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18.18

Disorders of the thoracic cage and diaphragm

John M. Shneerson and Michael I. Polkey

ESSENTIALS

Disorders of the thoracic skeleton can lead to a severe restrictive ventilatory defect, the risk of respiratory failure being highest with (1) scoliosis—particularly if the following characteristics are present: early onset, severe angulation, high in the thorax, respiratory muscle weakness, low vital capacity; (2) kyphosis—but only if of very sharp angulation (gibbus), most commonly seen following tuberculous osteomyelitis; and (3) after thoracoplasty—historically performed as treatment for pulmonary tuberculosis. While not a disorder of the skeleton, a similar pathophysiological pattern is seen in extreme obesity, and this is the fastest growing cause of referral to home ventilation centres

Diaphragmatic weakness—unilateral paralysis rarely causes symptoms unless there is coexisting lung disease or weakness of other respiratory muscles. Bilateral paralysis usually presents as orthopnoea, which (by contrast to orthopnoea in cardiac failure) is relieved promptly by sitting up, and on examination the abdomen moves paradoxically inwards as the diaphragm ascends during inspiration. Vital capacity in the sitting position is about 50% of that predicted and may fall by a further 50% when supine. Diaphragmatic screening or ultrasound examination may reveal paradoxical diaphragmatic movement during sniffing.

Respiratory failure—this occurs initially during sleep, when the normal sleep related reduction in respiratory drive is insufficient to overcome the work of breathing, and then in wakefulness. Pulmonary hypertension and right heart failure often develop once the arterial Pco2 is elevated during the day. Arterial blood gases and quality of life can both be readily improved with noninvasive ventilation, usually using a nasal or face mask. Survival in most skeletal disorders after starting ventilation is around 80 to 90% at 1 year, 75% at 3 years and 50% at 5 to 10 years.

Other clinical features—some conditions of the thoracic cage, particularly pectus excavatum and the straight back syndrome, can cause cardiac problems due primarily to distortion of the heart and major vessels. Ankylosing spondylitis leads to apical bullae, pleural thickening/effusions, and cricoarytenoid arthritis, but rarely causes respiratory failure in the absence of other comorbidities.

Introduction

Skeletal disorders of the thorax are an important group of conditions that frequently impair ventilation. They are often associated with respiratory muscle weakness due to neuromuscular disorders, which are described elsewhere. Most of these conditions restrict the development and/or the expansion of the lungs so that alveolar ventilation rather than intrapulmonary gas exchange is primarily impaired.

Disorders of the spine

Scoliosis

Scoliosis is defined as a lateral curvature of the spine, but it is invariably also associated with rotation of the vertebral bodies (Fig. 18.18.1). This results in an unstable lordosis rather than a

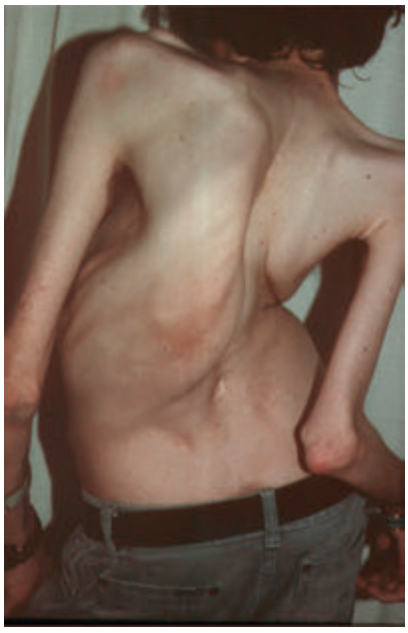

Fig. 18.18.1 Scoliosis following poliomyelitis.

Box 18.18.1 Causes of scoliosis

- Idiopathic
  - Infantile, adolescent
- Osteopathic
  - Congenital (e.g. hemivertebrae)
  - Thoracoplasty
- Neuromuscular (examples that follow are not an exhaustive list)
  - Syringomyelia
  - Friedreich's ataxia
  - Poliomyelitis
  - Duchenne's muscular dystrophy
- Connective tissue disorders
  - Marfan's syndrome
  - Neurofibromatosis
  - Osteogenesis imperfecta
- Pleuropulmonary
  - Empyema
  - Pneumonectomy
  - Unilateral lung fibrosis
- Complex surgery (e.g. cardiac) as an infant

kyphosis, and hence the frequently used term kyphoscoliosis is inaccurate. A mild degree of scoliosis is very common. Angles of curvature of 5° or 10° have been used to define when it becomes pathological, but these are arbitrary figures. Postural scoliosis can be distinguished from a structural scoliosis by its temporary nature and because it disappears on bending forward.

The age of onset and natural history of scoliosis vary according to its cause (Box 18.18.1). When it is due to a neuromuscular disorder ('paralytic' scoliosis) it usually arises during childhood or adolescence, or in poliomyelitis within about 2 years of the acute infection. Typically, the curve has a long C shape and may be severe. The scoliosis is due to asymmetrical weakness of the axial muscles causing the spine to rotate and move to one side. Weakness of chest wall muscles is almost invariable, occurs in a pattern which is characteristic of each disorder, and may have a profound influence on the clinical features.

When the scoliosis is due to a congenital abnormality, such as a hemivertebra or a segmentation defect, it usually becomes apparent early in childhood. The scoliosis of neurofibromatosis and Marfan syndrome is probably due to an abnormality of connective tissue. Scoliosis due to pleural or pulmonary disease is less common than in the past, now that chronic infections are less frequent and more successfully treated.

The commonest type is adolescent idiopathic scoliosis, where the spinal deformity develops at the time of the pubertal growth spurt. It is around four times as common in girls as in boys, and the convexity of the deformity is on the right in 80% of cases. The scoliosis may continue to worsen slightly even after growth of the spine stops. An infantile form of idiopathic scoliosis is less common and can progress to a severe deformity, although it may resolve spontaneously.

