting of diffuse calcification of the interspinous ligament. The most common error when using the paramedian technique is that the needle entry site is placed too far off midline, which makes the vertebral laminae barriers to insertion of the needle. In the paramedian approach, a skin wheal is raised 1 cm lateral and 1 cm caudad to the corresponding spinous process. A longer needle (e.g., 3-5 cm) is then used to infiltrate deeper tissues in a cephalomedial plane. The spinal introducer and needle are next inserted 10 to 15 degrees off the sagittal plane in a cephalomedial plane (see Fig. 45.6). Similar to the midline approach, the most common error is to angle the needle too far cephalad on initial insertion. Nevertheless, if the needle contacts bone, it is redirected slightly in a cephalad direction. If bone is again contacted, but at a deeper level, the slight cephalad angulation is continued because it is likely that the needle is being “walked up” the lamina. As



**Fig. 45.5** Insertion of the spinal needle. (A) The palpating fingers are “rolled” in a side-to-side and a cephalad-to-caudad direction to identify the inter-spinous space. (B) During needle insertion, the needle should be stabilized in a tripod fashion while placed in the hand, similar to a dart being thrown.



**Fig. 45.6** Vertebral anatomy of the midline and paramedian approaches to centroneuraxis blocks. The midline approach highlighted in the inset requires anatomic projection in only two planes: sagittal and horizontal. The paramedian approach shown in the inset and in the posterior view requires an additional oblique plane to be considered, although the technique may be easier in patients who are unable to cooperate in minimizing their lumbar lordosis. The paramedian needle is inserted 1 cm lateral and 1 cm caudad to the caudad edge of the more superior vertebral spinous process. The paramedian needle is inserted approximately 15 degrees off the sagittal plane, as shown in the inset. (Courtesy the Mayo Foundation, Rochester, MN.)

in the midline approach, the characteristic feel of the ligaments and dura is possible, but only once the ligamentum flavum is reached because the needle this time is not passing through the supraspinous and interspinous ligaments. After CSF is obtained, the block is carried out in a manner similar to that described for the midline approach.

## SPECIAL SPINAL TECHNIQUES

### Continuous Spinal Anesthesia

Continuous spinal anesthesia allows incremental dosing of local anesthetic and therefore predictable titration of the block to an appropriate level, with better hemodynamic stability than a single-shot spinal.<sup>40</sup> It is useful in controlling arterial blood pressure in such patients with severe aortic stenosis or pregnant women with complex cardiac disease. In obstetrics, it may also be used in patients with morbid obesity and where previous spinal surgery may hinder epidural spread. Spinal catheters also serve as an alternative to the CSE technique for prolonged cases and have been used in selected patients for laparotomies where general anesthesia may be too great a risk.<sup>234</sup> If a continuous spinal anesthetic is undertaken, a needle with a laterally facing opening may be used to perform the lumbar puncture (Fig. 45.7). A midline or paramedian approach may be used, with some experts suggesting that use of the paramedian approach facilitates insertion of the catheter.<sup>235</sup> The catheter should be threaded 2 to 3 cm into the subarachnoid space and the needle withdrawn over the catheter. The catheter must never be withdrawn back into the needle shaft in case a piece of the catheter is sheared off and left in the subarachnoid space. Care must also be taken to ensure that the catheter is not inserted more deeply into the subarachnoid space when the needle is withdrawn over the catheter. Spinal

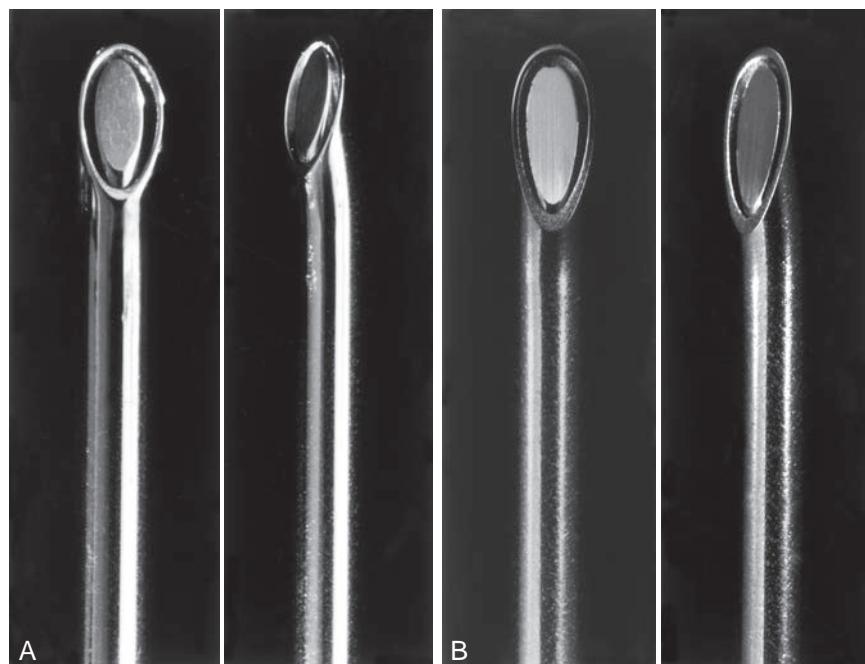
microcatheters exist, but these have been associated with cauda equina syndrome,<sup>5</sup> probably because of lumbosacral pooling of local anesthetic. Catheter-over-the-needle devices are also available for use with continuous spinal anesthesia, with the advantage of minimizing leakage of CSF around the catheter,<sup>236</sup> but these may be more difficult to insert.<sup>236</sup> Finally, epidural doses of local anesthetic should not be infused or “bloused” into spinal catheters, and strict attention must also be paid to sterile technique.

### Unilateral Spinal Anesthesia and Selective Spinal Anesthesia

The terms *unilateral spinal anesthesia* and *selective spinal anesthesia* overlap slightly, but both refer to small-dose techniques that capitalize on baricity and patient positioning to hasten recovery. A recent systematic review found that a dose of 4 to 5 mg of hyperbaric bupivacaine with unilateral positioning was adequate for knee arthroscopy.<sup>171</sup> This technique has also been used for unilateral inguinal hernia repair with a dose of 8 mg bupivacaine. In selective spinal anesthesia, minimal local anesthetic doses are used with the goal of anesthetizing only the sensory fibers to a specific area.<sup>237,238</sup> These doses are discussed in more detail in the chapter on anesthesia for ambulatory surgery (see Chapter 72).

