Invasive and Noninvasive Blood Pressure Monitoring

Nitin Shah, M.D.
Robert F. Bedford, M.D.

Systemic Arterial Pressure

The arterial pulse-pressure wave results from the left ventricular stroke volume creating aortic distention within the closed vascular system. Peak aortic blood flow acceleration produces the initial rate of rise of the pressure pulse, whereas the ejection of ventricular volume fills out and sustains the pulse waveform. The initial rapid upstroke of the aortic root pulse reaches a peak that can be viewed as the isotropic component of the pressure-pulse wave. The pressure and flow phenomena at this time expand primarily the upper aorta and produce a higher pressure than would occur if the entire aorta were to distend uniformly. The rounded, sustained portion of the aortic pulse-pressure wave represents a combined effect of (1) ventricular volume ejection, (2) distention of the entire aorta (capacitance), and (3) runoff into the branches of the aorta. The initial peak of the arterial waveform is followed by a more or less well-defined notch and subsequently by a second peak, the systolic pressure. The second peak falls away to the descending limb of the waveform, which often contains a diastolic notch (Fig. 13-1). The nadir of the pulse-pressure wave is defined as the diastolic pressure, occurring immediately before the subsequent systolic upstroke begins.

Ventricular ejection produces both a true pressure wave and a flow wave in the ascending aorta. The aortic blood flow is not transmitted to the periphery with the pulse-pressure wave. The left ventricular stroke volume is absorbed by the distensible elastic aortic arch, which serves as a "fixed-capacity, high-pressure reservoir." While the blood flow wave moves out of the aorta at a relatively slow 0.5 m/second during aortic elastic recoil from the volume ejected from the left ventricle, the pulse-pressure wave moves at the rate of 10 m/second. In fact, by the time ventricular systole is completed, the dorsalis pedis artery has already started to receive the arterial pulse-pressure wave.

As the pulse-pressure wave moves away from the aortic root, there is a delay in transmission; the initial upstroke becomes steeper, the high-frequency components (such as the anacrotic and dicrotic notches) disappear, and the systolic maximum becomes progressively more 'peaked' (Fig. 13-2). The dicrotic notch starts out as an insinuation and gradually gets lost in transmission, becoming a deep, drawn-out hump or anacrotic wave in the upper extremities, while virtually disappearing into the diastolic pressure in the femoral system. The tidal wave after the primary systolic peak appears in the axillary-brachial-radial system but does not appear in the femoral artery. Mean pressure must decrease peripherally for flow to continue, although mean pressure changes less than either systolic or diastolic pressure. In general, the farther into the periphery blood pressure (BP) is measured, the greater the increase in systolic and pulse pressure, the lower the diastolic and mean values, and the narrower the waveform appears.

The reasons for the changing pattern of the arterial pulse wave are extremely complex, and yet they are important for the clinician's understanding of BP monitoring techniques. Because BP is usually measured in peripheral arteries, probably the most important factor in modifying the pulse-pressure waveform obtained clinically--particularly the systolic component--is the reflection of waves from the periphery. Just as surface waves are produced by dropping an object into a pool of water, when the waves hit the edge of the pool they are reflected back, and those reflected waves produce a standing wave that adds to the incident wave (Fig. 13-3). In the arterial tree, the artery-arteriole junction is thought to be the principal site of reflection, and standing waves are produced that add or subtract from different portions of the pulse wave. It has been estimated that as much as 80% of the incident wave is reflected with normal arterial resistance. When peripheral vasodilatation occurs (vasodilator therapy, systemic inflammatory response syndrome, exercise, arteriovenous fistula), the energy in the pressure pulse is passed on into the periphery and absorbed without reflection, resulting in marked changes in the pulse-pressure contour. Conversely, when a cannulated radial or dorsalis pedis artery is occluded by a catheter or thrombus, the site of wave reflection is at the catheter tip, and the summation of the reflected and incident waves results in augmentation of the systolic pressure value.

Reflection of the arterial waveform also is thought to occur at branching points of vessels. The changes in the shape of the dicrotic notch are thought to result from reflected waves from the lower aorta summating with the incident pulse-pressure wave, because there is no dicrotic notch visible in the femoral arterial tree, whereas it is clearly evident in the arteries of the upper extremities.

There are other causes of change in the configuration of the arterial pulse-pressure wave as it moves peripherally:

1. The decreasing content of elastic fibers (and lower compliance) as the more peripheral arteries become more muscular.
2. The tapering of vessel diameter, which acts to amplify arterial waves similar to the way an ear trumpet amplifies sound waves (see Fig. 13-3).
3. The fact that the high pressure levels of the arterial pulse travel faster than the low pressure levels so that the peak of the arterial pulse curve "catches up" and summates
with the earlier pressure components in the more peripheral arteries.  

The observation that older patients have less discrepancy between systolic pressures measured in the aorta and peripherally is thought to be due to less vessel wall pliability and a faster pulse-wave velocity with increasing age. Conversely, the marked augmentation of the dicrotic notch (actually a wave) often observed in children's radial arteries is a function of greater vessel compliance and greater opportunity for wave reflection and amplification due to slower wave transmission time.

The changes in arterial waveform, particularly those of the systolic component, account in large part (although not entirely) for the disparities observed between cuff pressures measured in the brachial artery and invasive pressures measured at a more distal site such as the radial or dorsalis pedis arteries.

In summary, the arterial system functions as a damped, resonant transmission line, transmitting various frequencies with different degrees of attenuation. The reshaping of the aortic pulse-pressure wave as it travels into the peripheral


![Figure 13-2. Configuration of the pressure-pulse wave at various sites in the arterial tree. See text for a more complete description of the changes as the arterial pulse wave travels to the periphery.](From Bedford RF, Shah NK: Blood pressure monitoring: Invasive and noninvasive. In Blitz CD, Hines RL: Monitoring in Anesthesia and Critical Care Medicine. New York, Churchill Livingstone, 1995, p 95.)

![Figure 13-3. Some factors affecting the arterial pressure-pulse wave shape: Reflection at the artery-arteriole junction and progressive decrease in diameter of arterial lumen. See text for further description.](Proximal \rightarrow Distal artery \overset{\text{diameter}}{\longrightarrow} \text{Pulse-Presure Wave})

**Noninvasive Methods for Blood Pressure Measurement**

Considerable effort has been expended in refining the technology for noninvasive blood pressure (NIBP) measurement. Ever since 1905, when Cushing first advocated clinical use of BP measurement, most arterial pressure monitoring has been done noninvasively, either with a manually operated sphygmomanometer or with an automated noninvasive device. Currently there are approximately 200,000 automated noninvasive BP devices in clinical use worldwide, both in operating rooms and critical care units.

One of the problems with NIBP measurement is the considerable variance in BP data, both within and between the different techniques available. Common to nearly all the contemporary methods for noninvasive arterial pressure measurement is an inflatable circumferential cuff that is placed around an extremity and inflated to a pressure exceeding systolic pressure and that stops either blood flow or arterial wall motion. However, there is little standardization for the estimation of NIBP, and there are multiple techniques available for measuring changes in systolic, diastolic, mean arterial, and pulse pressures.