Pathophysiology

Scoliosis causes the compliance of the chest wall to be reduced, meaning that the generation of a specific amount of negative intrathoracic pressure results in less inspiratory airflow. This problem may be compounded by mechanical problems so that tension generation in the respiratory muscles does not fully translate to negative intrathoracic pressure and by associated respiratory muscle weakness (Fig. 18.18.2). Reduced compliance becomes more marked in older people, possibly owing to degenerative changes in the costovertebral joints. The compliance of the lungs is also reduced, largely because they are at the lower end of the pressure volume curve. In addition, the distortion of the ribcage puts

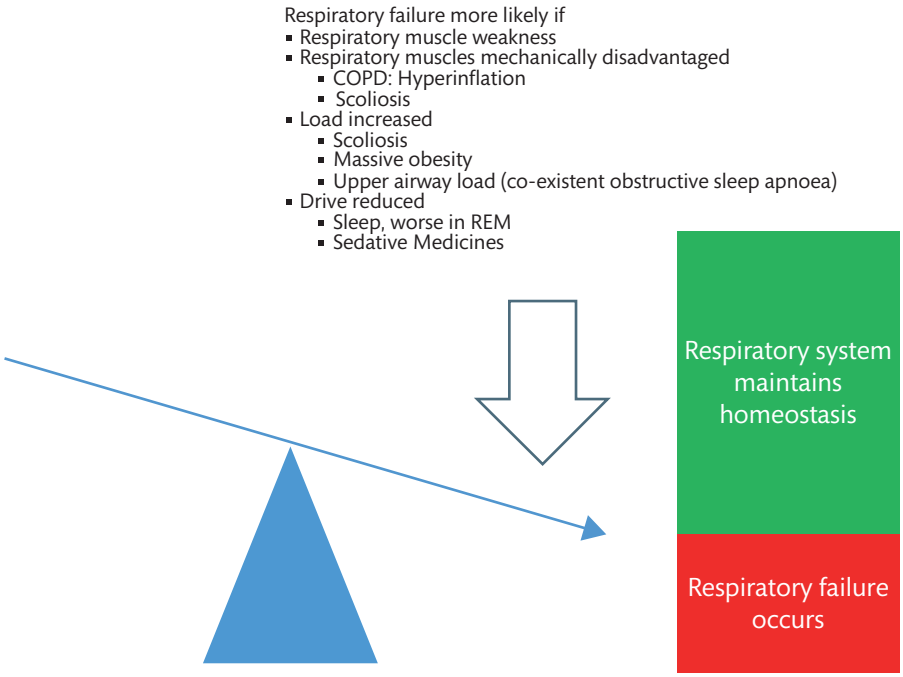

Fig. 18.18.2 Factors leading to respiratory failure in scoliosis and other disorders.

the inspiratory muscles at a mechanical disadvantage; those on the side of the convexity of the scoliosis are shortened and those on the side of the concavity lengthened. A restrictive defect and reduction of the maximum inspiratory and expiratory pressures develops even in the absence of any muscle weakness, but is more marked if this is present.

In adults with severe scoliosis, exercise capacity is linked to the degree of reduction of the vital capacity and the forced expiratory volume in 1 s (FEV_1). On exercise the tidal volume increases initially and then remains constant, while respiratory rate rises as exercise becomes more intense. Ventilation at any given oxygen uptake is greater than normal, and maximal exercise ventilation, which limits exercise capability, is often severely curtailed. The cardiac output may increase normally during exercise, but pulmonary artery pressure rises rapidly, and its rate of increase is linearly related to oxygen uptake and inversely related to the vital capacity.

In mild scoliosis, the arterial blood gases are often normal, but the first abnormality is a fall in the partial pressure of oxygen (P_{O_2}). This is due to suboptimal ventilation and perfusion matching, particularly at the bases of the lungs. Even when the anatomical distortion of the two lungs is gross, there is usually rather less difference in function between the two lungs than might be expected.

Effect of sleep

Acute ventilatory failure may be precipitated by an intercurrent episode (e.g. a chest infection or administration of an anaesthetic for other reasons), but chronic hypoventilation initially occurs during rapid eye movement sleep. Sleep is associated with loss of the voluntary respiratory drive and a reduction in the reflex drive in response to hypoxia, hypercapnia, and other stimuli. Within each stage of nonrapid eye movement (NREM) sleep the respiratory pattern is regular, but it varies as NREM sleep moves from one stage to another. Central apnoeas may appear and the arterial P_{CO_2} rises slightly despite a reduction in metabolic rate. However in rapid eye movement (REM) sleep particularly the respiratory drive to non-diaphragmatic muscles, and thus to the respiratory muscles overall, is less than during NREM sleep, and it is much more variable from moment to moment. Muscle activity is reduced, and whereas in NREM sleep this affects all the respiratory muscles to an equal extent, in REM sleep diaphragmatic activity is selectively retained. Moreover, loss of activity in the upper airway dilator muscles increases the upper airway resistance and the work of the chest wall muscles.

These changes during sleep are particularly important in scoliosis, where the diaphragm is attached to an asymmetrical ribcage and the respiratory pump often has little reserve. The effects of sleep are accentuated when the scoliosis is the result of neuromuscular disorders because the presence of muscle weakness in addition to the skeletal deformity reduces tidal volume and increases respiratory frequency, leading to alveolar hypoventilation. Arousals initially occur in REM sleep, which becomes fragmented, and at a later stage in NREM sleep, with loss particularly of slow wave sleep (stage 3). Sleep fragmentation itself reduces the respiratory drive promoting a vicious circle in which there are progressively more respiratory-induced arousals and deterioration in respiratory drive. Central apnoeas and hypopnoeas develop; hypercapnia then appears during wakefulness as well as in sleep.

Risk factors for respiratory failure

Chronic hypercapnia during the day is uncommon in childhood and is influenced in patients with scoliosis by the following:

- Age of onset—if the scoliosis appears before the age of about 8 years it may prevent normal alveolar multiplication so that the lungs fail to develop fully. The capillary surface area is reduced and there is an increased risk of developing respiratory and right heart failure later in life. The later onset of adolescent idiopathic scoliosis is probably the main reason why these complications only rarely occur in this condition.
- Level of the scoliosis—in general, the higher the curve in the thoracic spine, the more marked are the cardiac and respiratory problems. Thoracolumbar or lumbar scoliosis has virtually no effect on respiration.
- Severity of scoliosis—the angle of scoliosis is closely related to the reduction in lung volume. This association is seen with all measures of lung volumes, including residual volume, total lung capacity, and functional residual capacity, as well as with vital capacity, except in patients with associated neuromuscular disorders where the changes in lung volumes are due also to the weakness of the respiratory muscles as well as the degree of deformity. The changes in lung volumes become significant when the angle of scoliosis is greater than about 100°.
- Presence of muscle weakness—the functioning of the respiratory muscles is impaired in scoliosis. Where the underlying aetiology is a neuromuscular disorder, this will precipitate respiratory failure at a lesser degree of angulation. Historically, maximum static mouth pressures have been used to assess respiratory muscle weakness, but it is now considered that the maximal sniff nasal inspiratory pressure is the most appropriate test. While the lower limit of normal is considered 60 cm H_2O for women and 70 cm H_2O for men, a serious contribution to respiratory failure may be expected when values of 40 cm H_2O or less are observed
- Small lung volumes—respiratory failure usually occurs when lung volumes have been reduced to a degree such that vital capacity is less than 1.0 to 1.5 1.

