Chapter 29: Arterial Access

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INTRODUCTION

FOCUS POINTS

1. Arterial catheterization allows continuous blood pressure monitoring and facilitates arterial blood sampling.
2. Knowledge of anatomy, advantages/disadvantages of different cannulation sites, and pitfalls during placement and interpretation of the arterial waveform are crucial.
3. There are two approaches to arterial catheterization: through a technique in which a guidewire is used to thread a catheter into the vessel and through a direct puncture technique in which only one wall of the artery is punctured and the catheter is directly threaded into the vessel.
4. Ultrasound can facilitate arterial catheterization and has been shown to increase the chance for first-attempt success and reduce mean attempts to success.
5. Overdampening and underdampening of the transducer system cause incorrect blood pressure readings and should be evaluated with the “flush test.”

Monitoring of arterial blood pressure is often needed in critically ill adults and pediatric patients. Compared to adult anesthesia practice, arterial cannulation is performed less frequently in the pediatric population. As such, many procedures for which anesthesiologists would routinely perform arterial cannulations in adults are conducted in children with noninvasive blood pressure monitoring. In fact, arterial cannulation requires practice and becomes more challenging in younger and smaller size children. In this chapter, we will review the basic physiology, indications, contraindications, sites, and techniques for arterial cannulation.

BASIC PHYSIOLOGY

Invasive blood pressure monitoring via arterial catheterization is regarded as the “gold standard” for accurate hemodynamic assessment. The underlying physiology is based on pressure transduction via a fluid-filled catheter in the arterial blood vessel. Blood pressure fluctuations caused by cardiac ejections reach the arterial catheter, cause pulsations of the saline column that are transmitted to a diaphragm. The excursions of the diaphragm cause a change of resistance in the strain gauge transducer (Wheatstone bridge). This change in resistance is measured electronically, and processed, amplified, and converted into a visual display (waveforms).

Interpretation of the waveforms is presented below.

INDICATIONS

Arterial cannulation can theoretically be performed in any setting, but the need for monitoring equipment often limits the availability of arterial monitoring to the operating room, intensive care unit, or emergency department. While there are no absolute indications, most practitioners consider arterial cannulation if one or more of the following conditions apply:

- Tight blood pressure control (eg, resection of a secreting pheochromocytoma)

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- Blood pressure monitoring during anticipated pharmacological or mechanical cardiovascular manipulation (eg, open heart surgery)
- Blood pressure monitoring in the setting of non-pulsatile blood flow (cardiopulmonary bypass, left ventricular assist device)
- Arterial blood sampling (eg, pH, gas, electrolyte, hemoglobin monitoring)
- Inability to acquire reliable blood pressure measurements via a noninvasive route
- Inability to use noninvasive blood pressure monitoring (eg, burns)

There is an increasing interest on ways to determine fluid responsiveness with changes in stroke volume, pulse pressure variation, and stroke volume variation. A large body of literature supports the use of pulse pressure variation in the adult population to predict fluid responsiveness, for example, in the intensive care unit and operating room, and some authors have even reported beneficial effects on outcomes.[1–3] In contrast, only few studies have been conducted in the pediatric population, and the available studies have been contradictory.[4–7]

CONTRAINDICATIONS

Specific contraindications for arterial cannulation include the presence of vascular malformations, pseudo-aneurysms, arteriovenous fistulas, and impaired collateral circulation (Table 29-1). Severe coagulopathy and local infection at the puncture site are considered relative contraindications. Coagulopathy can raise the likelihood for significant bleeding and hematoma, especially if multiple attempts are required.