The lack of standardization is further complicated by the multiplicity of sites available for NIBP measurement. As discussed in the section on invasive BP monitoring, the intraarterial pressure changes as it moves away from the aortic root, a consequence of changes in vessel diameter, vessel wall elasticity, and the state of arteriolar tone. It is because of these limitations and the observed inconsistencies in NIBP measurement that Brunner and colleagues concluded, "Blood pressure is a function of the way it is measured."
**History**

Although the circulation of blood in the human body had been known since first described in 1628 by William Harvey, it was not until 1876 that Von Basch developed a technique for occluding a peripheral artery using hydraulically applied pressure over a bone. The pressure was increased until palpations in the artery disappeared; this point was taken as the systolic pressure. A variation of this technique of arterial occlusion was undertaken in 1876 by E. J. Marey, who inserted a subject’s arm through a seal into a cylinder of water that could have its pressure recorded as well as changed. Marey also developed a somewhat less bulky method using a cylinder that fit tightly around one finger, but this method did not win clinical acceptance, perhaps because of the low amplitude of the oscillations in the manometer.14

The use of a pneumatic cuff around the arm was first described in 1896 by Riva-Rocci and in 1897 by Hill and Barnard.15 Using palpation of the radial artery (the so-called palpatory method) the cuff was gradually inflated until the radial pulse first disappeared; the cuff was then deflated and the pressure at which the pulse then reappeared was recorded. These two readings were averaged to give the systolic pressure.

The auscultatory method of BP determination was first proposed in 1905 by Korotkoff.16 He believed that the sounds that were heard through a stethoscope placed over the brachial artery distal to an occluding cuff were caused by the breakthrough of a pulse wave and that the subsequent lessening and then disappearance of the sounds were caused by the passage of an unobstructed pulse wave. He noted that the first sound occurred at a higher pressure than was obtained with palpation of the radial artery and concluded that more of the pulse waveform had to pass down the artery before the pulse was palpable.

**Methods of Measurement**

NIBP measurement is currently performed either manually or with a variety of automated electromechanical devices employing techniques such as auscultation, oscillometry, blood flow detection, and photoelectric pulse wave delay.7 The following is a partial list of techniques and devices used in contemporary medical practice. Each will be discussed in some detail:

- **Auscultation**
- **Oscillometry**
- Blood flow detection: palpation, ultrasonic, and photoelectric
- Ultrasonic detection of arterial wall movement

![Diagram](image)

**Infrasound (Puritan Bennett)**
- Finapres
- Arterial tonometry
- Photometric wave velocity

**Auscultation**

The auscultatory or Riva-Rocci method for NIBP monitoring has been, and continues to be, the most commonly used NIBP measurement technique.16 It relies on Korotkoff sounds, a complex series of audible frequencies produced by turbulent flow, instability of the arterial wall, and shock wave formation that are created as external occluding cuff pressure on a major artery is reduced.17 The pressure at which the first sound (phase I) is heard is usually taken as the systolic value. The sound character changes (phases II and III), then becomes muffled (phase IV), and finally absent (phase V). Diastolic pressure is recorded at phase IV or V, although phase V may never occur in certain pathophysiologic states, such as aortic regurgitation.18

As familiar as the standard BP cuff may be, a number of caveats should be considered in its use. It is of paramount importance to match the size of BP cuff to the size of the patient’s arm. Too small a cuff, or one that is wrapped too loosely, will result in falsely elevated BP readings because of the excessive cuff pressure required to occlude a deep artery (Fig. 13-4). Other causes of falsely elevated BP include the extremity being placed below heart level or uneven cuff compression transmitted to the underlying artery. Falsely low estimates result when cuffs are too large, when the extremity is above heart level, or if the cuff is deflated too rapidly to detect appropriate Korotkoff sounds.19

Geddes14 stated that the width of the BP cuff should be 40% of the circumference of the arm. The pneumatic bladder should span at least one half of this circumference and should be centered over the artery. One of the cuffs shown in Table 13-1 will be accurate in most patients.

| Table 13-1. Commonly Available Blood Pressure Cuff Sizes |
|---------------------------------|-----------------|
| **Cuff** | **Arm Circumference (cm)** | **Bladder Size (cm)** |
| Newborn | 6-11 | 2.5 x 5 |
| Infant | 10-19 | 6 x 12 |
| Child | 18-26 | 9 x 18 |
| Adult | 23-35 | 12 x 23 |
| Large arm | 33-47 | 15 x 33 |
| Thigh | 46-66 | 18 x 36 |

Courtesy of WA Baum Co., Inc., Copiague, NY.
Consideration should also be given to placement of the stethoscope over the brachial artery. Loose-fitting diaphragm-type stethoscopes, a poor seal with a bell-type stethoscope, or motion of either stethoscope will result in attenuation of the Korotkoff sounds. The Diason stethoscope bell is particularly helpful for achieving good skin contact over the brachial artery.

The cuff deflation rate should be slow enough for the sensing process to detect appropriate Korotkoff sound changes and to assign them to the pressure of the cuff. Failure to do so will result in falsely low pressures. A deflation rate of 3 mmHg per second limits this source of error. Coupling of the deflation rate to heart rate (2 mmHg per beat) has been found to further improve accuracy.

Oscillometry

The oscillometric method of NIBP monitoring senses variations in the pressure within a BP cuff during deflation. The cuff is pressurized until no oscillations are seen and is then allowed to deflate until sudden fluctuations in the pressure of the cuff are noted on a pressure gauge. At this point, the cuff pressure is at or near the systolic pressure. The inflation pressure is then allowed to fall further, until the oscillations are seen to reach a maximum and begin to decrease. This point has been shown to be near the mean arterial pressure, not the diastolic pressure as had been previously thought (Fig. 13-5). Two cardiac cycles are compared at each increment if "noise" conditions are low. With increased noise (patient or cuff movement), inflation is held until successive comparative beats occur. Under these conditions, measurement becomes time-dependent, although normally the entire sequence from measurement to display is 20 to 45 seconds. The averaged pairs of oscillations and the corresponding cuff pressures are stored and analyzed electronically to determine systolic, diastolic, and mean pressures. The heart rate is the median of rates obtained by analysis of all pressure pulses in a given determination.

The first commercially produced automatic oscillometric BP monitor, the Dinamap (Carestream, Tampa, FL), entered routine clinical use in 1976. Initially, it determined only mean arterial pressure (MAP), primarily because a change in MAP is easier to interpret than changes in systolic or diastolic pressure, which can often move in opposite directions. Also, at the capillary bed level, most of the pulsation caused by the oscillations of systolic and diastolic pressure has been damped out by the resistance and compliance of the proximal vascular bed. In addition, MAP measurement is less affected by changes in vascular tone than systolic or diastolic pressure measurement because it is determined when the oscillations of cuff pressure reach the greatest amplitude. This property allows MAP to be measured reliably even in cases of hypotension with vasoconstriction and diminished pulse pressure. In fact, oscillometry is the only noninvasive method that directly estimates mean BP.