Consequences of respiratory failure

Hypoxia causes pulmonary vasoconstriction, which increases the pulmonary vascular resistance and leads to pulmonary hypertension, but the rate of rise of pulmonary artery pressure during exercise correlates with the degree of restriction of lung volumes rather than arterial P_{O_2}. Right ventricular and atrial hypertrophy develop if hypoxia is prolonged. Significant pulmonary hypertension is rarely seen unless the arterial P_{O_2} is less than about 8 kPa, and pulmonary hypertension by itself rarely causes right heart failure, hence the exact mechanisms underlying these right-sided cardiac changes are uncertain. The increase in sympathetic activity and circulating catecholamines associated with hypoxia cause renal vasoconstriction and a reduction in renal blood flow. This activates the renin–angiotensin–aldosterone system, leading to sodium and water retention. Hypercapnia is associated with an increase in renal tubular hydrogen ion excretion with sodium reabsorption in exchange for hydrogen. This leads to fluid retention, which is accentuated by an increase in antidiuretic hormone secretion. Hypercapnia

probably also increases capillary permeability, which contributes to the appearance of oedema.

Unlike patients with obstructive sleep apnoea, polycythaemia as a result of renal release of erythropoietin is seldom seen at presentation in patients with scoliosis since NIV is usually offered either as a result of ongoing monitoring or symptoms related to hypercapnia. When present polycythaemia serves to increase oxygen carrying capacity of the blood, but also raises blood viscosity, increasing the work of the right and left ventricles and predisposing to arterial and venous thrombosis.

Symptoms and physical signs

The earliest symptom of scoliosis is usually a change in the appearance of the patient, such as asymmetry of the shoulders or prominence of the posterior rib hump. Backache is a late and uncommon presenting symptom, though it may cause patients with established scoliosis distress. With mild curvatures there may be no respiratory symptoms, but mild shortness of breath on exertion is common and a change in this often signifies the development of complications. Orthopnoea, or dyspnoea in water, suggests that diaphragmatic function is impaired. When respiratory failure develops, fatigue, ankle swelling, and even syncope may indicate that pulmonary hypertension and right heart failure are present. Frequent awakenings during sleep, associated with excessive daytime somnolence, indicate sleep fragmentation due to apnoeas and hypopnoeas, and are important symptoms that warn of impending respiratory failure.

Physical examination may reveal the cause of the scoliosis, such as Marfan syndrome or neurofibromatosis, and other congenital abnormalities. Any associated muscle weakness or congenital heart disease may be apparent. Ribcage expansion may be predominantly lateral or anterior, or achieved by extension of the spine. In some subjects, chest expansion is mainly oblique because of the rotation of the spine, and some areas of the chest wall may move paradoxically. Accessory muscle action is usually prominent. The presence of central cyanosis indicates that the arterial oxygen saturation is below around 80%. Signs of hypercapnia may also be present, including tachycardia, large volume pulse, peripheral venous dilatation, papilloedema, a flapping tremor, reduction in tendon reflexes, small pupils and—if severe—confusion and coma ('CO_2 narcosis').

Investigations

The severity of scoliosis can be demonstrated radiologically, but chest radiography is often unhelpful in thoracic scoliosis because rotation of the spine obscures much of the lung fields. This can be overcome by obtaining an oblique view of the chest which, by aligning the spine behind the heart, simulates a posteroanterior view.

Lung function testing reveals a restrictive defect with reduction in all lung volumes, although the change in residual volume is least marked such that the ratio of residual volume to total lung capacity is increased. TL_{CO} is reduced but K_{CO} is raised, as in other chest wall disorders that cause a restrictive defect and in which the lung tissue is normal. Maximum inspiratory and expiratory pressures, sniff nasal and transdiaphragmatic pressure may be reduced. Chest wall and lung compliance are less than normal, and exercise tolerance is impaired.

Arterial blood gas analysis reveals a slightly low P_{CO_2} in mildly affected subjects, but later in the course of disease a rise in P_{CO_2} and a proportional fall in P_{O_2} develop. Sleep studies show a variable degree of hypoxia and hypercapnia which are usually most marked in REM sleep. Electrocardiography and echocardiography may be required to establish if pulmonary hypertension or congenital heart disease is present and identify precise abnormalities.

Prognosis

The prognosis in adolescent idiopathic scoliosis is virtually normal, but life expectancy is reduced in many of the other forms of scoliosis. This is particularly so in scoliosis of early onset, when it is both severe and high in the thorax and associated with respiratory muscle weakness, low vital capacity, and abnormal blood gases.

In most patients the cause of death is either cardiac or respiratory. Pneumonia and respiratory failure are particularly common in neuromuscular disorders, but hypoxic dysrhythmias during sleep are probably responsible for some deaths. Congenital heart defects, which have an increased prevalence in those with scoliosis, particularly when this is due to a congenital abnormality or of the idiopathic type, also contribute to mortality.

Management

Surgical

Mild scoliosis does not need any specific treatment. The prognosis is normal and there is minimal respiratory deficit. However, as the scoliosis becomes more severe, spinal fusion or a costectomy, in which the parts of the ribs comprising the posterior hump are removed, may occasionally be of cosmetic value. Spinal fusion or rod insertion may also be required to prevent progression of the scoliosis, to stabilize the spine, particularly in neuromuscular disorders, and in selected cases to try to improve cardiac or respiratory function or to prevent its deterioration.