## BLOCK MONITORING

Once the spinal anesthetic has been administered, the onset, extent, and quality of the sensory and motor blocks must be assessed while heart rate and arterial blood pressure are also being monitored for any resultant sympathetic blockade. There are many methods of assessing sensory block, but cold sensation and pinprick representing C- and A-delta fibers, respectively, are used more often than mechanical stimuli such



**Fig. 45.7** Examples of continuous spinal needles, including a disposable, 18-G Hustead (A) and a 17-G Tuohy (B) needle. Both have distal tips designed to direct the catheters inserted through the needles along the course of the bevel opening; 20-G epidural catheters are used with these particular needle sizes.

as touch, pressure, and von Frey hairs, which reflect the A-beta nerves. Loss of sensation to cold usually occurs first, verified using an ethyl chloride spray, ice, or alcohol, followed by the loss of sensation to pinprick, verified using a needle that does not pierce the skin.<sup>20</sup> Finally, loss of sensation to touch occurs. Dermatomal block height also varies with the method of assessment, but in general, peak height is measured most cephalad using loss of cold, and is measured lower with pinprick, and lowest with touch.<sup>239</sup> Assessing dermatomal block height assumes that absence of sensation to these stimuli equates to blockade of the nociceptive fibers, but this is not necessarily the case.<sup>240</sup> Other electrical and experimental chemical methods of assessing pain have been used but gentle pinprick remains the simplest.<sup>91,241</sup> Motor block may also be measured in a variety of ways. The modified Bromage scale (Box 45.1) is most commonly used, although this represents only lumbosacral motor fibers.<sup>242</sup> Electromyography and pulmonary function tests have been used to measure abdominal and thoracic motor function, but these are neither practical nor specific.

In practice, the combination of sympathetic block with an adequate sensory level and motor block (inability to straight-leg raise ensures at least that lumbar nerves are blocked) is used to confirm spinal efficacy. Ensuring that the level of block using cold or pinprick is two to three segments above the expected level of surgical stimulus is commonly considered adequate.

## Epidural Anesthesia

### FACTORS AFFECTING EPIDURAL BLOCK HEIGHT

The epidural space is a collapsible, distensible reservoir through which drugs spread and are removed by diffusion, vascular transport, and leakage. Spread of anesthetic within the epidural space, and subsequent block height, is related to a variety of factors, not all of which can be manipulated by the anesthesiologist (Table 45.5).<sup>26</sup>

#### BOX 45.1 Modified Bromage Scale

- 0: No motor block
- 1: Inability to raise extended leg; able to move knees and feet
- 2: Inability to raise extended leg and move knee; able to move feet
- 3: Complete block of motor limb

### Drug Factors

The volume and total mass of injectate are the most important drug-related factors that affect block height after the administration of local anesthetic in the epidural space. As a general principle, 1 to 2 mL of solution should be injected per segment to be blocked. Although additives such as bicarbonate, epinephrine, and opioids influence onset, quality, and duration of analgesia and anesthesia, these do not affect spread.

### Patient Factors

Age can influence epidural block height.<sup>26</sup> There appears to be a stronger correlation with age and block height in thoracic epidurals, with one study suggesting that 40% less volume is required in the elderly (see Chapter 65).<sup>243</sup> Possible reasons include decreased leakage of local anesthetic through intervertebral foramina, decreased compliance of the epidural space in the elderly resulting in greater spread, or an increased sensitivity of the nerves in the elderly. As with spinal anesthesia, it appears that only the extremes of patient height influence local anesthetic spread in the epidural space. Weight is not well correlated with block height in the settings of either lumbar or TEA.<sup>244</sup> Less local anesthetic is required to produce the same epidural spread of anesthesia in pregnant patients. Although this may be in part a result of engorgement of epidural veins secondary to increased abdominal pressure, the effect also occurs in early pregnancy.<sup>245</sup> Also, continuous positive airway pressure increases the height of a thoracic epidural block.<sup>246,247</sup>

### Procedure Factors

The level of injection is the most important procedure-related factor that affects epidural block height. In the upper cervical region, spread of injectate is mostly caudal, in the midthoracic region spread is equally cephalad and caudal, and in the low thoracic region spread is primarily cephalad.<sup>248</sup> After a lumbar epidural, spread is more cephalad than caudal. Some studies suggest that the total number of segments blocked is less in the lumbar region compared with thoracic levels for a given volume of injectate. Patient position has been shown to affect spread of lumbar epidural injections, with preferential spread and faster onset to the dependent side in the lateral decubitus position.<sup>249</sup> The sitting and supine positions do not affect epidural block height. However, the head-down tilt position does increase cephalad spread in obstetric patients.<sup>250</sup> Needle bevel direction

**TABLE 45.5** Factors Affecting Epidural Local Anesthetic Distribution and Block Height

	More Important	Less Important	Not Important
Drug factors	Volume Dose	Concentration	Additives
Patient factors	Elderly age Pregnancy	Weight Height Pressure in adjacent body cavities	
Procedure factors	Level of injection	Patient position	Speed of injection Needle orifice direction

Modified from Visser WA, Lee RA, Gielen MJ. Factors affecting the distribution of neural blockade by local anesthetics in epidural anesthesia and a comparison of lumbar versus thoracic epidural anesthesia. *Anesth Analg*. 2008;107:708–721.

and speed of injection also do not appear to influence the spread of a bolus injection.

## PHARMACOLOGY

Local anesthetics for epidural use may be classified into short-, intermediate-, and long-acting drugs. A single bolus dose of local anesthetic in the epidural space can provide surgical anesthesia ranging from 45 minutes up to 4 hours depending on the type of local anesthetic administered and the use of any additives (Table 45.6). Most commonly, an epidural catheter is left in situ so that local anesthetic-based anesthesia or regular analgesia can be extended indefinitely.

### Short-Acting and Intermediate-Acting Local Anesthetics

**Procaine.** Similar to spinal anesthesia, procaine is not commonly used for epidural anesthesia. Five-percent procaine has a slow onset and the resultant block can be unreliable and of poor quality.