Table 29-1

Indications and Contraindications of Arterial Line Placement

Indications	Contraindications
Blood pressure monitoring in acute hemodynamic changes and in patients supported with extracorporeal mechanical devices (extracorporeal membrane oxygenation, ventricular assist devices) Blood sampling (gases, electrolytes, etc.) Inability to use noninvasive blood pressure monitoring	Vascular malformations Pseudo-aneurysms Arteriovenous fistulas Severe coagulopathy (may lead to bleeding) Infection at site of placement

The Allen test, described in 1929,[8] has been used to assess the collateral circulation of the hand prior to placement of an arterial line. It is important to note that a negative Allen test is not an absolute contraindication to arterial line placement. Slogoff et al showed no ischemic complications despite the presence of radial artery occlusion in 25% of the patients.[9]

AVAILABLE CANNULATION SITES

Upper Extremity

Radial Artery

This is the most common site of cannulation in pediatric anesthesia practice; it is easily accessible and palpable. It is considered safe, since the circulation of the hand is predominately supplied by the larger ulnar artery in most patients. In the past, the Allen's test was recommended for assessment of adequacy of the collateral circulation, but that has recently come into question.[10]

Ulnar Artery

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The ulnar artery is a viable alternative to the radial artery. If an ultrasound-guided technique is used, it is worthwhile to scan both radial and ulnar artery prior to cannulation. For both the ulnar and radial locations, placement should be avoided on the side of an existing or planned systemic-to-pulmonary artery shunt (eg, modified Blalock-Taussig shunt) because the blood pressure readings may be erroneously low.

Brachial Artery

The brachial artery can be catheterized in the antecubital fossa. Although it is a large caliber vessel that can easily be palpated and visualized, there are concerns about the lack of sufficient (if any) collateral flow to the distal upper extremity especially if it is compromised by occlusion, thrombosis, or spasm. Schindler et al reviewed their institutional experience with arterial catheterization in neonates and infants and did not find permanent ischemic damage in their cohort of 385 patients who underwent brachial artery catheterization.[11]

Axillary Artery

If an upper extremity arterial catheter is needed and radial or ulnar cannulation is unsuccessful or not possible, the axillary artery may be an option. Compared to the brachial artery, the axillary artery has collaterals that can supply the distal aspects of the arm in case of an occlusion. Lawless and Orr reported a small number of axillary artery catheterizations in pediatric patients and no major complications were noted.[12]

Lower Extremity

Femoral Artery

The femoral artery is often chosen for cannulation in neonates and small infants if initial attempts at other sites fail. From all available cannulation sites, the femoral artery has the largest diameter and is easily accessible by palpation or ultrasound-guided techniques. If the patient is vasoconstricted, more distal sites become increasingly difficult to cannulate. While collaterals are present, femoral artery occlusion can lead to serious adverse events including limb ischemia and loss. In addition, femoral artery catheters are at higher risk for infection due to their location in the inguinal crease and possible contamination with stool in infants wearing a diaper. Dumond et al reported the use of femoral artery catheters in 282 patients.[13] Twenty percent of patients were noted to have pedal pulse discrepancies between the catheterized extremity and the opposite limb, while 6.8% of patients lost pedal pulses by palpation and Doppler after catheter placement. All pulses recovered after femoral catheter removal and no patient suffered from ischemic complications, although four patients were treated with an intravenous vasodilator (papaverine). The group noted that predictors for loss of pedal pulses after femoral artery catheterization were catheter size greater than 2.5 Fr and duration of catheterization.

Dorsalis Pedis Artery and Posterior Tibial Artery

Both of these lower extremity arteries are accessible by palpation and ultrasound guidance and are part of a collateral network that supplies the foot. They are safe to access because of the available collaterals. Those sites are avoided in procedures involving cardiopulmonary bypass as the arterial pressure waveform may become inaccurate in the post-cardiopulmonary bypass period due to peripheral vasoconstriction.

Other Sites

Superficial Temporal Artery

The superficial temporal artery is the least frequently used site for arterial catheterization and its use is currently reported by only a limited number of centers.[14,15] While the site is easily accessible, concerns have been raised about the proximity to the cerebral vasculature and the potential for causing cerebral embolization and infarction with introduction of air or dislodgement of plaques during catheter flushing.[16] Nevertheless, it represents a back-up option in case catheterization attempts at other sites fail. Furthermore, Bhaskar et al suggested superficial temporal artery catheterization in patients presenting for repair of aortic coarctation or who require administration of anterograde cerebral perfusion in the presence of aberrant origin of the right subclavian artery.[17]