The value of spinal fusion to prevent cardiorespiratory deterioration in adolescent idiopathic scoliosis is still under debate. Many studies of respiratory function before and after surgery have shown remarkably little change in lung volumes, blood gases, or exercise ability. However, in some patients with muscle weakness, particularly Duchenne's muscular dystrophy, the rate of fall of the vital capacity can be slowed considerably, and it can even be improved in patients who have had poliomyelitis. However, despite these short-term improvements, there have been no properly conducted randomized controlled studies which indicate whether or not spinal fusion performed in childhood or adolescence prevents respiratory failure from appearing later in life.

Respiratory failure

If respiratory failure does develop, any acute illness—most commonly an infection or bronchial asthma—that has precipitated it should be actively treated. Noninvasive ventilation or endotracheal intubation and ventilation may be required during the acute illness. A Cochrane systematic review in 2017 found no evidence to determine whether noninvasive or invasive mechanical ventilation should be preferred. If the latter is needed, the patient is then weaned from this either completely or on to a noninvasive method of long-term respiratory support.

Chronic ventilatory failure usually responds to long-term mechanical respiratory support. Administration of oxygen at night and/or during the day may be dangerous because of the risk of hypercapnia. Nasal or face mask positive-pressure ventilation is the treatment of choice, although a negative-pressure system, such as a cuirass or jacket, is a historical alternative, as is a rocking bed. Noninvasive

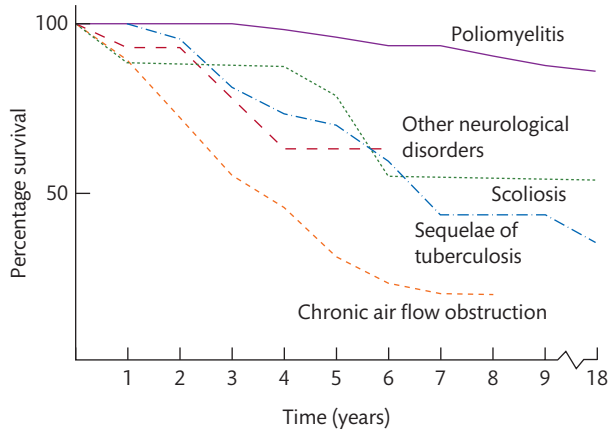

Fig. 18.18.3 Actuarial survival during treatment with ventilatory assistance for respiratory failure.
Reproduced from Shneerson JM (1988). *Disorders of ventilation*, Blackwell, Oxford.

ventilation is usually only required during sleep, but some patients benefit from 1 or 2 h treatment during the day as well. A tracheostomy is rarely required to provide ventilatory support, but in complex neuromuscular disorders it may be indicated to bypass upper airway obstruction (e.g. due to vocal cord adduction, or to gain access to the tracheobronchial tree to aspirate secretions, or to protect the airway from aspiration of material from the pharynx).

Noninvasive ventilatory support at night can improve the quality of sleep, breathlessness on exertion, daytime sleepiness, and early morning headaches. Activities of daily living may be carried out more easily and the number of visits required by general practitioners and the quantity of drugs prescribed can be reduced. Sleep architecture, daytime arterial blood gases and nocturnal oxygen saturation, and transcutaneous P_{CO_2} can all be improved. Survival once treatment has been instituted is around 75–85% at 5 years and 60% at 10 years (Fig. 18.18.3).

Kyphosis

Exaggeration of the normal thoracic kyphosis is most commonly due to osteoporosis and is not usually associated with any significant changes in respiratory function. The exception to this is when a very sharp kyphosis (gibbus) develops, usually caused by tuberculous osteomyelitis of the spine (Pott's disease), although other conditions such as radiotherapy can cause a similar picture.

The spine becomes rigid in the region of the gibbus, and when tuberculosis is the cause the costovertebral joints also become ankylosed and limit the expansion of the ribcage. A restrictive defect in which the total lung capacity is reduced more than the residual volume is characteristic, but respiratory problems are uncommon unless the gibbus is high in the thoracic spine and develops in early childhood. This is probably because in this circumstance the thoracic deformity prevents the normal development of the lungs in a similar way to early-onset scoliosis. Hypoxia and hypercapnia appear during sleep before they become apparent during wakefulness, but may be severe. Pulmonary hypertension and right heart failure frequently develop once chronic hypercapnia has become established.

Slight breathlessness on exertion is common in the presence of a gibbus, but is rare in other types of kyphosis. Physical examination reveals the spinal deformity and limitation of ribcage expansion.

The posteroanterior chest radiograph shows superimposition of the spinal deformity on the lung fields and heart, which makes it difficult to interpret. The extent and severity of the kyphosis is usually well seen on a lateral projection. The typical changes in lung volumes have been described earlier. The arterial P_{O_2} and P_{CO_2} are usually as in scoliosis, the earliest abnormalities are revealed by sleep studies.

Treatment of acute tuberculous infection with chemotherapy often prevents a gibbus from developing. Once it has been established and respiratory failure has developed, the only effective treatment is long-term respiratory support. This is best provided noninvasively by a nasal positive-pressure ventilator, rather than a negative-pressure system, because the sharp kyphosis makes it difficult to lie in the supine position required for negative-pressure ventilation.

Ankylosing spondylitis

The initial manifestation of ankylosing spondylitis is usually painful inflammation of the sacroiliac joints, but this may spread to affect almost any joint including the intervertebral, costovertebral, manubriosternal, costochondral, and chondrosternal joints. When the inflammatory phase of the disease subsides, the joints become ankylosed and the spinal ligaments calcify.

The effect of ankylosing spondylitis on the thorax is that the ribcage becomes rigid. There is little spinal mobility, and a pronounced kyphosis often develops. The changes in lung volumes are characteristic in that, unlike all other skeletal disorders affecting the thorax, functional residual capacity increases. This is because the ribcage becomes fixed at its own relaxation volume, which is greater than the normal functional residual capacity that is influenced by the inward pull of the elastic recoil of the lungs. Total lung capacity and vital capacity are slightly reduced, and residual volume often increases.

The immobility of the ribcage leads to atrophy of the intercostal muscles and both maximal inspiratory and expiratory pressures are reduced. However, there is no impairment of diaphragmatic or abdominal muscle function, and this largely compensates for the restriction of ribcage expansion. The ventilatory responses to exercise are virtually normal and exercise is usually limited by musculoskeletal and circulatory rather than respiratory factors.