**Chloroprocaine.** Chloroprocaine is available preservative-free in 2% and 3% concentrations for epidural injection, with the latter preferable for surgical anesthesia because the former may not produce muscle relaxation. The 3% preparation has an onset time of 10 to 15 minutes and a duration of up to 60 minutes. Adding epinephrine prolongs the block for up to 90 minutes. Before the development of preservative-free preparations, large volumes (>25 mL) of chloroprocaine had been associated with deep, aching, burning lumbar back pain.<sup>251</sup> This was thought to be secondary to the ethylenediaminetetraacetic acid that chelated calcium and caused a localized hypocalcemia. In addition, chloroprocaine can antagonize the effects of epidural morphine.<sup>242</sup> This may be a result of opioid receptor antagonism by either the chloroprocaine or a metabolite. Antagonism of an intracellular messenger and decreased morphine availability caused by a reduction in perineural pH are also proposed mechanisms. However, morphine and chloroprocaine seem like an illogical combination because the beneficial ultrashort duration of action of chloroprocaine is offset by the addition of morphine.

**Articaine.** Articaine is not widely used for epidural anesthesia and has not been studied extensively. When 2% articaine was compared with epidural lidocaine in one study, it had a similar latency, spread, duration, and motor block.<sup>252</sup> It has also been used for obstetric epidural analgesia.<sup>148</sup>

**Lidocaine.** Lidocaine is available in 1% and 2% solutions; it has an onset time of 10 to 15 minutes and a duration of up to 120 minutes, which can be extended to 180 minutes with the addition of epinephrine. Unlike spinal anesthesia, TNS are not commonly associated with epidural lidocaine.<sup>253</sup>

**Prilocaine.** Prilocaine is available in 2% and 3% solutions. The 2% solution produces a sensory block with minimal motor block. Onset time is approximately 15 minutes, with a duration of approximately 100 minutes. When compared with lidocaine, prilocaine has a more marked sensory blockade and a longer duration (different from Cousins).<sup>242</sup> In large doses, prilocaine is associated with methemoglobinemia.<sup>156,254</sup>

**Mepivacaine.** Mepivacaine is available as 1%, 1.5%, and 2% preservative-free solutions. The 2% preparation has an onset time similar to lidocaine of approximately 15 minutes, but a slightly longer duration (up to 200 minutes with epinephrine), making it a preferred option by some centers for surgery of an intermediate duration.

### Long-Acting Local Anesthetics

**Tetracaine.** Tetracaine is not widely used for epidural anesthesia because of unreliable block height and, in larger doses, systemic toxicity.

**Bupivacaine.** Bupivacaine is available in 0.25%, 0.5%, or 0.75% preservative-free solutions. The onset time is around 20 minutes with a duration of up to 225 minutes, which is prolonged only slightly by the addition of epinephrine (to 240 minutes). More dilute concentrations such as 0.125% to 0.25% can be used for analgesia. However, disadvantages include cardiac and central nervous system toxicity and the potential for motor block from larger doses. Solutions of 0.5% and 0.75% are used to provide surgical anesthesia.

**TABLE 45.6** Comparative Onset Times and Analgesic Durations of Local Anesthetics Administered Epidurally in 20- to 30-mL Volumes

Drug	Concentration (%)	Onset (min)	DURATION (MIN)	
			Plain	1:200,000 Epinephrine
2-Chloroprocaine	3	10-15	45-60	60-90
Lidocaine	2	15	80-120	120-180
Mepivacaine	2	15	90-140	140-200
Bupivacaine	0.5-0.75	20	165-225	180-240
Etidocaine	1	15	120-200	150-225
Ropivacaine	0.75-1.0	15-20	140-180	150-200
Levobupivacaine	0.5-0.75	15-20	150-225	150-240

Modified from Cousins MJ, Bromage PR. Epidural neural blockade. In: Cousins MJ, Bridenbaugh PO, eds. *Neural Blockade in Clinical Anesthesia and Management of Pain*. Philadelphia: JB Lippincott; 1988;255.

Liposomal bupivacaine is currently under investigation for epidural use. An epidural bolus of liposomal 0.5% bupivacaine provided similar onset but longer-lasting analgesia to boluses of plain bupivacaine.<sup>255</sup> It does not appear to be more toxic than plain bupivacaine or to have a differing cardiac safety profile. The benefit, as with extended-release morphine (discussed later), is the lack of need for an epidural catheter. Conversely, such extended-release boluses are less titratable if for any reason the epidural needs to be terminated early.

**Levobupivacaine.** Levobupivacaine can be used as an epidural local anesthetic in 0.5% to 0.75% concentrations for surgical anesthesia, whereas analgesia can be achieved with concentrations of 0.125% to 0.25%. Levobupivacaine administered epidurally has the same clinical characteristics as bupivacaine.<sup>129,256,257</sup> The advantage of levobupivacaine is that it is less cardiotoxic compared with bupivacaine.<sup>175,258</sup>

**Ropivacaine.** Ropivacaine is available in 0.2%, 0.5%, 0.75%, and 1.0% preservative-free preparations. For surgical anesthesia, 0.5% to 1.0% is used, whereas 0.1% to 0.2% is used for analgesia. Ropivacaine is associated with a superior safety profile compared with bupivacaine.<sup>259,260</sup> Data from animal models suggest that bupivacaine has a 1.5 to 2.5 lower seizure threshold than ropivacaine. Ropivacaine is also less cardiotoxic. When compared with bupivacaine and levobupivacaine, ropivacaine at equivalent concentrations has a relatively similar clinical profile. Ropivacaine has a slightly shorter duration of action and less motor block, although the reduced motor block may in fact reflect different potencies of the drugs rather than a true motor-sparing effect of ropivacaine. Epidurally administered ropivacaine is 40% less potent than bupivacaine.<sup>179,180,261</sup>