Umbilical Artery

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Umbilical artery catheterization is frequently performed in neonates who require invasive blood pressure monitoring. As a result, pediatric anesthesiologists typically utilize those catheters but are often times not experienced in their placement. It is helpful to understand some unique aspects of umbilical artery catheters: (1) in emergency situations, they can be used to deliver resuscitation medications, fluids, and blood products (although application via an umbilical venous catheter is preferred); (2) these arteries can only be accessed within the first 3 to 4 days of life; (3) the catheter tip should be positioned “high” (ie, above the diaphragm at the T6–T9 level); and (4) the Center for Disease Control and Prevention (CDC) issued a recommendation that umbilical artery catheters should be left in place for a maximum of 5 days.[18]

Commonly used arterial catheter sizes are listed in Table 29-2. This should only serve as a guide and clinical judgment should be exercised with an individualized approach to each patient.

Table 29-2

Arterial Catheter Sizing

Age/Weight	Arterial Line Sizes
Infants <5 kg	24-gauge catheter for radial 2.5 Fr, 2.5 cm for radial 2.5 Fr, 5 cm for femoral
Infants/Toddlers <10 kg	22- or 24-gauge catheter for radial 2.5 Fr, 2.5 cm for radial 2.5 Fr, 5 cm for femoral
Preschool children <20–25 kg	20- or 22-gauge catheter for radial 3 Fr, 5 cm for femoral
Older children	20- or 22-gauge catheter for radial

COMPLICATIONS

Multiple cannulation attempts with arterial wall puncture, especially in the setting of coagulopathy, may result in bleeding with local hematoma formation. A hematoma has the potential of compressing surrounding structures including blood vessels and nerves. Idiopathic pseudo-aneurysms have also been reported with repeated cannulation attempts. Distal ischemia can occur due to placement of an arterial cannula that is too large in relation to the vessel diameter due to flow interruption.

Dislodgement of vascular plaques can occur during arterial cannulation. This causes distal embolization and may result in ischemia. A similar problem can arise if an arterial cannula in situ develops a thrombus that can dislodge and occlude the distal vascular bed.

One study reported an overall incidence of indwelling arterial catheter-related thrombosis of 3.25% primarily with femoral arterial catheters.[19]

Indwelling vascular catheters represent a possible nidus for bacterial colonization and infection; in comparison to central venous catheters, arterial catheters are less likely to become infected. One cohort analysis reported an incidence of 2.3% for catheter-related local infection and 0.6% for possible catheter-related septicemia.[20]

Accidental injection of drugs or solutions into the arterial catheter represents a preventable iatrogenic complication that can lead to severe ischemia and loss of a limb. That being said, no adverse events have been observed after accidental intraarterial injection of atropine, midazolam, fentanyl,

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succinylcholine, pancuronium, and vecuronium. In contrast, intraarterial injections of propofol, ketamine, diazepam, thiopental, meperidine, atracurium, and *cis*-atracurium have resulted in ischemia and/or necrosis.[21,22] Therefore, it is important to adequately label the arterial catheter and arterial pressure transducer system, especially around the various access points (eg, stopcocks). Attempts should be made to limit the number of access points to further reduce the risk of accidental injections.

Overall, the incidence of complications from arterial cannulation is low. This is supported by an analysis of the American Society of Anesthesiologists Closed Claims database in which only 13 out of 6894 claims (0.19%) were related to arterial cannulation.[23]

GENERAL APPROACH TO CANNULATION OF AN ARTERIAL BLOOD VESSEL

Preparation

Based on the institutional policy, a verbal and/or written consent from the patient is needed after explaining the procedure as well as the risks and benefits of invasive arterial monitoring.

Equipment

The equipment should include arm board, tape, chlorhexidine prep solution, sterile occlusive dressing, connector, arterial catheter, sterile gloves, sterile towels, saline flush, and the transducer system. Arterial cannulation in general should be conducted in a clean manner and it should be conducted in a sterile manner with gown and hat when central cannulation (axillary and femoral) is being used. One may use a standard peripheral angiocatheter or a commercially available specially designed arterial cannulation catheter. If a Seldinger technique is used, appropriately sized guidewires are also needed.