Respiratory failure is extremely uncommon in ankylosing spondylitis, probably as a result of the normal diaphragmatic function, unless another complication develops, which may be one of the following:

- Airflow obstruction—cricoarytenoid arthritis is a feature of ankylosing spondylitis and may present with stridor, hoarseness of the voice, breathlessness, obstructive sleep apnoeas, or respiratory failure.
- Pleural thickening and effusion—these rare complications of ankylosing spondylitis may precipitate respiratory failure.
- Aspiration pneumonia—oesophageal motility is often impaired in ankylosing spondylitis and aspiration pneumonia may develop.
- Bullas—apical fibrobullous lung disease is a feature of ankylosing spondylitis and may be complicated by opportunist infections such as *Aspergillus fumigatus* or saprophytic mycobacteria, and occasionally by pulmonary tuberculosis.
- Abdominal surgery—this restricts diaphragmatic function on which adequate respiration depends. Conversely, thoracic surgery has relatively little effect on respiration because of the small contribution that ribcage expansion plays.

Chest pain during sudden movements such as coughing and laughing is common if the active phase of inflammation affects the thorax. These symptoms, which originate in either the joints or the muscles, become less prominent as the disease advances. Breathlessness and other respiratory symptoms are uncommon. Cricoarytenoid arthritis may occasionally present with hoarseness, stridor, or breathlessness, and extensive fibrobullous disease may also cause breathlessness.

The most obvious physical sign related to the chest is restriction of ribcage movement associated with prominent accessory muscle activity and abdominal respiratory movements.

Chest radiography may show calcification of the paraspinal ligaments (bamboo spine) and reveal evidence of complications of ankylosing spondylitis such as pleural thickening, aspiration pneumonia, and apical fibrobullous disease. The changes in lung volumes have been described earlier. Chest wall compliance is reduced but lung compliance is normal. The K_{CO} is increased and arterial blood gases are normal during both rest and exertion.

Physiotherapy and nonsteroidal anti-inflammatory drugs may improve vital capacity and chest expansion, particularly in the early phase of the disease or during acute exacerbations.

Disorders of the sternum and ribs

Congenital abnormalities

Congenital abnormalities of the ribs and sternum rarely cause any important respiratory problems. Multiple congenital rib abnormalities may occasionally lead to paradoxical movement of the chest wall or impair diaphragmatic function if they occur in the region of its insertion. Severe congenital defects of the sternum (e.g. agenesis or a bifid sternum) are rare, but may require surgery in the neonatal period in order to stabilize the anterior chest wall.

Pectus excavatum

Pectus excavatum is a depression deformity of the sternum that is often present at birth but may worsen during the adolescent growth spurt. It is occasionally familial and may be associated with other abnormalities such as the straight-back syndrome or scoliosis. It appears to result either from an increased inward pull on the sternum by the sternal diaphragmatic fibres or from an abnormally compliant chest wall.

Transient paradoxical movement of the sternum during respiration is seen in neonates, particularly in the presence of upper airway obstruction or pneumonia. The sternal depression may become permanent even if the cause, such as enlarged tonsils, resolves completely.

In adults, pectus excavatum rarely causes any symptoms. Lung volumes are normal or only slightly diminished, and chest wall mobility appears to be normal. Arterial blood gases are normal both at rest and during exercise. Very occasionally, right ventricular filling can be impaired if the heart is compressed between the depressed sternum and the spine, and compression of the pulmonary outflow tract may cause a systolic murmur. These problems are most marked in the erect position and during exercise. Occasionally atrial dysrhythmias develop, and opening of a patent foramen ovale induced by hyperventilation may lead to a right-to-left shunt and arterial hypoxaemia.

Surgery is sometimes performed for cosmetic reasons, although the result can be disappointing. It has little or no effect on the mild restrictive defect or exercise ability, except in the rare situation when right ventricular filling is impaired or atrial dysrhythmias have developed.

Pectus carinatum

Pectus carinatum is a protrusion deformity of the sternum in which the chest is often narrowed transversely. It becomes most marked during the pubertal growth spurt, although it may be present from birth and is occasionally associated with severe childhood asthma or ventricular septal defects. It is probably the result of excessive growth of the ribs or costal cartilages, and if this is asymmetrical the sternum becomes oblique.

The respiratory consequences of pectus carinatum have hardly been investigated. Chest pain may arise at the insertions of the intercostal muscles anteriorly, or in the costal cartilages and anterior ribs. Lung volumes appear to be normal. Surgery is indicated only for cosmetic reasons and not in order to improve respiratory function or exercise ability.

Acquired abnormalities

Flail chest

A flail chest is one in which multiple rib fractures cause paradoxical movement of the chest wall during respiration. It may be associated with other injuries, such as rupture of the aortic arch or spleen, and with fractures of the skull and long bones. It is frequently associated with pulmonary contusion, pneumothorax, or haemothorax.

Surgical stabilization of the chest wall is rarely required. Sufficient analgesia to enable the patient to cough adequately may be all that is needed in less severe cases, as long as the paradoxical movement does not impair alveolar ventilation. Positive-pressure ventilation can achieve 'pneumatic splinting' of the flail segment if the problem is more severe. The effectiveness of this has not been definitely established, but it appears that positive end expiratory pressure or continuous positive airway pressure is beneficial by preventing any negative pressure swings within the pleura.

Thoracoplasty

The operation of thoracoplasty was developed for the treatment of pulmonary tuberculosis, when varying lengths of up to 11 ribs were removed to collapse the chest on the affected side (**Fig. 18.18.4**). This has been superseded by antituberculous chemotherapy, although thoracoplasty has recently been reported in multidrug resistant tuberculosis, and the procedure is occasionally required to treat chronic infections, particularly when there is a problem in obliterating the pleural space after pulmonary resection.

It is estimated that as many as 30 000 operations were carried out in the United Kingdom between 1951 and 1960: some of these patients still survive, and increasing numbers are being seen by chest physicians because of the late complications of the surgical procedure. Other surgical approaches used at the time (phrenic nerve crush, recurrent therapeutic pneumothoraces and plombage) may also contribute to respiratory failure by reducing the capacity of the respiratory muscle pump or increasing the load. A similar picture is increasingly being seen after patients have survived extensive surgery (e.g. pneumonectomy for cancer or decortication for empyema).