### Epidural Additives

**Vasoconstrictors.** Epinephrine reduces vascular absorption of local anesthetics in the epidural space. The local anesthetics vary in their responsiveness to epinephrine. The effect is the most with lidocaine,<sup>262</sup> mepivacaine, and chloroprocaine (up to 50% prolongation), with a lesser effect with bupivacaine, levobupivacaine, and etidocaine, and a limited effect with ropivacaine, which already has intrinsic vasoconstrictive properties (see Table 45.6). Epinephrine itself may also have some analgesic benefits because it is absorbed into the CSF, where it can act on dorsal horn  $\alpha_2$  receptors.<sup>263</sup> Phenylephrine has been used in epidural anesthesia less widely than in spinal anesthesia, perhaps because it does not reduce peak blood levels of local anesthetic as effectively as epinephrine does during epidural use.<sup>264</sup>

**Opioids.** Opioids synergistically enhance the analgesic effects of epidural local anesthetics, without prolonging motor block. A combination of local anesthetic and opioid reduces the dose-related adverse effects of each drug independently. The analgesic benefits of neuraxial opioids must be balanced against the dose-dependent side effects. As with intrathecal opioids, there appears to be a therapeutic ceiling effect above which only side effects increase. Opioids

may also be used alone, particularly when there are concerns regarding hemodynamic instability. Epidural opioids work by crossing the dura and arachnoid membrane to reach the CSF and spinal cord dorsal horn. Lipophilic opioids, such as fentanyl and sufentanil, partition into epidural fat and therefore are found in lower concentrations in CSF than hydrophilic opioids, such as morphine and hydromorphone. Fentanyl and sufentanil are also readily absorbed into the systemic circulation, and several studies suggest that this is the principal analgesic mechanism.<sup>265,266</sup>

Epidural morphine is administered as a bolus of 1 to 5 mg, with an onset time of 30 to 60 minutes and duration of up to 24 hours. The optimal dose that balances analgesia while minimizing side effects is 2.5 to 3.75 mg.<sup>267</sup> Alternatively, morphine can be administered continuously in doses of 0.1 to 0.4 mg/h through an epidural catheter. Hydromorphone is more hydrophilic than fentanyl but more lipophilic than morphine. It can be administered as a bolus of 0.4 to 1.5 mg, with onset at 15 to 30 minutes and a duration of 18 hours. Hydromorphone used as an infusion is delivered at rates between 5 and 20  $\mu$ g/h. The onset of epidural fentanyl and sufentanil is 5 to 15 minutes and lasts only 2 to 3 hours. Bolus doses of 10 to 100  $\mu$ g may be used to provide analgesia. Diamorphine is available in the United Kingdom and used in doses of 2 to 3 mg as epidural boluses, or approximately 0.05 mg/mL in an infusion.

DepoDur is an extended-release liposomal formulation of morphine used as a single-shot lumbar epidural dose, thereby avoiding issues and side effects of a continuous local anesthetic infusion and indwelling catheters, particularly in patients receiving anticoagulants. When administered before surgery (or after clamping of the cord in cesarean deliveries), DepoDur can provide up to 48 hours of pain relief.<sup>268,269</sup> A dose of 10 to 15 mg is recommended for lower abdominal surgery, and 15 mg is recommended for major lower limb orthopedic surgery.

**$\alpha_2$ -Agonists.** Epidural clonidine can prolong sensory block to a greater extent than motor block. The mechanism appears to be mediated by the opening of potassium channels and subsequent membrane hyperpolarization<sup>270</sup> rather than an  $\alpha_2$ -agonist effect. The addition of clonidine reduces both epidural local anesthetic and opioid requirements.<sup>271-273</sup> Other benefits of clonidine may include a reduced immune stress and cytokine response.<sup>274</sup> Epidural clonidine does have a variety of side effects including hypotension, bradycardia, dry mouth, and sedation. The cardiovascular effects may be greatest when clonidine is administered in the epidural space at the thoracic level.<sup>275</sup> In preliminary studies, epidural dexmedetomidine has also been shown to reduce intraoperative anesthetic requirements, improve postoperative analgesia, and prolong both sensory and motor block.<sup>276</sup>

**Other Drugs.** Conflicting reports exist regarding the benefit of epidural ketamine and whether it is neurotoxic.<sup>277-279</sup> Epidural neostigmine provides labor analgesia before local anesthetic infusion without causing respiratory depression, hypotension, or motor impairment.<sup>280</sup> Midazolam, tramadol, dexamethasone, and droperidol have also been studied but are not commonly used.

**Carbonation and Bicarbonate.** Many local anesthetic preparations have a pH between 3.5 and 5.5 for chemical stability and bacteriostasis. At these low pHs, a higher proportion of the drug is in the ionized form and is therefore unable to cross nerve membranes to reach the internal binding site on sodium channels. Both carbonation of the solution and adding bicarbonate have been used in an attempt to increase the solution pH, and therefore the non-ionized free-base proportion of local anesthetic. Although carbonation may theoretically increase the speed of onset and quality of the block by producing more rapid intraneuronal diffusion and more rapid penetration of connective tissue surrounding the nerve trunk,<sup>281,282</sup> available data suggest that there are no clinical advantages for carbonated solutions.<sup>235,283</sup>

## EPIDURAL TECHNIQUE

### Preparation

Patient preparation as previously described for spinal anesthesia must equally be applied to epidural anesthesia, namely consent, monitoring, and resuscitation equipment, intravenous access, and choosing the patient and drugs appropriately depending on comorbidities and the nature of surgery. Sterility is arguably even more important than spinal anesthesia because a catheter is often left in situ. The extent of the surgical field must be understood so that the epidural may be inserted at the appropriate level—that is, the lumbar, low-, mid-, or high-thoracic, or less commonly, cervical.<sup>26</sup> A variety of epidural needles have been used for epidural anesthesia, but Tuohy needles are most common (Fig. 45.8). These needles are usually 16- to 18-g in size and have a 15- to 30-degree curved, blunt “Huber” tip designed to both reduce the risk of accidental dural puncture and guide the catheter cephalad. The needle shaft is marked in 1-cm intervals so that depth of insertion can be identified. The catheter is made of a flexible, calibrated, durable, radiopaque plastic with either a single end hole or multiple side orifices near the tip. Several investigators have found that multiple-orifice catheters are superior, with a reduced incidence of inadequate analgesia.<sup>284-286</sup> However, the use of multiorifice catheters in pregnant women resulted in a more frequent incidence of epidural vein cannulation.<sup>287</sup>

The method of identifying the epidural space must also be predetermined. Most practitioners use a loss-of-resistance technique to either air or saline, rather than the hanging drop technique, both of which are described later. If a loss-of-resistance technique is used, an additional decision about the type of syringe (i.e., glass vs. low-resistance plastic and Luer-Lok vs. friction hub) is required.