The technique for ideal oscillometric NIBP measurement is illustrated in Figure 13-6. All three pressures are determined individually, and, in contrast to the manual auscultatory method, there is little effect on the accuracy of the measurement when venous engorgement from cuff inflation is not allowed to subside.

Difficulties in BP measurement by oscillometry may arise due to (1) incorrect cuff size, (2) incorrect cuff application, (3) undetected leaks in the cuff, hoses, or connectors, (4) failure to keep the cuff at heart level, (5) arm movement, and (6) inadequate pulse-pressure waves due to shock or vascular compression proximal to the cuff.

In spite of these potential difficulties, numerous reports attest to the accuracy and reliability of the Dinamap monitor in both neonates and adults. Most of these studies have shown that there is less than 5 mmHg mean error with a standard deviation of less than 8 mmHg when a Dinamap is compared with a centrally placed arterial catheter. The current models of the Dinamap display systolic, mean, and diastolic BP as well as heart rate (Fig. 13-7).

Blood Flow Detection

There are three commonly used techniques for measurement of systolic BP by detection of blood flow distal to an occlusive cuff. There is no way to measure the mean or the diastolic pressure using this technique.

Palpation. The first method utilizes palpation of the arterial pulse distal to a pneumatic cuff. In brief, an arm cuff of sufficient width is inflated to a point 30 mmHg higher than the point of disappearance of the pulse. The cuff is deflated at a rate of 2 to 3 mmHg per heartbeat. The point of return of the radial pulse denotes the systolic pressure. Patients with irregular heart rates such as those in atrial fibrillation will demonstrate a wide range of systolic pressures, particularly if the cuff is allowed to deflate rapidly. Whenever two systoles occur in close proximity, there is less time for filling of the left ventricle and both stroke volume and BP are lower during the second beat. It is thus possible to miss a beat or two and interpret the BP as lower than it actually is. If the palpated vessel is some distance from the cuff, flow transmission time will delay sensing of systolic pressure slightly (flow velocity is approximately 8 to 10 m/second). Overall, systolic BP measurements by palpation are lower than those determined with Korotkoff systems. This technique has been found useful in neonates, infants, obese patients, and those in whom Korotkoff sounds are inconsistent. In infants, the "flush" method, a variation of the palpation method wherein the pressure at which limb color
Figure 13-6. Blood pressure measurement technique illustrating the ideal measurement condition in the absence of artifact. The cuff pressure and oscillation amplitude (AMP) are plotted on the same axis, with the cuff pressure amplitude axis on the left and the oscillation amplitude axis on the right. Mean arterial pressure (MAP, M) is calculated from systolic (SYS, S) and diastolic (DYS, D) pressures. In this subject, cuff pressure is considerably above systolic pressure and no cuff pressure oscillations are visible either in the figure or the microprocessor. (From Ramsey M: Blood pressure monitoring: Automated oscillometric devices. J Clin Monit Comput 1991; 7:56.)

returns, is noted. The flush method depends highly on speed of cuff deflation, peripheral perfusion, and operator skill.

Ultrasonic. More sensitive than the palpation method of measurement of blood flow, an ultrasonic blood flow detector employs an ultrasonic Doppler unit placed over a distal artery. The Doppler transceiver monitors blood flow in the artery by sensing the velocity of erythrocytes. As the ipsilateral upper arm cuff is inflated above systolic BP, the audio output from the unit becomes silent as arterial erythrocyte movement ceases. Systolic pressure is signaled by the cuff pressure at which “chirps” from the Doppler unit indicate blood flow that rhythmically follows the heartbeat. Diastolic pressure is signified by the point at which full pulsatile flow occurs. This method is particularly useful when the peripheral pulse is faint or absent as in patients who are cold and in shock and in infants or obese patients whose Korotkoff sounds may be absorbed by fatty tissue.

A significant disadvantage of ultrasonic blood flow detectors is that electro-surgical equipment produces audible interference, which can be annoying or even render BP determination impossible. Newer Doppler flow detectors employ circuits to eliminate this problem by automatically shutting off the external speaker circuit when the electro-surgery unit is activated.

Photocell. This technique measures the absorption of light from a source placed against the skin, most conveniently on a finger. The pulsatile changes in blood volume associated with blood flow produce changes in absorption of infrared light. If a cuff is inflated above arterial pressure and then allowed to deflate, a sudden small oscillation in the output of the blood flow detector is seen that is equivalent to the systolic pressure. When the pulse volume amplitude no longer increases, diastolic pressure is reached.

The technique fails, however, if the blood vessels in the finger become constricted due to either hypothermia or hypotension. Furthermore, the constant light source produces a moderate amount of heat that, in combination with poor blood flow under the transducer, may lead to thermal injury.

Ultrasonic Detection of Arterial Wall Movement
In addition to detecting the flow of erythrocytes, the Doppler principle can be used to indirectly measure BP by detecting motion of an arterial wall distal to an occlusive pneumatic cuff (Arteriosonde 1216, Roche Medical Electronics Division, Cranbury, NJ). A dual-piezoelectric crystal ultrasonic transducer is placed over the artery. One crystal acts as the transmitter of an ultrasonic signal (commonly 2 to 10 MHz), while the other receives the reflected sound wave. With no target (artery) movement, the receiving crystal senses a constant signal frequency. When the cuff pressure falls just below systolic pressure, the vessel opens and then quickly closes as the peak (systolic) pressure wave subsides. This sudden movement of the arterial wall causes a Doppler frequency shift, which is noted by the receiving crystal. The initial arterial opening is taken as the systolic pressure read-

Figure 13-7. Dinamap. (Courtesy of Critikon, Tampa, FL.)
Diastolic pressure is determined when cuff pressure falls to the point where the artery is open throughout the pulse cycle so that the rhythmic arterial opening and closing is no longer present. Several studies comparing NIBP measured by ultrasound to direct intra-arterial pressures in both adults and infants found satisfactory results in most clinical applications.

InfraSonde

The InfraSonde (Puritan Bennett Corp., Carlsbad, CA) uses the auscultatory method to automatically determine systolic and diastolic pressures. Like the Dinamap, the InfraSonde provides for automatic inflation of an arm cuff. Two crystal microphones are positioned over the brachial artery and are used to determine the point at which the Korotkoff sounds first appear. The cuff deflates at a rate selected by the operator, a determination is then made of the systolic, mean, and diastolic BPs. Accuracy is ensured by a display of the signal strength, a useful feature that aids the operator both in accurately positioning the cuff and for indicating the signal-to-noise ratio under which the machine is operating. As one might infer, the leading disadvantage of the InfraSonde is that it must have its sensors placed accurately over an artery. If the sensors shift away from the artery, the signal strength drops and the machine is unable to give a satisfactory NIBP reading. Unlike the Dinamap, the InfraSonde cannot be placed easily over any portion of an extremity. It thus trades convenience of cuff placement for rapidity of BP determination.

Finapres

First described by Pernaz in Czechoslovakia, the Finapres (finger arterial pressure) consists of a small cuff placed over a patient's finger. The cuff is connected to a very rapidly responding solenoid that inflates and deflates the cuff, keeping the volume of the finger constant as pulsatile blood flow increases or decreases. When the instrument senses that finger volume is expanding due to inflow of blood under the constricting cuff, the solenoid pressurizes the cuff just enough to prevent further blood flow. Thus, the device tends to track the mean arterial BP in digital arteries underlying the cuff by nulling the transmural pressure under the cuff. A waveform that closely approximates arterial BP in the finger is displayed on the screen.