If the operator plans to utilize ultrasound, the following equipment should also be prepared: ultrasound machine with probe, sterile transducer sheath, and sterile transduction gel.

Placement Using Palpation of the Arterial Pulsations

Standard Peripheral Angiocatheter

The operator holds the cannula with the dominant hand while palpating the radial pulse with the non-dominant hand using the index and middle fingertips. One should not press too firmly as this commonly compresses the radial artery so that no pulsation can be appreciated. After identification of the artery, the skin is punctured with the cannula. The cannula is then advanced slowly at a 45-degree angle toward the artery. Successful entry is noted by seeing blood return in the cannula lumen. At this juncture, the operator has two options. The first option is to directly cannulate the vessel by carefully dropping to a shallower angle (10 to 20 degrees), advancing the cannula with the needle in place by another 1 to 2 mm and then threading off the cannula over the needle into the arterial vessel. The second option is to transfix the artery by advancing the cannula with needle through the anterior and posterior arterial wall. The needle is then removed. The operator then slowly withdraws the angiocatheter until the cannula's end is pulled through the posterior arterial wall into the vessel lumen at which point pulsatile blood immediately fills the catheter. The guidewire, held with the dominant hand, is then advanced through the cannula into the vessel. The guidewire should pass without resistance. If resistance is felt, it indicates that the catheter is malpositioned (eg, against the vessel wall, outside the vessel) and forcing the guidewire into the cannula against resistance can result in the creation of a false tract or pseudo-aneurysm. After successful placement of the guidewire, the operator can then advance the cannula into the vessel.

Butterfly Needle or Specialized Arterial Puncture Needle/Catheter System

A butterfly needle can be used to directly cannulate an arterial vessel, but it needs to be prepared by cutting off the tubing that extends from the needle end. With the butterfly needle or a dedicated arterial puncture needle, the same cannulation process as described in the previous paragraph. As soon as the artery is punctured, a guidewire can be advanced into the vessel lumen. The needle is then removed and an arterial cannula can be placed over the guidewire.

When using the Seldinger technique, it is imperative to ensure that the wire used fits the catheter planned. If a peripheral venous catheter is used, it can be moved forward and backward after the guidewire has been inserted to function as a dilator. When threading the arterial catheter, the dominant

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hand should grasp the catheter as close to the skin as possible to avoid dislodgement or malpositioning. Skin tension can be helpful while threading the catheter through the skin. The catheter can then be advanced over the guidewire into the vessel. Occasionally, a twisting motion of the catheter over the wire can help overcome skin resistance. The operator should never force the catheter into the skin as excessive pressure can create a false tract, damage the catheter, or bend the guidewire. If the catheter still cannot be advanced through the skin, a small skin incision can be performed with a scalpel. The incision has to be exactly at the guidewire entry site and care must be taken to not cut the guidewire.

Placement with Ultrasound Guidance

As with all techniques, the successful use of ultrasound for arterial catheterization is operator-dependent and has a learning curve. Nevertheless, a recent systematic review and meta-analysis showed an increased chance for first-attempt success and significantly reduced mean attempts to success with ultrasound guidance.[24]

An out-of-plane ultrasound-guided technique is the preferred method and is performed as follows: The ultrasound probe is covered with a sterile sleeve. A sterile gel is applied inside the sleeve and on the skin. The ultrasound probe is applied to the skin gently to avoid compression of the artery and the depth is adjusted based on patient's size. In order to use the ultrasound-guided technique successfully, the operator should be able to manipulate the probe and the needle while looking at the ultrasound screen.

The artery is visualized by ultrasound and centered on the image on the screen. A 20–24G catheter (brand) based on the size of the patient is used. The catheter is placed close to the probe at a 15 to 30 degree angle in an out-of-plane technique. The catheter should be visualized above the center of the radial artery. If the position of the catheter is inadequate, it is withdrawn to the skin, and then reapplied aiming to the center of the artery. Fine adjustments are made with the needle until the tip is seen in contact with the anterior wall of the artery. At this point one of the following approaches can be taken:

- Use of a guidewire (Seldinger technique)

    The needle is advanced through the artery. Then the ultrasound probe is placed down. The metal stylet is removed and if there is a flash of blood, a wire is inserted through the catheter and advanced into the artery using the Seldinger technique. If there is no flash of blood after the stylet is removed, the cannula is withdrawn until blood flow is seen, and then a wire is inserted. The catheter is inserted inside the lumen, then the wire is removed while keeping proximal pressure to the artery to avoid bleeding from the catheter.