### Position

The sitting and lateral decubitus positions necessary for epidural puncture are the same as those for spinal anesthesia (see also Chapter 62). As before, inadequate positioning of the patient can complicate an otherwise meticulous technique. Shorter insertion times occur in the sitting position for thoracic epidurals compared with the lateral decubitus position, but ultimately, success rates are comparable.<sup>288</sup> As with spinal anesthesia, epidurals are performed with the patient awake.<sup>76</sup>

### Projection and Puncture

The level of needle insertion depends on the location of surgery (Table 45.7). Important surface landmarks include the intercrisal line (corresponding to the L4-L5 interspace), the inferior angle of the scapula (corresponding to the T7 vertebral body), the root of the scapular spine (T3), and the vertebra prominens (C7). Ultrasonography may be useful to identify the correct thoracic space<sup>233</sup>; it is less commonly used for thoracic epidural insertion, however, because the acoustic shadows make visualization of landmarks such as the ligamentum flavum and intrathecal space more difficult.<sup>289</sup> A variety of different needle approaches exist: midline, paramedian, modified paramedian (Taylor approach), and caudal.

A midline approach is commonly chosen for lumbar and low thoracic approaches. After local anesthetic infiltration of the skin, the nondominant hand can be rested on the back of the patient, with the thumb and index finger holding the needle hub or wing. The angle of approach should be only slightly cephalad in the lumbar and low-thoracic regions, whereas in the midthoracic region, the approach should be more cephalad because of the significant downward angulation of the spinous processes (Fig. 45.9). In a controlled fashion, the needle should be advanced with the stylet in place through the supraspinous ligament and into the interspinous ligament, at which point the stylet can be removed and the syringe attached. If it is in the correct location, the needle should rest firmly in the tissues. Some advocate needle placement in the ligamentum flavum for both the loss-of-resistance and hanging-drop methods before attaching the syringe, but this may be difficult, particularly for novices; however, this may allow an improved appreciation of epidural anatomy for the operator. If the needle is merely inserted into the supraspinous ligament and then loss-of-resistance or hanging-drop insertion is begun, there is an increased chance of false loss-of-resistance, possibly because of defects in the interspinous ligament.<sup>290</sup> Such false-positive rates can be as high as 30%.

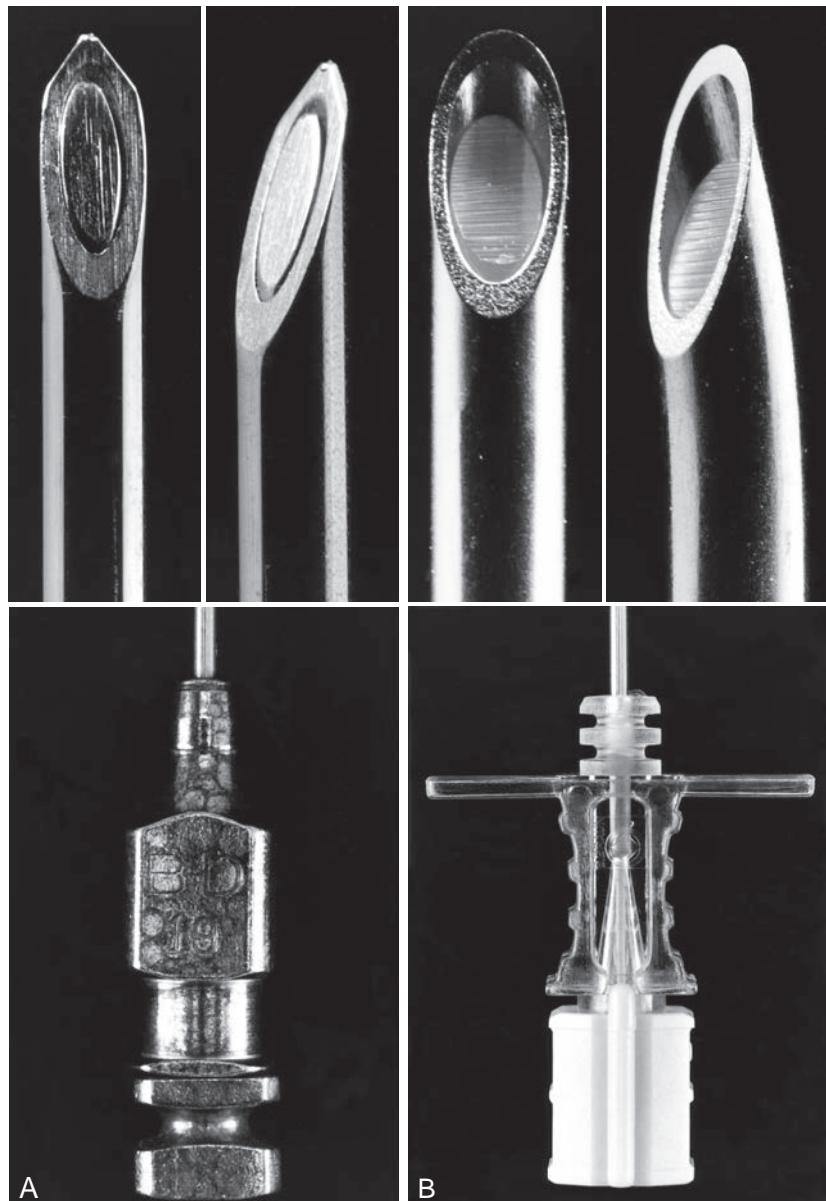
Air or saline are the two most common noncompressible media used to detect a loss-of-resistance when identifying the epidural space. Each involves intermittent (for air) or constant (for saline) gentle pressure applied to the bulb of the syringe with the dominant thumb while the needle is advanced with the nondominant hand. A combination of air and saline may also be used, incorporating 2 mL of saline and a small (0.25 mL) air bubble. Usually the ligamentum flavum is identified as a tougher structure with increased resistance, and when the epidural space is subsequently entered, the pressure applied to the syringe plunger allows the solution to flow without resistance into the epidural space. There are reports that air is less reliable in identifying the epidural space, results in a higher chance of incomplete block, and may also cause both pneumocephalus (which can result in headaches) and venous air embolism in rare cases. If air is chosen, the amount of air injected after loss-of-resistance should therefore be minimized. Evidence suggests that there is no difference in adverse outcome in the obstetric population when air or saline is used.<sup>291</sup> Another meta-analysis found that fluid inserted through the epidural needle

before catheter insertion reduces the risk of epidural vein cannulation by the catheter.<sup>287</sup> One proposed disadvantage of using saline is that it may be more difficult to readily detect an accidental dural puncture.