The accuracy of the Finapres has been the subject of considerable study. Stokes and coworkers compared Finapres values with invasive arterial pressures and concluded that, while providing useful beat-to-beat information on arterial pressure trends, the Finapres could not be recommended as a universal substitute for invasive arterial pressure monitoring. Kuriki et al. looked at the optimal measurement conditions and factors affecting reliability. They found that pressures measured in the thumb correlate with intra-arterial pressure better than do pressures measured in other digits. Changes in hemoglobin saturation affect the transmission of light to the device but not the pressure readings. Gorback and associates compared the Finapres with the Dinamap and found that readings by both correlated well for diastolic and mean arterial pressures, while the accuracy of the Finapres appeared to be slightly superior for systolic pressure. Epstein and coworkers compared Finapres and Dinamap measurements with intra-arterial pressures. They found that the Finapres had a significantly higher bias than the Dinamap for diastolic and mean BP when compared to intra-arterial pressure. They concluded that the Finapres monitor could not be relied on to accurately measure BP (without a second method of BP measurement) in patients undergoing general anesthesia.

Additional studies comparing NIBP and invasive arterial pressure readings were performed by Brunner and colleagues and are summarized in Figures 13-8, 13-9, and 13-10. In their series of patients, they found that the correlation between invasive and automated noninvasive measurements was not very good for systolic pressures and that the correlation with diastolic pressures was even worse. In contrast, the correlation between Riva-Rocci systolic pressure and intra-arterial catheter occlusion pressure was found to be quite good.

Arterial Tonometry

The technique of arterial tonometry utilizes a pressor sensor positioned over a superficial artery and records arterial wall displacement, which is then converted into an electrical signal. It requires an adequately sized superficial artery that is supported by a bony structure. The sensor exerts pressure...
on the artery, partially flattening it against the underlying bone (Fig. 13-11). The force exerted by the blood vessel is then transmitted through the skin with near-perfect fidelity. The technique is based on the following assumptions: (1) the skin thickness is insignificant compared to the arterial diameter; (2) the arterial wall behaves essentially as an ideal membrane; and (3) the sensor is smaller than the flattened area of the artery and is centered above the flattened area. It has been shown that the electrical output signal of the generated force is directly proportional to the intra-arterial BP.

The CEM-3000 (Colin Medical Instruments Corp., San Antonio, TX) is a multiparameter monitor that employs the newly developed transducer array for tonometric BP monitoring. The transducer array is incorporated into a sensor that is placed over the radial artery just proximal to the wrist joint. The sensor assembly is formed to hold the wrist with the proper degree of extension. A microprocessor analyzes the signal from each transducer of the sensor array and selects the transducer that is properly positioned based on maximum pulse amplitude of the signal. Hold-down pressure is set via microprocessor control of a pneumatic bladder that is incorporated into the sensor assembly. The tonometric BP readings require calibration to oscillimeter cuff measurements at user-selected intervals of either 5 or 10 minutes.

Figure 13-11. Diagram of the multsensor arterial tonometer in use. The tonometer is placed over the artery and secured with sufficient force to partially flatten the artery. The arterial waveform is then recorded with near-perfect fidelity. (From Eckel JS: Arterial tonometry. In Webster JG (ed): Encyclopedia of Medical Devices and Instrumentation. New York, John Wiley & Sons, 1988, pp 2270-2283.)

Several studies have compared tonometric BP measurements against invasive radial artery pressure tracings in anesthetized patients. A good correlation was found between the two techniques, with identical pressure waveforms found in both tonometric and intra-arterial BP recordings.40-42

Photometric Wave Velocity Technique

The refinement of pulse oximetry technology has led to advances in photometric sensor development and signal processing techniques that permit NIBP measurement without use of artery occlusion. Instead, systolic and diastolic BP values are determined by measuring arterial pulse wave velocity and changes in local blood volume. The ARTRAC 7000 monitor uses two photometric sensors similar to those used by pulse oximeters, one of which is placed on the ear and the other on a finger. The pulse oximeters sense each heartbeat, with the proximal (ear) pulse arriving before the distal (finger) pulse. The difference in arrival time is called the pulse transit time. The proximal sensor also senses changes in microvascular volume. The pulse wave velocity is a relative measure of diastolic pressure, so that an initial calibration with a traditional BP cuff is necessary to obtain absolute pressure values.

When compared with NIBP data obtained with a BP cuff, the ARTRAC has been found to be within the American Association of Medical Instrumentation (AAMI) and American National Standards Institute (ANSI) standards. When compared with invasive arterial pressures, the bias was within standards for systolic and mean pressures and within a mean value of 7 mmHg for diastolic pressures (D. H. Wong and D. R. Bogard, personal communication, 1999.)

Special Situations

NIBP Measurement at Rest and During Exercise

Accurate and reliable determination of BP is important for assessment and interpretation of exercise tests. Unfortunately, both "gold standard" methods of BP measurement, intraarterial and manual auscultatory sphygmomanometry, are problematic and unreliable.44,45 A new motion-tolerant BP monitor, the CardioDyne NIBP 2000 unit (Luxtec, Worcester, MA), uses a proprietary differential sensor to detect the Korotkoff sounds produced during BP measurement. This machine was compared with standard manual sphygmomanometry at rest and during exercise in 19 healthy normotensive subjects. The automated device largely eliminated prob-
lems associated with manual measurement, such as variable hearing acuity among technicians, intertechnician variability, and technician terminal digit bias. MacRae and Allen found Cardiodyne Nelson 2000 to provide accurate and verifiable information.

Ambulatory Blood Pressure Monitor in Children

The importance of BP in early life has been highlighted by Barker et al., and 24-hour studies in children have been carried out by a number of groups. If NIBP monitoring devices are to be used in children, they should be validated in the pediatric population, as BP measurement in children poses specific problems. The Takeda 2421 (A & D, Japan) is a monitor that uses both the oscillometric and auscultatory (Korotkoff) methods of BP measurement in normal school children. From a study in 529 school children, O'Sullivan et al. found that the Korotkoff method gave more satisfactory readings as compared with oscillometric readings.

Blood Pressure Measurement in Pregnancy

The indirect measurement of BP has an established place in antenatal care, although there is no universal agreement regarding the use of the fourth (K4, muffling prior to final disappearance) versus fifth (K5, final disappearance) Korotkoff sounds to identify the diastolic BP. The World Health Organization (WHO) and International Society for the Study of Hypertension in Pregnancy (ISSHP) favor the use of K4 to determine the diastolic BP in pregnant women, whereas K5 is favored in the United States. Duggan, from a study of 132 pregnant women, found K5 to be more often and more reliably detected than K4.