- Direct puncture

    The needle is slowly advanced into the artery while care should be taken to avoid puncturing the posterior wall. The ultrasound probe is adjusted to find the needle tip inside the artery. The needle orientation is then adjusted to position the tip in the middle of the artery and the needle is again advanced slightly under ultrasound guidance. This sequence (ultrasound probe adjustment, needle adjustment, needle advancement) is repeated until enough catheter length is within the blood vessel to allow threading off the catheter from the needle.

The monitoring tubing system is then connected to the catheter. In some instances, the catheter is replaced with a commercially available arterial catheter over the guidewire (please see the online video atlas section on arterial access).

Several advantages of using ultrasound-guided technique exist. Ultrasound pre-scanning allows the evaluation of vessel size at different potential access sites, vessel patency, and location and allows the exclusion of arterial thrombus, hematoma, or dissection. The use of ultrasound also helps visualize distortion or displacement of the artery caused by needle advancement. Furthermore, a lack of blood flashback during transfixation technique may occur frequently and is appreciated with the ultrasound-guided technique.

RADIAL ARTERIAL LINE CANNULATION

As mentioned earlier, the radial artery is common in adults and pediatrics and therefore a brief description of the landmarks and a video illustrating the arterial catheter placement are available (please see the online video atlas section on arterial access).

Anatomical Landmarks

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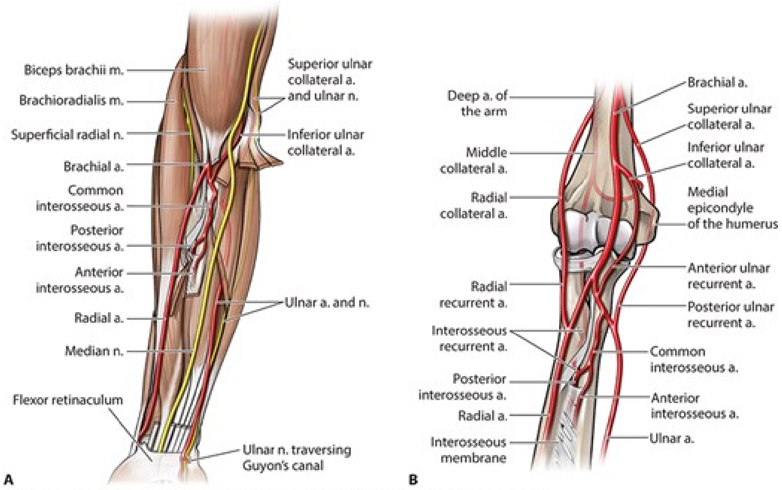
Within the antecubital fossa, the brachial artery divides into the radial and ulnar artery. The radial artery runs anteriorly and laterally on the forearm. At the wrist, it passes between the radial collateral ligament and the tendons of the abductor pollicis longus and extensor pollicis brevis. In the hand, it crosses between the heads of the first dorsal interosseous muscle forming the deep palmar arch and joining the ulnar artery (Figure 29-1).

Figure 29-1

Arterial anatomy. **A**. Arteries and nerves of the anterior forearm. **B**. Arteries of the elbow and forearm. (Reproduced with permission, from Morton DA, Foreman KB, Albertine KH: *The Big Picture: Gross Anatomy*. 2nd ed. 2019. https://accessmedicine.mhmedical.com. Copyright © McGraw Hill LLC. All rights reserved.)



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Although the radial artery is the most commonly used vessel for arterial cannulation, other possible upper and lower extremity sites include the ulnar artery, brachial artery, axillary artery, dorsalis pedis, posterior tibial, and femoral artery.