An alternative method of identifying the epidural space is the hanging-drop technique. After the needle is placed into the ligamentum flavum, a drop of solution such as saline is placed within the hub of the needle. When the needle is advanced into the epidural space, the solution should be “sucked in.” The theory behind this maneuver has traditionally been attributed to subatmospheric pressure in the epidural space, although recent experimental evidence in the cervical region suggests that using negative-pressure methods are poorly reliable and only useful in the sitting position.<sup>292</sup> The subatmospheric pressure has been related to expansion of the epidural space

as the needle pushes the dura away from the ligamentum flavum.<sup>293</sup> The negative intrathoracic pressure may influence the pressure in the epidural space in the thoracic region and should be maximal during inspiration. Timing needle advancement to coincide with inspiration may be difficult, however.

When a lumbar midline approach is used, the depth from skin to the ligamentum flavum commonly reaches 4 cm, with the depth in most (80%) patients being between 3.5 and 6 cm; it can be longer or shorter in obese or very thin patients, respectively. Ultrasonography may be useful to predict the depth before needle insertion.<sup>233</sup> In the lumbar region, the ligamentum flavum is 5 to 6 mm thick in the midline. When a thoracic approach is chosen, needle control is of equal or greater importance because injury to the spinal cord is possible if the needle is advanced too far,



**Fig. 45.8** Epidural needles with catheter assortment. (A) A 19-G reusable Crawford epidural needle. (B) A 19-G disposable Tuohy needle. (C) Single-end-hole epidural catheter. (D) Closed-tip, multiple-side-hole catheter. (E) Spring wire-reinforced, polymer-coated epidural catheter.

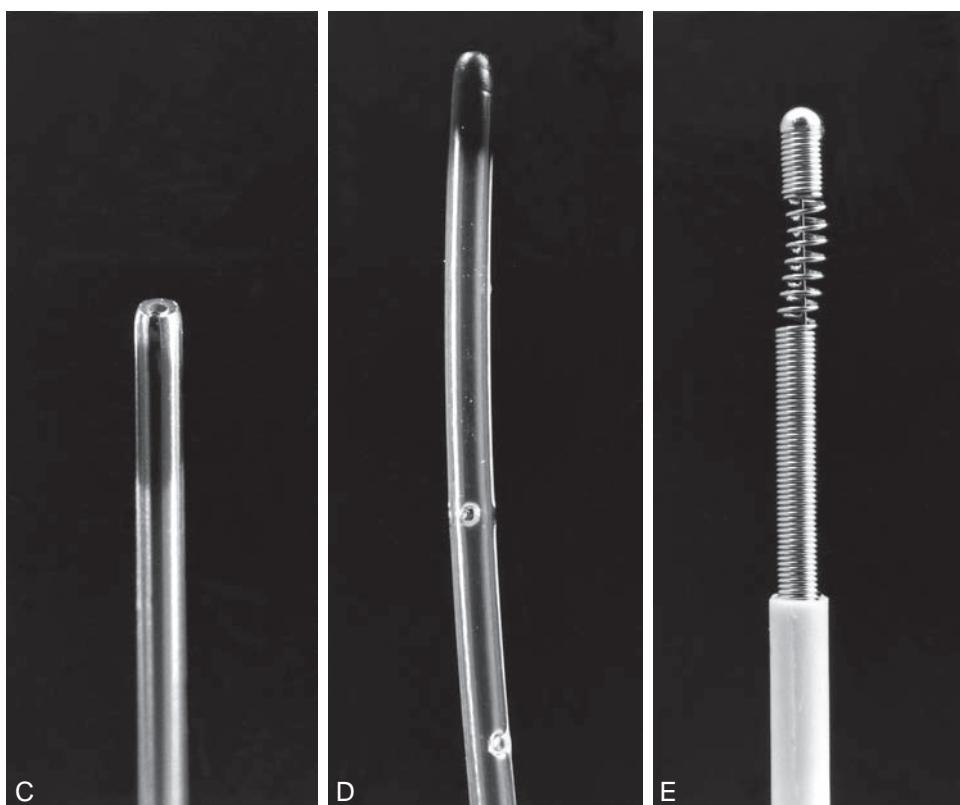


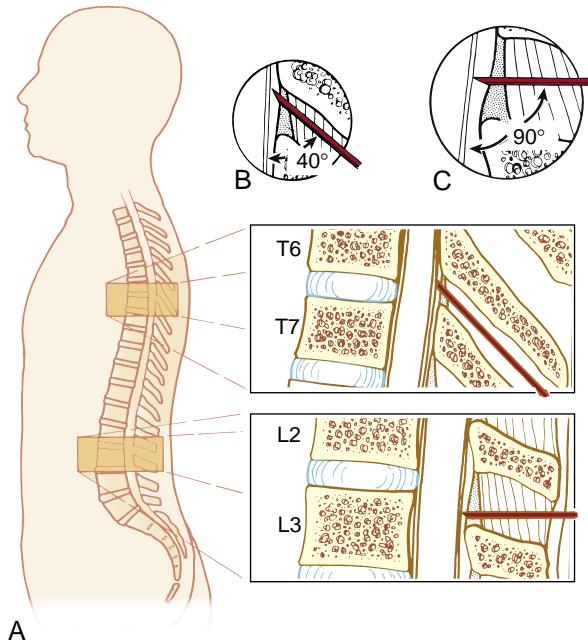
Fig. 45.8, cont'd

**TABLE 45.7** Suggested Epidural Insertion Sites for Common Surgical Procedures

Nature of Surgery	Suggested Level of Insertion	Remarks
Hip surgery	Lumbar L2-L5	
Lower extremity		
Obstetric analgesia		
Colectomy, anterior resection	Lower thoracic T6-T8	Spread more cranial than caudal
Upper abdominal surgery		
Thoracic	T2-T6	Midpoint of surgical incision

Modified from Visser WA, Lee RA, Gielen MJ. Factors affecting the distribution of neural blockade by local anesthetics in epidural anesthesia and a comparison of lumbar versus thoracic epidural anesthesia. *Anesth Analg*. 2008;107:708-721.

although there are no data to suggest that approaching the epidural space at the lumbar level is any more or less safe than at the thoracic level. This may be partly because those using the thoracic technique are most often anesthesiologists with considerable experience in lumbar epidural anesthesia.<sup>294</sup> In addition, the increased angle of needle insertion in the thoracic region may theoretically provide an element of safety in that the more acute angle necessary to gain access to the epidural space provides some margin of safety (see Fig. 45.9).