Complications of Noninvasive Blood Pressure Devices

Skin and tissue compression from NIBP monitors, which can lead to skin irritation and bruising, are probably the most common complications. Prolonged use and frequent BP determinations can lead to venous pooling and congestion. Excessive venous pressure can lead to tissue ischemia and nerve damage; in fact, ulnar nerve damage has been reported when a cuff applied too distally on the arm caused direct compression of the ulnar nerve in the ulnar groove. Intravenous injection of irritating substances during cuff inflation may cause tissue damage owing to a locally increased concentration. Accidental injection of succinylcholine into a vein distal to the inflated cuff of an automated device during a rapid-sequence anesthetic induction may preclude timely intubation.

Invasive Blood Pressure Monitoring

Catheter Insertion Technique

By definition, invasive BP monitoring involves insertion of a hollow device into the lumen of the arterial tree so that it can be connected to an appropriate pressure transducer via a fluid-filled tube (Fig. 13-12). Whereas the radial artery is by far the most common cannulation site, there are a number of additional sites that may be indicated depending on the patient’s size and physical limitations (Fig. 15-13). Since the early 1960s, the most widely used technique for percutaneous cannulation for direct arterial monitoring has been the “catheter-over-needle” approach first described for radial artery cannulation by Burr. This approach requires meticulous antiseptic skin preparation, identification of the course of the artery by palpation, and advancing of the catheter-stylet device at a shallow angle relative to the vessel. When blood is observed in the flush chamber of the stylet, the catheter is advanced into the lumen of the vessel (Fig. 13-14).

Because peripheral arteries are frequently difficult to palpate in hypotensive or vasoconstricted patients, a variety of techniques have evolved to assist in successful cannulation. Among these are use of transillumination to help identify arteries in infants and fine-tip Doppler ultrasound probes to identify weakly palpable arteries in adults (Fig. 13-15). A common clinical problem is that the tip of the needle may enter the vessel but the catheter, being larger, will not “thread” into the lumen. Minature, flexible guidewire introducers for 20- and 22-gauge catheters have helped to obviate this problem, since the small guidewire usually can be introduced into the vessel lumen and inserted past intima, atheromas, or other obstructions that prevent successful catheter passage. Additional techniques to rescue cannulation from the “no thread” phenomenon include removing the needle from the catheter and alternately (1) withdrawing the catheter until a flash of blood indicates that the catheter tip is in the middle of the lumen, or (2) attaching an air- or fluid-filled plastic extension tube to the catheter and withdrawing the catheter until the air bubble pulsates maximally, again indicating that the catheter tip is in a central location in the vessel lumen. Either of these techniques and a bit of good fortune, the catheter can then be advanced up the lumen of the vessel. A variant on these techniques is the “liquid stylet” approach, where a 10mL syringe is applied to the cannula hub after a “no thread” is encountered. The cannula is withdrawn while suction is applied to the syringe until blood flows readily; the cannula is then advanced while 1 to 2 mL is injected with the syringe. Because the “no thread” phenomenon usually results from the catheter impinging on the lateral or deep wall of the artery while only part of the needle tip is in the arterial lumen, meticulous identification of the vessel and stabilization of the extremity all seem to help to minimize this problem.

Physical Factors of Arterial Cannulas

Arterial catheters are manufactured from a variety of plastics, each with different structural properties and tissue reactivity. Most utilize polytetrafluoroethylene (Teflon), polypropylene, polyvinyl chloride, or polyethylene. Although polyethylene catheters were originally popular because they were stiff enough to avoid kinking and could be extruded into a very fine tip, several clinical studies found them to be more thrombogenic than Teflon catheters. While Teflon catheters are prone to kink, particularly at fine gauges (22 to 25), Teflon is currently the most widely used plastic catheter material because both in vivo animal testing and clinical use in humans have shown it to be less thrombogenic than polyethylene, polyvinyl chloride, or polyethylene. Although heparin coating or impregnation has been shown to be of short-term value for arterial cannulation, the heparin leaches out of the plastic after a day or two and no further reduction in thrombogenicity is gained. The size of an arterial catheter is also an important consideration, both for the monitoring system to perform optimally and for minimizing vascular damage induced by the
catheter. In terms of minimizing vascular damage, it appears that the smaller an arterial catheter is relative to the size of the artery, the lower the incidence of vessel thrombosis. Conversely, however, smaller catheters are manufactured with thinner walls and are more prone to kink between the skin and the artery (Fig. 13–16). Within 24 hours of insertion, 20% of 20-gauge radial artery catheters kink, resulting in significant degradation of catheter performance. The BP pulse wave becomes damped, and difficulty is encountered in recovery of blood samples. Occasionally, a kinked catheter can be straightened by rotating the catheter through a 180-degree arc, or by applying distal traction and withdrawing it slightly. In the case of a kinked radial artery catheter, the temptation to hyperextend the wrist to straighten the kink and restore a pulse-pressure wave should be avoided, as this may lead to stretching of the median nerve with subsequent hand numbness. As a last resort, a kinked catheter may be replaced by inserting a sterile, flexible guidewire into the catheter while it is straightened with distal traction; the old catheter is then removed, and a new one is introduced into the vessel over the guidewire.

**General Hazards of Invasive Blood Pressure Monitoring**

In general terms, the hazards of invasive arterial pressure monitoring can be summarized as (1) vascular compromise, (2) disconnection, (3) accidental injection, (4) infection, and (5) damage to nearby nerves. The problems of vascular compromise and nerve damage will be considered in the individual sections discussing the various sites suitable for arterial cannulation.

In a monitoring system exposed to systemic arterial pressures, it should go without saying that a disconnection could potentially result in a patient’s rapid exsanguination. Accidental injection of noxious substances into a peripheral artery can be disastrous for an entire limb. The serious complications of intra-arterial thiopental and thiopental injection are well known, as are those of intravenous vasoconstrictors. Ketamine injected via a dorsalis pedis artery catheter caused severe skin necrosis that extended proximally over the anterior and lateral portion of the leg and foot, and required 5
weeks for the patient to recover.71 Similarly, retrograde injection of blood clots via a radial artery cannula have resulted in cerebrovascular ischemia,72 as well as distal embolization and ischemia.66,71

Arterial monitoring catheters may result in nosocomial infection due to either local or systemic sepsis. Local infections are thought to be caused by introduction of cutaneous bacteria at the time of cannulation and are usually of staphylococcal origin. The longer the cannula is in place, the greater the risk of local infection.74-76 Unlike peripheral venous catheters, however, femoral arterial cannulas are not associated with a higher infection rate than other cannulation sites.79 Ointments applied to intravascular catheter sites reduced the local infection rate from 6.5% in nontreated patients to 3.6% with Iodophor and 2.2% with polymyxin, neomycin, or bacitracin ointment. However, these ointments have been associated with an increased incidence of Candida infections. Iodophor ointment is recommended for intravascular cannulation sites.80 In addition, use of antibiotic-impregnated catheters has been advocated to reduce infectious complications from peripheral arterial catheters.81