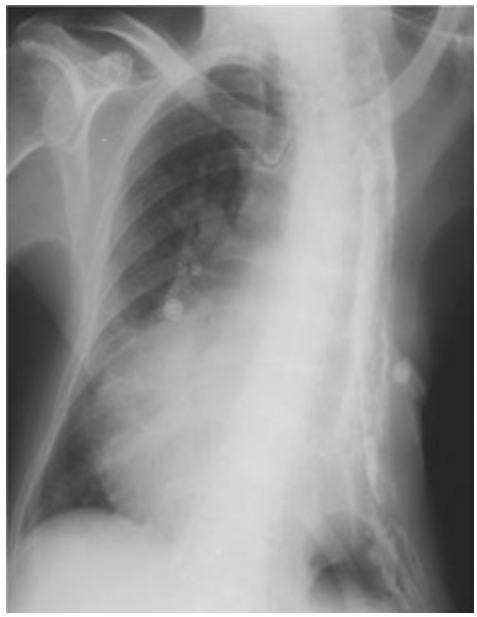

Fig. 18.18.4 Chest radiograph showing effects of thoracoplasty.

Consequences on respiratory function

The consequences of thoracoplasty on respiratory function have been hard to elucidate because they are often combined with the effects of the underlying lung disease for which the surgery was carried out, and those of other treatments such as lung resection. However, the removal of the ribs has the direct result of flattening the chest and reducing the volume of the thorax. The normal movements of the ribcage may be impaired and paradoxical movement at the site of the thoracoplasty is common. The compliance of the chest wall is reduced, and it may fall further because the small range of movements of the costovertebral joints after surgery probably induces soft tissue changes which further limit the mobility of these joints. Chest wall compliance is also reduced by the almost invariable development of a thoracic scoliosis. This is convex to the side of the thoracoplasty and may progress for several years after the surgery. The severity of the scoliosis correlates with the number of ribs removed, but also depends on the details of the surgical technique.

Respiratory muscle function is impaired by a thoracoplasty. The intercostal and shoulder girdle muscles are directly damaged by the surgery, and distortion of the ribcage and the development of a scoliosis put the inspiratory muscles at an additional mechanical disadvantage. Diaphragmatic excursion is reduced, particularly on the side of the thoracoplasty, but also occasionally contralaterally.

The combination of reduced chest wall compliance and impaired respiratory muscle function accounts for the restrictive defect. All lung volumes are reduced, and in general the severity of the restrictive defect is proportional to the number of ribs that have been resected. A rapid respiratory rate with a small tidal volume is the characteristic respiratory pattern, particularly during exertion. Exercise is limited by ventilatory factors rather than by the cardiovascular system. Chronic airflow obstruction, which may be due to either tuberculous endobronchitis or the effects of tobacco smoking, may be significant in some patients, resulting in a progressive fall in exercise ability and contributing to the development of respiratory failure.

Ventilation and perfusion of the lung on the side of the thoracoplasty are usually reduced equally, hence the arterial P_{O_2} often remains virtually normal. The function of the contralateral lung is much more important in determining the blood gases. Hypoxaemia usually first appears during sleep, as in scoliosis, and may be associated with hypercapnia. The presence of daytime hypercapnia correlates with the reduction in maximal inspiratory and transdiaphragmatic pressures.

Clinical features and management

The symptoms of patients with a thoracoplasty are similar to those with a scoliosis; recurrence of pulmonary tuberculosis is theoretically possible, but extremely unusual in practice. Right heart failure often develops insidiously, either when respiratory failure appears or subsequently. It may be manifested by progressively worsening ankle swelling and fatigue. Physical examination reveals a thoracotomy scar and a flattened area of chest in the region of the thoracoplasty which may move paradoxically. Accessory muscle activity, particularly on the side of the thoracoplasty, is often marked.

The chest radiograph shows the extent of the thoracoplasty, other features which indicate the site and extent of previous tuberculous infection, and the sequelae of treatment such as a previous phrenic nerve crush or an artificial pneumothorax, which often causes extensive, calcified pleural thickening. The characteristic physiological defect is restrictive, but airflow obstruction may also be significant. Maximum inspiratory and expiratory pressures and transdiaphragmatic pressures are reduced. Most patients are mildly hypoxic, but later in the clinical course the arterial P_{CO_2} may rise, particularly during sleep.

Life expectancy is reduced after a thoracoplasty for pulmonary tuberculosis, with death occurring particularly from respiratory but also from cardiac causes. These complications are related to the extent of the tuberculosis and to whether or not an artificial pneumothorax was induced on the contralateral side to the thoracoplasty, since this often leads to pleural thickening and may indicate extensive tuberculous damage of the underlying lung. Respiratory failure can develop quite suddenly after a long period of stability, even when an acute illness such as a chest infection is not responsible.

Conventional treatment of airflow obstruction with (for instance) bronchodilators may be effective, and right heart failure may respond to diuretics and angiotensin-converting enzyme inhibitors.

Chronic ventilatory failure usually responds well to nocturnal, noninvasive respiratory support. A few patients can be managed adequately with oxygen during the day and/or at night as long as the P_{CO_2} remains normal or only slightly raised. When respiratory support is required, nasal positive-pressure ventilation is usually effective. Some patients gradually require more intensive support, so that treatment is needed during the day as well as at night. This deterioration may be due to progressive worsening of small airway obstruction or respiratory muscle function, or to a fall in oxygen delivery to the tissues caused by a deteriorating cardiac output associated with advancing pulmonary hypertension. Survival at 1 year is around 90%, at 3 years 75–85%, and at 5 years 50–65%.

Disorders of the diaphragm

Aetiology

Diaphragmatic paralysis or paresis may be due to lesions affecting the diaphragm itself, or the phrenic nerve, its nucleus, or higher control centres or pathways. The most common causes of diaphragmatic weakness are shown in Table 18.18.1. Often no cause is found in unilateral weakness, which is then presumed to be due to a cryptogenic phrenic neuropathy, either as part of a widespread peripheral neuropathy or isolated to the phrenic nerves.

In clinical practice, patients without known neurological disease presenting to an outpatient service will most likely turn out to have diaphragm weakness associated with neuralgic amyotrophy, but clinicians should exclude adult onset Pompe disease since enzyme replacement therapy is now available. Follow up is recommended since a more sinister neurological disease may emerge: respiratory muscle weakness is a presenting feature in approximately 3% of patients with motor neuron disease.