Positioning

The course of the radial artery is identified by palpation. The hand is dorsiflexed and immobilized. Mild dorsiflexion is applied to avoid injury to the median nerve and collapse of the artery. The skin is prepped with an antiseptic and draped.

Placement

Cannulation of the radial artery is described in the video. Studies looking at ultrasound-guided arterial cannulation attempts in pediatric patients have reported that trisomy 21 and depth of the artery (<2 mm and >4 mm) were independent predictors of catheterization difficulty. Subcutaneous artery depth of 2 to 4 mm showed a statistically significant better success rate for first-attempt and overall cannulation success. The subcutaneous saline injection for patients with artery depth of <2 mm can bring the vessel into the 2 to 4 mm depth range and has been used to improve overall catheterization success and catheterization time.[25]

WAVEFORM INTERPRETATION

With each heartbeat, the ventricles eject an amount of blood called stroke volume (SV). The contraction produces a pressure wave that propagates throughout the vascular tree and is detected through an arterial catheter. It has a characteristic shape dependent on the sampling location. The shape of the pressure wave is further influenced by the speed of ejection of blood from the ventricle, the compliance of the vascular tree, and the rate at which the ejected blood can flow from the central arterial vascular compartment to the peripheral tissues.

When we break down the arterial pressure tracing itself, we can appreciate the following components:

- Systolic blood pressure (peak of the pressure tracing)

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- Diastolic blood pressure (lowest point of the pressure tracing)
- Mean arterial blood pressure (area under the curve)
- Dicrotic notch (reflects aortic valve closure)
- Pulse pressure (difference between systolic and diastolic pressure)
- Anacrotic limb (initial upstroke of waveform, which reflects the rapid ejection of blood from ventricle through aortic valve)
- Dicrotic limb (downward slope of waveform after systolic peak has been reached, which reflects the distribution of blood into peripheral tissues)

Depending on the sampling location, blood pressures will vary slightly: at a more distal sampling site, systolic blood pressure is higher while diastolic blood pressure is lower, leading to an increase in pulse pressure. The contractility of the left ventricle is reflected by the slope of the upstroke (anacrotic limb). A steeper slope is associated with a quicker rise and a higher contractility. Pulse pressure reflects arterial compliance but is also influenced by stroke volume and contractility. Compliance is a major factor, which explains the differences in pulse pressure between elderly patients (arteriosclerosis leads to stiff vessels with low compliance = larger pulse pressure) and neonates (highly compliant vessels = smaller pulse pressure). Peripheral vascular resistance is reflected in the downslope of the waveform (dicrotic limb). Low peripheral vascular resistance, as encountered in sepsis, vasodilator therapy, or neurogenic shock, the waveform exhibits a sharp downslope. A shallow downslope can be found in states with intense vasoconstriction.[26] Table 29-3 lists waveform findings that can be found in common disease states.

Table 29-3

Arterial Waveforms in Common Disease States

Aortic stenosis	• Blunted anacronic limb (Pulsus tardus) • Narrowed pulse pressure (Pulsus parvus) • Systolic peak may be lower • Dicrotic notch may disappear
Aortic regurgitation	• Steep rise of anacronic limb • Widened pulse pressure • Low diastolic blood pressure • Occurrence of second systolic peak (Pulsus bisferiens)
Hypertrophic cardiomyopathy	• Steep dicrotic limb, followed by second peak from reflected wave (Pulsus bisferiens)

PROBLEMS DURING MONITORING

Dampening of the arterial pressure transducer system may result in incorrect blood pressure readings. An inverse relationship exists: overdampened systems will underestimate blood pressure, while under-dampened systems will overestimate blood pressure. To determine the dampening condition of the measurement system, the “flush test” is used: a small volume of normal saline is rapidly injected into the arterial pressure transducer system. Directly after the injection, oscillations are observed on the arterial waveform tracing (Figure 29-2).