Bacteremia is also associated with use of arterial monitoring systems. This may be the result of contamination of the tubing system,82-84 or the catheter itself may become a nidus for infection due to seeding from septicemia. Stopcocks are often the route of access when bacteria are manually transferred to the tubing system (see Fig. 13-12), although the use of contemporary isolated disposable transducer systems (as opposed to the disposable dome shown in Fig. 13-12) has markedly reduced the risks of bacterial contamination85

and studies support the use of these systems for up to 4 days without replacement.86 Arterial thrombi induced by monitoring catheters also may act as a septic nidus,87 occasionally requiring surgical removal of the thrombus to treat the infection.89,90

Current Centers for Disease Control and Prevention (CDC) recommendations93 for prevention of infections related to peripheral arterial cannulas include the following:

1. Use sterile technique, including gown, mask, and gloves and sterile drapes for catheter insertion.
2. Cleanse the skin site with appropriate antiseptic before catheter insertion and allow antiseptic to remain in the insertion site for an appropriate duration before insertion.
3. Replace dressings when damp, loose, or soiled.
4. If local cutaneous infection is present at the skin puncture site, remove the catheter.
5. If catheter-related infection is suspected, remove the catheter using guidewire assistance. If catheter-related infection is documented, remove the catheter.
6. Use disposable, rather than reusable, transducer assemblies with closed, continuous flush systems whenever possible.
7. Sterilize and disinfect reusable transducers in a central processing area.
8. Treat stopcocks as a sterile field and keep covered with a cap or syringe when not in use. Do not use arterial catheters for routine blood sampling that does not require arterial blood.
9. In adults, replace catheters, transducers, and flush tubing at 96-hour intervals.
10. If persistent bacteremia occurs while an arterial catheter is in place, remove the catheter 24 to 48 hours from the time antimicrobial therapy has been started.

Sites for Invasive Blood Pressure Cathulation

Radial Artery Cathulation

Advantages and Disadvantages. Percutaneous radial artery cannulation rapidly achieved widespread popularity for invasive BP monitoring shortly after its initial description by Barr in 1951.34 The reasons for this popularity are obvious (1) the vessel is superficial and easy to identify; (2) the cannulation site is accessible; (3) the procedure is reasonably reliable and pain-free for the patient; and (4) collateral circulation to the hand is abundant and easy to document and the likelihood of inducing distal vascular ischemia is quite low.

On the other hand, the radial artery is not the ideal cannulation site for acquiring hemodynamic data. The radial pulse-pressure wave is subject to considerable systolic pressure augmentation because it is distal and close to the point of pulse wave reflection. Furthermore, the radial artery lumen diameter is relatively small (2 to 3 mm), and it frequently becomes occluded by either the catheter or catheter-induced thrombus.82 Thus, the site of pulse wave reflection is right at the site of cannulation, and systolic pressure becomes augmented with high-frequency pressure wave transients that give a falsely elevated systolic pressure value.

Radial arterial pressures are also fraught with abnormal pressure gradients between the aortic and radial arteries associated with cardiothoracic operations85 and separation
from cardiopulmonary bypass, particularly during and following rewarming. It is thought that the latter differences (up to 32 mmHg) may be due to changes in vaso-motor tone associated with the wide temperature fluctuations and endocrine responses to cardiopulmonary bypass.

A previous diagnostic catheterization performed in the brachial artery should probably precede use of the ipsilateral radial artery, since pulse-pressure waves may be markedly damped and a low-flow state may tend to induce hand ischemia. Other factors that might affect the site of radial artery cannulation include use of the right radial artery for thoracic aneurysm surgery, because the left subclavian is often occluded during surgery, or use of the right radial in premature infants with a patent ductus arteriosus, where the left side would receive desaturated blood from the ductus arteriosus. Finally, cannulation of the radial artery in a hand with inadequate ulnar artery collateral circulation may result in limb ischemia.

There are probably as many techniques for cannulation of the radial artery as there are clinicians performing it. The radial artery is quite tortuous as it passes over the wrist joint (Fig. 13–18). Just palpating a pulse at one point near the wrist does not indicate where the vessel may be when the catheter reaches the depth of the artery, and it does not guarantee that the catheter will be aligned with the vessel lumen when it enters the vessel wall. Accordingly, dorsiflexion and immobilization of the wrist, and identification of the course of the vessel with palpating fingers or a skin-marking pencil may increase the likelihood of successful cannulation (see Fig. 13–14). Cannulation of the radial artery proximal to

Figure 13–15. The Smart Needle Doppler device for cannulation of peripheral and central veins with ultrasound localization. Both 18- and 20-gauge cannulas may be inserted using this technique. (From Lake CL: Cardiovascular Anesthesia. New York, Springer-Verlag, 1985, p 54.)
the wrist joint (where it is straighter) may also improve the success rate. Although its greater depth may make it more difficult to palpate, the catheter may slide into the vessel lumen more readily because the vessel is straighter at this location. The improved cannulation success rate of the Arrow radial artery catheterization set (Arrow International, Reading, PA), with its built-in flexible guidewire, is possibly due to the propensity of most clinicians to go where the artery is most superficial rather than where it is straightest.68 Once the vessel lumen is entered, the flexible guidewire can negotiate turns that a straight needle and catheter assembly cannot manage.

The impact on vessel function of multiple arterial punctures during attempted cannulation is controversial. Some think that traumatic cannulation is responsible for most ischemic problems related to invasive BP monitoring,99 whereas others have found no evidence for such a claim.100 Transfixion of the radial artery during cannulation has not been found to cause a higher incidence of vascular occlusion than techniques where only the superficial wall of the vessel is punctured during cannulation.101-105 Pseudoaneurysm formation, however, is a well-recognized complication of radial artery cannulation.106 This is usually heralded by the presence of a pulsatile hematoma at the cannulation site as a result of a persistent hole in the vessel wall, often associated with anticoagulation. Conservative management, with Doppler-guided compression over the site of leakage, is thought to be the treatment of choice.106

Trauma during radial artery cannulation may, however, result in nerve damage or compartmental syndrome, or both, at the wrist related to persistent bleeding from puncture sites.106 Figure 13-19 shows extravasation of radiopaque contrast material outside of a radial artery that had just been cannulated by a transfixing technique. With multiple arterial punctures, particularly in anticoagulated patients, considerab-ly more extravasation probably occurs. While the radial nerve lies close to the radial artery, it is the median nerve that has been associated with evidence of neuropathy (pain, weakness, hand wasting) following multiple radial artery punctures, cutdown cannulation, or traumatic attempted percutaneous cannulation.107, 108 Postmortem examination has shown hematomas from the radial artery extending over the flexor carpi radialis and compressing the median nerve proximal to the transverse carpal ligament. Presumably the median nerve is more susceptible because it is confined within the carpal tunnel and is subject to compression by spreading hematoma. Another possible cause of hand pain after radial artery cannulation is prolonged dorsiflexion of the wrist with stretching of the median nerve.109 Thus, it is probably advisable to return the wrist to a more neutral position after cannulation.