Pathophysiology

Unilateral weakness of the diaphragm causes it to move upwards (paradoxically) into the thorax during inspiration, instead of descending. This decreases the tidal volume and the mechanical efficiency of breathing. It is worse in the supine position (or in water), when the weight of the abdominal contents pushes the paralysed diaphragm further into the thorax and decreases the functional residual capacity. The diaphragm is splinted in an expiratory position so that it moves relatively little, even though it is paralysed. When the subject lies on one side, the lower half of the diaphragm behaves in this way if it is paralysed, but if the upper half is paralysed it moves paradoxically. Patients with unilateral diaphragm weakness tend to be more comfortable sleeping with the affected side downward (so the contralateral side can move freely), in contrast to other conditions (e.g. pleural effusion) where patients are more comfortable with the diseased side up to preserve ventilation/perfusion (VQ) matching in the unaffected lung.

The loss of inspiratory muscle strength is partially compensated by recruitment of intercostal and accessory muscles, but the maximum inspiratory and transdiaphragmatic pressures are reduced. The vital capacity in the upright position is approximately 20 to 25% less than normal, and a further fall of about 15% occurs when lying supine. There are similar changes in the total lung capacity and functional residual capacity; residual volume is unchanged and expiratory muscle strength is largely preserved.

The distribution of ventilation and perfusion is affected by unilateral diaphragm weakness. Ventilation is slightly diminished, particularly at the base on the side of the diaphragmatic paralysis in the sitting position, but this is more marked when supine. Similar changes occur with perfusion on a regional basis, but ventilation–perfusion matching is impaired and hypoxia results. Hypercapnia does not occur during wakefulness or sleep.

The physiological abnormalities seen with bilateral diaphragmatic weakness in adults are much more marked than in unilateral diaphragmatic disorders. The diaphragm moves paradoxically during inspiration and expiration, and intrapleural pressure changes are transmitted across it so that abdominal pressure falls during inspiration and the anterior abdominal wall moves paradoxically. The maximum transdiaphragmatic pressure falls in proportion to the degree of diaphragm weakness, and since the diaphragm is the main inspiratory muscle, the maximum inspiratory pressure is correspondingly reduced. The vital capacity in the sitting position is about 50% of that predicted and may fall by a further 50% when supine, the influence of the supine position being greater than with unilateral diaphragmatic weakness because the weight of the abdominal contents pushes both halves of the diaphragm into the thorax. Ventilation is particularly reduced at the bases in the supine position, with less change in perfusion so that the arterial Po_2 falls. This postural change is partly responsible for the hypoxia that has been observed during sleep, but the rapid respiratory rate, small tidal volume, and short inspiratory time contribute to this and to hypercapnia.

Symptoms and physical signs

Unilateral diaphragmatic paralysis in adults rarely causes symptoms unless there is coexisting pulmonary disease or weakness of other respiratory muscles. In contrast, bilateral weakness can cause severe breathlessness. This may occur during exertion, but a specific feature is orthopnoea: this occurs within a few seconds of lying flat and is relieved promptly by sitting up, in contrast to left ventricular failure and nocturnal asthma with which it is frequently confused. Breathlessness may also occur when standing in water, since the passive inspiratory descent of the diaphragm due to gravity is prevented by the externally applied hydrostatic pressure. Patients will complain of dyspnoea on picking things from the floor, tying their shoelaces and getting out of a car: these are all manoeuvres which increase intra-abdominal pressure.

The physical signs of unilateral diaphragm weakness can be subtle. Dullness to percussion over the lower part of the thorax may be present. The normal inspiratory outward movement of the abdomen may be reduced or absent on the side of diaphragmatic paralysis, and expansion of the lower chest may lag behind the normal expansion of the other side.

The physical signs of bilateral diaphragmatic paralysis are much more obvious. Orthopnoea is usually readily apparent, and the abdomen moves paradoxically inwards as the diaphragm ascends during inspiration. A maximum transdiaphragmatic pressure of less than 30 cmH_2O is necessary for this sign to be detected. The accessory muscles are active, particularly in the supine position. The quality of sleep is often poor and as a result excessive daytime

Table 18.18.1 Main causes of diaphragmatic weakness

Unilateral	Bilateral
Neuralgic amyotrophy	Neurological disease (motor neurone disease, muscular dystrophies, adult onset Pompe disease, myopathies)
Congenital (e.g. agenesis, eventration)	Trauma
Surgery (cardiac, thyroid)	High cervical cord lesions
Trauma, causing phrenic nerve avulsion	Poliomyelitis
Adjacent mass (e.g. neoplasm, aneurysm)	Peripheral neuropathy, including Guillain Barre
Herpes zoster	ICU acquired diaphragm weakness
Mononeuritis	

somnolence may be a problem. Bilateral, basal dullness due to the high diaphragms is characteristic, but can be mimicked by bilateral pleural effusions.

Investigations

In unilateral diaphragmatic paralysis the chest radiograph may show elevation of the affected diaphragm, and usually reveals any adjacent mass that may be responsible. Both the diaphragms are raised if there is bilateral paralysis, and there is often some basal linear shadowing due to subsegmental lung collapse. Overall, however, the chest radiograph cannot be considered a reliable tool to confirm or refute diaphragm paralysis

Diaphragmatic screening or ultrasound examination reveals that the diaphragm moves paradoxically, particularly during sniffing, a test which should be carried out in the supine position with a weight on the abdomen. These precautions reduce the likelihood of abdominal muscle contraction during expiration from mimicking diaphragmatic activity by reducing the end expiratory volume below functional residual capacity, so that inspiration then occurs through the elastic recoil of the lungs and chest wall. Nevertheless, this type of imaging carries a false positive rate of approximately 6%.