**Fig. 45.9** (A) Lumbar and thoracic epidural technique. The increased angle of needle insertion during thoracic epidural cannulation may provide a slightly longer distance of "needle travel" before entering the subarachnoid space. In contrast to lumbar epidural cannulation (B), the distance traveled is modified by a more perpendicular angle of needle insertion (C).

When the epidural space is identified, the depth of the needle at the skin should be noted. The syringe can then be removed and a catheter gently threaded to approximately the 15- to 18-cm mark to ensure a sufficient length has entered the epidural space. The needle can then be carefully withdrawn, and the catheter is withdrawn to leave 4 to 6 cm in the space. Catheter space less than 4 cm in length in the epidural space may increase the risk of catheter dislodgement and inadequate analgesia, whereas threading more catheter may increase the likelihood of catheter malposition or complications.<sup>295-298</sup>

As described earlier, a false loss-of-resistance can occur and is one of the causes of a failed block. The Tsui test may be used to confirm the epidural catheter position.<sup>299</sup> This test stimulates the spinal nerve roots with a low electrical current conducted through normal saline in the epidural space and an electrically conducting catheter. A metal-containing catheter must be used, with the cathode lead of the nerve stimulator connected to the catheter via an electrode adapter, whereas the anode lead is connected to an electrode on the patient's skin. At currents of approximately 1 to 10 mA, corresponding muscle twitches (i.e., intercostal or abdominal wall muscles for thoracic epidural catheters) can be used to identify catheter tip location. Subarachnoid and subdurally positioned epidural catheters elicit motor responses at a much lower threshold current (<1 mA), because the stimulating catheter is in very close or direct contact with highly conductive CSF.<sup>300,301</sup>

When the catheter is positioned at the desired depth, it must be secured to the skin. Commercial fixation devices exist, and some are superior to tape alone.<sup>302</sup> Tunneling can reduce catheter migration and improve lasting block success.<sup>303</sup> However, tunneling has not been compared with noninvasive catheter fixation devices in a well-designed study.

### Paramedian Approach

The paramedian approach is particularly useful in the mid- to high-thoracic region, where the angulation of the spine and the narrow spaces render the midline approach problematic. The needle should be inserted 1 to 2 cm lateral to the inferior tip of the spinous process corresponding to the vertebra above the desired interspace. The needle is then advanced horizontally until the lamina is reached and then redirected medially and cephalad to enter the epidural space. The Taylor approach is a modified paramedian approach via the L5-S1 interspace, which may be useful in trauma patients who cannot tolerate or are not able to maintain a sitting position. The needle is inserted 1 cm medial and 1 cm inferior to the posterior superior iliac spine and is angled medially and cephalad at a 45- to 55-degree angle.

Before initiating an epidural local anesthetic infusion, a test dose may be administered. The purpose of this is to exclude intrathecal or intravascular catheter placement. A small volume of lidocaine 1.5% with epinephrine is traditionally used for this purpose. A recent systematic review found reasonable evidence that 10 to 15 µg of epinephrine alone in nonpregnant adult patients was the best pharmacologic method of detecting intravascular placement, using endpoints of an increase in systolic blood pressure more

than 15 mm Hg or an increase in heart rate more than 10 beats/min. The optimal method of detecting intrathecal or subdural placement, however, could not be ascertained.<sup>304</sup>

## Combined Spinal-Epidural

CSE anesthesia was first described in 1937 but has subsequently been modified over the past 30 years<sup>305-310</sup> and the CSE technique is now seeing increasing popularity. A CSE allows flexibility in a number of clinical settings because the more rapid onset of spinal block compared with epidural anesthesia allows the operative procedure to begin earlier, whereas the epidural catheter still provides both effective postoperative analgesia and allows anesthesia to be extended as the spinal resolves. This is particularly useful during labor, where opioid and a small dose of local anesthetic may be injected through a small spinal needle to provide rapid analgesia, whereas the epidural catheter can be used thereafter for both analgesia and surgical anesthesia if an operative delivery becomes necessary. Another significant advantage of CSE in general is the ability to use a low dose of intrathecal local anesthetic, with the knowledge that the epidural catheter may be used to extend the block if necessary. The addition of either local anesthetic or saline alone to the epidural space via the catheter compresses the dural sac and increases the block height. This latter technique is called epidural volume extension (EVE) and has been shown in cesarean delivery to provide a comparable sensory block to larger doses of intrathecal local anesthetic (with no EVE) but with significantly faster motor recovery.<sup>311</sup> The principle of using a lower dose of spinal anesthetic and titrating the epidural dose after the spinal anesthetic to reach the appropriate block height is a reduction in side effects<sup>312</sup> with faster recovery, which can in turn potentially hasten discharge. This sequential technique also provides greater hemodynamic stability for high-risk patients using a lower initial mass of drug for spinal anesthetic, with subsequent gradual extension of the block if necessary using the epidural.

### TECHNIQUE

The CSE technique most commonly involves placement of the epidural needle first, followed by either a "needle through needle" technique to reach the subarachnoid space or an altogether separate spinal needle insertion at either the same or different interspace. Some but not all studies have demonstrated greater success and lower failure rates with the separate needle insertion technique.<sup>313-316</sup> This method has the potential advantage of being able to confirm that the epidural catheter is functional before spinal anesthesia is administered, which, although it is time consuming, may be advantageous if the epidural catheter is to be relied upon for anesthesia when the spinal component resolves. Conversely, this method theoretically risks shearing the epidural catheter that is already in situ. If a needle-through-needle technique is chosen, special CSE kits are available with long spinal needles, some of which can be locked in place for the subarachnoid injection.