Radial artery thrombosis occurs frequently after cannulation for BP monitoring and may contribute to catastrophic ischemic injury to the hand (see below). In general, a higher incidence of arterial occlusion results from progressively longer periods of cannulation.104, 105, 110, 111 and the use of larger catheters made of non-Teflon-containing plastics. Data in adults patients suggest a 10% overall incidence of arterial occlusion in adults cannulated with 20-gauge Teflon catheters in place for a period of 1 to 3 days110 (Fig. 13-20), whereas use of 22-gauge Teflon catheters for 24 hours reduces the risk of arterial occlusion to close to zero.112

The size of the radial artery lumen relative to the cross-sectional area of the cannula also affects the incidence of vessel thrombosis.95 (See Fig. 13-16). Women have a higher incidence of radial arterial occlusion than men,110, 111 and the incidence of radial arterial occlusion in neonates reaches as high as 72% when 22-gauge catheters are left in place for up to 10 days.114 By contrast, adults sustain approximately a 50% incidence of occlusion when 20-gauge radial
move clot from the artery and reestablish blood flow past the area of occlusion.

The most common complication associated with radial artery cannulation that results in significant morbidity is not distal vascular insufficiency, but rather ischemic necrosis of the skin overlying the cannula (Fig. 13-27). This lesion requires several weeks to heal by secondary intention. Originally described as an incidental, isolated finding, this lesion is associated with 0.5% to 3.0% of all cannulations\(^{137}\) and 10% of all thrombosed radial arteries regardless of the duration of cannulation or the size of the cannula.\(^{64}\) Arteriography demonstrates occlusion of the small, cutaneous, perforating branches of the radial artery due to thrombosis around the cannula, and postmortem examination has found thrombus extending into the branches of the radial artery. The incidence of this problem has decreased with the use of smaller catheters, presumably because fewer thrombi are produced.\(^{14}\)

Given that there is a high incidence of radial artery occlusion associated with percutaneous cannulation, the importance of collateral circulation to the hand should not be underestimated. Coleman and Asano\(^{118}\) performed 659 anatomic dissections to identify the three arterial arches anastomosing between the radial and ulnar arteries: (1) a superficial volar arch (complete in 86% of specimens) formed primarily as a continuation of the ulnar artery; (2) a deep volar arch (complete in 50% of specimens) formed from the

---

**Figure 13-17.** Radiograph of a nonfunctional, 20-gauge radial artery catheter showing three sites of kinking: 1, above the skin; 2, between the skin and the artery; and 3, within the artery lumen. (From Bedford RE, Shab NJ. Blood pressure monitoring: Invasive and noninvasive. In: Ellis CD, Hines RL: Monitoring in Anesthesia and Critical Care Medicine. New York, Churchill Livingstone, 1995, p 95.)

**Figure 13-18.** Arteriogram performed by injecting contrast material through a radial artery catheter. Note the tortuosity of the artery as it passes over the wrist joint. (From Bedford RE, Shab NJ. Blood pressure monitoring: Invasive and noninvasive. In: Ellis CD, Hines RL: Monitoring in Anesthesia and Critical Care Medicine. New York, Churchill Livingstone, 1995, p 95.)
continuation of the radial artery, and (3) a dorsal arch (complete in 82% of specimens) formed primarily as a continuation of the dorsal radial artery and anastomosing with either the interosseous or ulnar arteries. These findings have been verified by radiologic examinations, such as that seen in Figure 13-28, in which collateral flow from the ulnar artery supplies blood to the entire hand and radial artery distal to a cuff-induced, occlusive lesion. Digital blood flow in turn radiates from the palmar arches, such that if occlusion of the radial artery is caused by a monitoring cannula, it rarely results in distal vascular ischemia of the hand because of the abundant collateral circulation from the ulnar and median interosseous arteries.

Accurate assessment of ulnar collateral circulation seems warranted because anatomic studies predict that approximately 3% to 6% of patients have incomplete palmar arterial arches. These findings have been verified clinically by Husain and Palm, who found that 6% of 250 patients undergoing cardiovascular surgery had inadequate unilateral flow unilaterally (determined by a systolic BP of < 40 mmHg in the thumb during radial artery occlusion) and 4% had inadequate ulnar flow bilaterally. Furthermore, several studies have found markedly impaired radial artery flow soon after cannulation such that the hand is entirely perfused by collateral flow. In patients with acromegaly, in which ulnar artery flow is often compromised by ligamentous hypertrophy at the wrist, it has been recommended either that radial artery cannulation be avoided or that particular attention be given to documenting adequate ulnar collateral circulation before the radial artery is cannulated.

Allen's test, devised in 1929 as a method for diagnosing occlusive arterial lesions at the wrist caused by thrombosing its obliteratoris, is both popular and controversial as a technique for documenting adequate collateral circulation from the ulnar artery to the entire hand. Allen described having the patient alternately squeeze and relax his hand to ennuliate it while the examiner occluded both the radial and ulnar arteries with fingertip pressure. Patency of the ulnar artery was indicated by a "prompt return to color" in the hand when pressure over the ulnar artery was released. Allen did not intend to document blood flow to the entire hand, but only to diagnose arterial occlusion at the wrist.

When used to document collateral flow, Allen's test "return to color" has been a source of confusion. Some clinicians have mistaken a blush in the center of the palm as indicative of blood flow passing all the way from the ulnar artery to the thumb and thenar eminence. Others thought that a 15-second "return to color" indicated satisfactory collateral circulation. The result of these misinterpretations was a 10% incidence of cold, white thumbs associated with radial artery occlusion. More recent studies using a 5-second limit on complete "return to color" of the hand, particularly the thumb and thenar eminence, have found Allen's test to be a satisfactory technique for documenting patency of ulnar collateral circulation, although Husain and Berthelot found a 1% chance of inadequate thumb flow.

Figure 13-19. Contrast material extravasating from the deep wall of a radial artery recently cannulated with a transfusing technique. Such extravasation appears to play a role in median nerve dysfunction associated with radial artery cannulation. (From Bedford RF, Shah NK: Blood pressure monitoring: Invasive and noninvasive. In Bitt CD, Hines RL: Monitoring in Anesthesia and Critical Care Medicine. New York, Churchill Livingstone, 1995, p 95.)

Figure 13-20. Incidence of radial artery thrombosis plotted against duration of cannulation for 18- and 20-gauge catheters. (From Bedford RF: Long-term radial artery cannulation: effects on subsequent vessel function. Crit Care Med 1978; 6:64.)
with a 6-second "return to color" time from the ulnar artery while the radial artery was occluded.123

Additional problems with Allen's test are: (1) the patient must be awake and cooperative; (2) it is difficult or impossible to interpret in patients who are burned, pale, or jaundiced; and (3) hyperextension of the digits may give a false pallor, resulting in misinterpretation of the test. Because of the problems in interpreting Allen's test, other techniques for documenting ulnar collateral circulation have been developed, including Doppler examination, pulse pressure measurement, or pulse oximetry distal to an occluding finger over the radial artery.144-147 Slogoff et al.115 concluded that Allen's test was not useful because they found no episodes of distal vascular ischemia after cannulating the radial arteries of 16 patients with markedly impaired flow to the hand. Because they failed to document the duration of the cannulation, the size of the catheters used, and what proportion of the patients were men (with large radial arteries and a lower incidence of thrombosis), the results remain controversial.