Figure 29-2

Fast-flush test demonstrates the harmonics of the pressure monitoring system. **A.** Optimally damped system: the pressure waveform returns to baseline after only one oscillation. **B**. Underdamped system: the pressure waveform oscillates above and below the baseline several times. **C.** Overdamped system: the pressure waveform returns to baseline slowly with no oscillations. (Reproduced with permission, from Kaplan JA, Reich DL,

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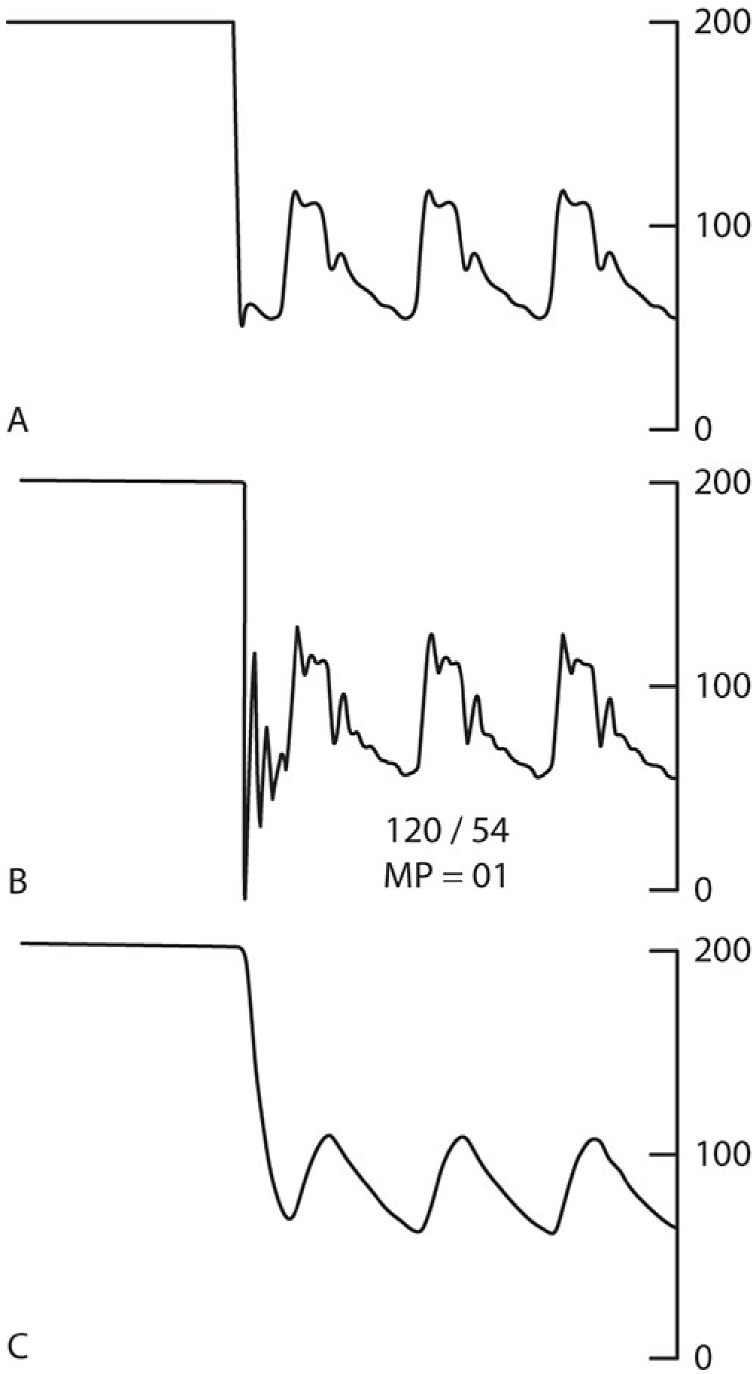

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One study examined arterial and noninvasive blood pressure monitoring in pediatric intensive care unit patients and noted several important findings:[28]

- Fifty-four percent of the examined arterial blood pressure monitoring systems were not optimally dampened, and neither demographic nor clinical variables predict the occurrence of optimal dampening; optimal dampening was dependent on the mechanical set-up of the system.
- There is much variability in the measured blood pressures (systolic, diastolic, and mean arterial blood pressures) between noninvasive and arterial blood pressure systems.

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- Noninvasive blood pressure measurements may not be accurate enough in critically-ill children to guide management, especially when inotropes or vasodilators are being used.

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