## Caudal Anesthesia

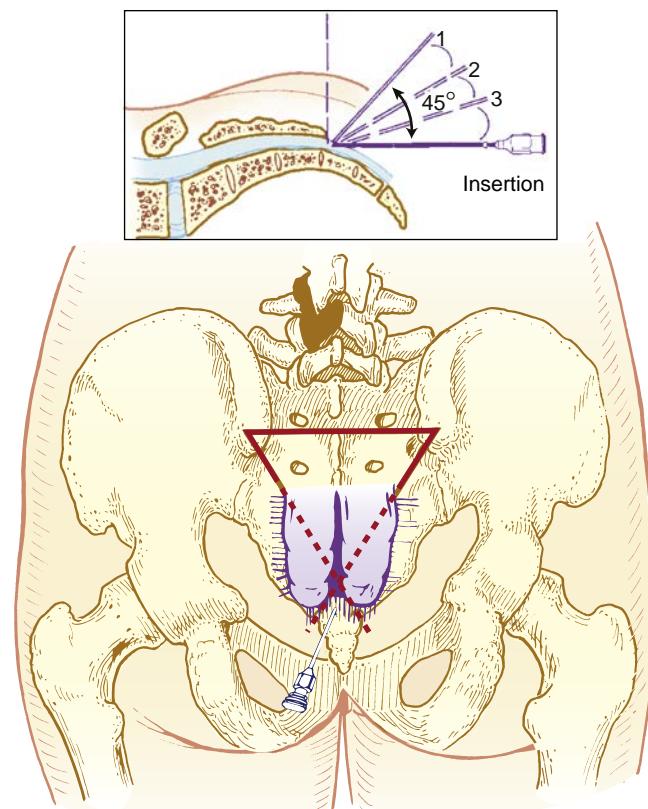
Caudal anesthesia is popular in pediatric anesthesia (see [Chapter 77](#)), but the technique also can be used in adults, although it is unpredictable when upper abdominal or thoracic spread is required. Its indications in adults therefore are essentially the same as those for lumbar epidural anesthesia, although it may be particularly useful when sacral anesthetic spread is desired (e.g., perineal, anal, rectal procedures), where a spinal surgery scar may prevent a lumbar anesthetic technique and, more commonly, in chronic pain and cancer pain management (see [Chapter 51](#)). The use of fluoroscopic guidance and, more recently, ultrasonography can help guide correct needle placement and reduce the rate of a failed block.<sup>317</sup> Ultrasonography is of even greater benefit in children because the lack of bony ossification allows visualization of both local anesthetic spread and the position of caudal epidural catheters.<sup>318,319</sup>

### PHARMACOLOGY

The local anesthetics used are similar to those described for epidural anesthesia and analgesia. However, in adults approximately twice the lumbar epidural dose is required to achieve a similar block with the caudal approach. The spread is also variable, making this technique in adults unreliable for procedures above the umbilicus.

### TECHNIQUE

Patient preparation as described before for spinal and epidural anesthesia must be equally applied to caudal anesthesia, namely consent, monitoring and resuscitation equipment, intravenous access, and the same asepsis precautions. Caudal anesthesia requires identification of the sacral hiatus. The sacrococcygeal ligament (i.e., extension of ligamentum flavum) overlies the sacral hiatus between the two sacral cornua. To facilitate locating the cornua, the posterior superior iliac spines should be located and, by using the line between them as one side of an equilateral triangle, the location of the sacral hiatus should be approximated ([Fig. 45.10](#)). Ultrasonography can also be used to identify these landmarks,<sup>317-319</sup> as can fluoroscopy. Three positions (see [Chapter 34](#)) are available for caudal anesthesia, with the prone position most often chosen in adults, the lateral decubitus position most chosen in children, and the knee-chest position the most infrequently used. The lateral decubitus position is used in children because it is easier to maintain a patent airway in this position than in the prone position, and the landmarks are more easily palpable than they are in adults (see [Chapter 76](#)). This consideration is valuable because caudal anesthesia is often combined with general anesthesia in pediatric patients to decrease the amount of volatile agent used intraoperatively or to provide postoperative analgesia. In contrast, a caudal block is often administered during preoperative sedation in adults and when the prone position is applicable. When placing a patient in the prone position, a pillow should be inserted beneath the iliac crests to rotate the pelvis and make cannulation of the caudal canal easier. An additional aid is to spread the lower extremities about 20 degrees with the heels rotated



**Fig. 45.10** Caudal technique. Palpating fingers locate the sacral cornua by using the equilateral triangle. Needle insertion is completed by insertion and withdrawal in a stepwise fashion (*inset*, so-called 1-2-3 insertion) until the needle can be advanced into the caudal canal and the solution can be injected easily (without creation of a subcutaneous “lump” of fluid).

laterally, which minimizes gluteal muscle contraction and eases needle insertion.

After the sacral hiatus is identified, the index and middle fingers of the palpating hand are placed on the sacral cornua, and after local infiltration, the caudal needle (or Tuohy needle if a catheter is to be placed) is inserted at an angle of approximately 45 degrees to the sacrum. While the needle is advanced, a decrease in resistance to needle insertion should be appreciated as the needle enters the caudal canal. The needle is advanced until bone (i.e., the dorsal aspect of the ventral plate of the sacrum) is contacted and then is slightly withdrawn, and the needle is redirected so that the angle of insertion relative to the skin surface is decreased. In male patients, this angle is almost parallel to the coronal plane; in female patients, a slightly steeper angle (15 degrees) is necessary. During redirection of the needle, loss-of-resistance is sought to confirm entry into the epidural space, and the needle advanced no more than approximately 1 to 2 cm into the caudal canal. In adults, the tip should never be advanced beyond the S2 level (approximately 1 cm inferior to the posterior superior iliac spine), which is the level to which the dural sac extends. Additional advancement of the needle increases the risk of dural puncture, and unintentional intravascular cannulation becomes more likely. One method of increasing the likelihood of correct caudal needle placement is to inject 5 mL of saline rapidly