A low vital capacity, which falls further in the supine position, is the hallmark of diaphragmatic weakness, particularly when this is severe and bilateral. All lung volumes are reduced except for the residual volume since expiratory muscle strength is largely preserved. Maximum inspiratory mouth and the maximum sniff nasal pressures are also reduced, but diaphragmatic weakness can be more specifically diagnosed by estimating the transdiaphragmatic pressure (the arithmetic difference between oesophageal and gastric pressure). This can be carried out by asking the patient to sniff or to take a maximum inspiratory effort. Where accurate quantification is required, or to investigate hemidiaphragm disease, magnetic stimulation of the phrenic nerve in the neck in conjunction with measurement of the transdiaphragmatic pressure is required. Care is required to carry out these investigations using a standardized method in order to obtain repeatable results. The function of the phrenic nerve can also be estimated by measuring its conduction time: this is normally less than about 9.5 ms, but is prolonged in some neurological diseases, although importantly not in axonal neuropathies.

The arterial P_{O_2} is characteristically slightly reduced, with a normal P_{CO_2} during the daytime and in sleep as long as pulmonary function is normal and there is no other muscle weakness. If either of these is present, however, bilateral diaphragmatic weakness can cause hypercapnia with profound hypoxia during sleep.

Treatment

Plication for hemidiaphragmatic paralysis is rarely required in adults and the procedure is best reserved for those in whom spontaneous recovery does not occur, where there is evidence of reduced lung function, and where frequent chest infections with radiological evidence of atelectasis are a problem.

Bilateral plication is not effective if there is bilateral weakness. Treatment with nasal positive-pressure ventilation is usually required. Ventilatory support is typically needed only at night and until the function of the diaphragm or phrenic nerve improves. However, the converse is true in progressive neurological conditions where diaphragm weakness is a feature: the patient will likely progress to daytime use of noninvasive ventilation (NIV), and the clinician will often need to have a discussion with the patient about the option of progressing to continuous tracheostomy ventilation at some point.

Phrenic nerve pacemakers are only worth considering when bilateral diaphragmatic weakness is due to lesions above the phrenic nerve nucleus in C3 to C5 or C6. Few centres offer this therapy, the commonest indication for which is a high cervical spinal cord injury due to trauma.

FURTHER READING

Benditt JO (2019). Respiratory care of patients with neuromuscular disease. *Respir Care*, **64**, 679–88.

Bredin CP (1989). Pulmonary function in long-term survivors of thoracoplasty. *Chest*, **95**, 18–20.

Budweiser S, *et al.* (2006). Impact of ventilation parameters and duration of ventilator use on non-invasive home ventilation in restrictive thoracic disorders. *Respiration*, **73**, 488–94.

Dolmage TE, Avendano MA, Goldstein RS (1992). Respiratory function during wakefulness and sleep among survivors of respiratory and non-respiratory poliomyelitis. *Eur Resp J*, **5**, 864–70.

Franssen MJAM, *et al.* (1986). Lung function in patients with ankylosing spondylitis. A study of the influence of disease activity and treatment with non-steroidal antiinflammatory drugs. *J Rheumatol*, **13**, 936–40.

Gibson GJ (1989). Diaphragmatic paresis: pathophysiology, clinical features, and investigations. *Thorax*, **44**, 960–70.

Haller JA Jr, *et al.* (1996). Chest wall constriction after too extensive and too early operations for pectus excavatum. *Ann Thorac Surg*, **61**, 1618–25.

Hart N (2002). The effect of severe isolated unilateral and bilateral diaphragm weakness on exercise performance. *Am J Respir Crit Care Med*, **165**, 1265–70.

Kafer ER (1975). Idiopathic scoliosis. Mechanical properties of the respiratory system and the ventilatory response to carbon dioxide. *J Clin Invest*, **55**, 1153–63.

Kinnear WJM, *et al.* (1988). The effects of one year of nocturnal cuirass-assisted ventilation in chest wall disease. *Eur Resp J*, **1**, 204–6.

Lindahl T (1954). Spirometric and bronchospirometric studies in five-rib thoracoplasties. *Thorax*, **9**, 285–90.

Luo F, *et al.* (2017). Invasive versus non-invasive ventilation for acute respiratory failure in neuromuscular disease and chest wall disorders. *Cochrane Database Syst Rev*, 12:CD008380. doi: 10.1002/14651858.CD008380.pub2.

Man WDC, *et al.* (2004). Magnetic stimulation for the measurement of respiratory and skeletal muscle function. *Eur Resp J*, **24**, 846–60.

Midgren B, *et al.* (1988). Nocturnal hypoxaemia in severe scoliosis. *Br J Dis Chest*, **82**, 226–36.

Newsom-Davis J, *et al.* (1976). Diaphragm function and alveolar hypoventilation. *Q J Med*, **145**, 87–100.

Nickol AH, *et al.* (2005). Mechanisms of improvement of respiratory failure in patients with restrictive thoracic disease treated with non-invasive ventilation. *Thorax*, **60**, 754–60.

Pehrsson K, Bake B, Larsson S, Nachemson A (1991). Lung function in adult idiopathic scoliosis: a 20 year follow up. *Thorax*, **46**, 474–8.

Phillips MS, *et al.* (1989). Exercise responses in patients treated for pulmonary tuberculosis by thoracoplasty. *Thorax*, **44**, 268–74.

Polkey MI, *et al.* (1995). Measurement of respiratory muscle strength. *Thorax*, **50**, 1131–5.

Polkey MI, *et al.* (1999). Respiratory aspects of neurological disease. *J Neurol Neurosurg Psych*, **66**, 5–15.

Shneerson JM (1978). The cardiorespiratory response to exercise in thoracic scoliosis. *Thorax*, **33**, 457–63.
Shneerson J (1998). Sleep in neuromuscular thoracic cage disorders. *Eur Resp Monogr*, **10**, 324–44.
Shneerson JM (2004). Respiratory failure in tuberculosis: a modern perspective. *Clin Med*, **4**, 72–6.
Shneerson JM, Simonds AK (2002). Noninvasive ventilation for chest wall and neuromuscular disorders. *Eur Respir J*, **20**, 480–7.
Simonds AK, Elliott MW (1995). Outcome of domiciliary nasal intermittent positive pressure ventilation in restrictive and obstructive disorders. *Thorax*, **50**, 604–9.
Smith IE, *et al.* (1996). Kyphosis secondary to tuberculous osteomyelitis as a cause of ventilatory failure: clinical features, mechanisms and management. *Chest*, **110**, 1105–10.
Tzelepis GE, McCool FD, Hoppin FG Jr (1989). Chest wall distortion in patients with flail chest. *Am Rev Resp Dis*, **140**, 31–7.