Despite apparent evidence of satisfactory ulnar collateral circulation, many case reports of severe distal vascular ischemia and gangrene of the hand have been associated with radial artery cannulation128-132 (see Figs. 13-27 and 13-29). To date, only one such case has been definitely associated with thromboembolic phenomena from the heart.133 More commonly, however, hand gangrene is associated with low-
flow states, high-dose vasopressor therapy, and no documentation of ulnar collateral flow. Although distal vascular ischemia has been relieved in some of these cases by thrombectomy, sympathetic blockade, intra-arterial local anesthetic, or papaverine, the 'condition in many patients was totally refractory to therapy,' and they ultimately required amputation of fingers, hands, or forearms. The overall incidence of severe vascular compromise has been estimated at 0.01% of all radial artery cannulations.142 Because these catastrophes usually begin with radial arterial thrombosis, and thrombus around the catheter often causes catheter dysfunction in the form of damped pulse-pressure waves or difficulty in obtaining samples, it has been recommended that evidence of catheter dysfunction probably should be a signal for decannulation.62 This should be performed preferably with vigorous aspiration on the catheter as it is withdrawn in an attempt to remove intra-arterial thrombus.116 Attempts at relieving catheter dysfunction by vigorous flushing, however, may only result in cerebral ischemia due to retrograde flow of clot and flush solution to the carotid or vertebral circulation.73 Such attempts have been shown to cause acute hypertension in neonates.149

Alternative Sites for Arterial Pressure Monitoring

Ulnar Artery. Ulnar artery cannulation is performed in a manner similar to cannulation of the radial artery, although it is somewhat more difficult because the vessel is not as superficial as the radial artery and it tends to be quite tortuous as it passes the wrist joint (see Fig. 13-28). Several studies have referred to the radial and ulnar arteries as interchangeable sites for peripheral arterial cannulation.8-97,119 Because dominant collateral flow to the hand can be from either the radial or ulnar artery, it seems advisable to document collateral flow from the radial artery to the entire hand prior to attempting cannulation of the ulnar artery. Likewise, virtually every technical problem and clinical complication ascribed to radial artery cannulation can also occur in association with ulnar artery cannulation.

Brachial Artery. Cannulation of the brachial artery offers several theoretical and practical advantages over radial and ulnar artery cannulation. It is a larger vessel than the radial or ulnar arteries and may be more amenable to cannulation in infants. In addition, it can accommodate a larger catheter with a higher natural frequency. Furthermore, it is more proximal and, therefore, less subject to systolic pressure augmentation due to reflection of the pulse-pressure wave from distal artery-arteriole junctions. As with other sites, however, the incidence of complications increases with duration of cannulation.140-144

In addition to vascular lesions, damage to the median nerve has also been reported with brachial artery cannulation, either associated with traumatic arterial puncture or hematoma formation.145,146 From a practical standpoint, brachial artery catheters work well when a patient is anesthetized but tend to be a problem in conscious patients in the intensive care unit in whom the elbow joint becomes more difficult to immobilize than the wrist.

Axillary Artery. There are several desirable aspects to cannulation of the axillary artery. The vessel is large, it can tolerate relatively large-bore catheters with a low incidence of thrombotic complications, and it leaves the patient's arms relatively unencumbered. The axillary artery is often palpable in critically ill infants47 and adults, when more peripheral vessels are faint or absent. In addition, the axillary pulse-pressure trace closely represents that in the aortic arch.148-153

Because the axillary arterial catheter is close to the central circulation, meticulous attention must be directed at preventing the entry of air bubbles or clots into the cerebral circulation during catheter flushing or blood sampling. The left axillary artery is the preferred site, since the tip of a 6-Fr catheter in the right axillary artery may lie in the innominate artery, with ready access to the cerebral circulation. Another disadvantage of the axillary artery is its location within a neurovascular sheath, where hematoma formation may result in neurologic consequences.104,167

The approach to the axillary artery is similar to that for an axillary brachial plexus block. Once the vessel lumen is punctured, cannulation can be performed using either a 23-
catheter-needle device or a 6-in. pediatric central venous pressure catheter advanced into the vessel over a guidewire.

Dorsalis Pedis Artery. Cannulation of the dorsalis pedis artery is indicated in clinical situations in which the arteries of the upper extremities are inaccessible, as in extensive burns, trauma, or previous arterial catheterizations. Due to its distal location, however, systolic and diastolic pressure readings are subject to considerable resonance and MAP is the only value that approximates aortic pressure values. Like other peripheral arteries, it is also subject to pseudoaneurysm formation following cannulation. Because it is a small vessel, there is a high incidence of both unsuccessful cannulation and postcannulation arterial occlusion. Fortunately, there is an arterial arcade in the foot that usually supplies collateral circulation from the posterior tibial circulation in the event of occlusion of the dorsalis pedis artery. However, wedge-shaped distal infarcts and impaired toe perfusion have been reported. To assess collateral circulation, Kaplan suggests occluding both the dorsalis pedis and posterior tibial pulses with digital pressure, then blanching the patient’s great toe with direct compression. If the toe color does not promptly (< 5 seconds) return to normal when the posterior tibial artery pressure is released, another site should be selected for arterial cannulation.

Femoral Artery. When used for BP monitoring in adults, the femoral artery has been found to be no more risky than radial artery cannulation. It is a large artery and should be relatively free from catheter-induced thrombosis. However, it is also subject to arteroma formation, which may lead to difficult cannulation, peripheral embolism, and possible distal vascular insufficiency. Several reports list an approximate incidence of 0.5% for ischemia requiring embolectomy after femoral artery cannulation, whereas transient self-limited vascular insufficiency occurs in approximately another 0.5%. In these studies, catheter sizes ranged from 14 to 20 gauge, with no obvious relationship between catheter diameter and the incidence of occlusive lesions. These data suggest that arteromas may act as a prime cause of occlusion while femoral arterial catheters are in place.

Hematoma and pseudoaneurysm formation are also prominent problems with femoral artery cannulation, with the former occurring in 8% to 13% of patients. Both are probably related to placement of catheters through larger needles or via a transfixed cannulation technique. Noncompressible retroperitoneal hematomas have also been reported as a result of unsuccessful femoral artery catheterization, occasionally leading to compartmental syndrome.

As is the case with other intravascular catheters, the incidence of infection increases with the duration of femoral artery cannulation. A 1- to 3-day period appears to be safe, whereas longer periods (4 to 12 days) produce catheter-related infections at a rate of 8% to 17%.

Indications for cannulation of the femoral artery include thoracic aortic surgery, in which the patency of a Gort shunt can be monitored by femoral artery pressure, patients in shock whose other peripheral pulses may be nonpalpable, or those suffering from burns or multiple trauma in whom other sites are inaccessible.

In children, 18- or 20-gauge catheters are often more
easily placed in the femoral than in the radial arteries. However, cannulation of the femoral artery is often avoided in children because of a high incidence of thrombosis in younger children with small vessels, its proximity to the retroperitoneum, the risk of hip capsule puncture with subsequent joint infection, and the potential for decreased limb growth if thrombotic occlusion should develop. In the series reported by Gleniski and coworkers, femoral catheterization was performed in 151 children undergoing cardiac surgery with only a 3.6% failure rate. Decreased limb perfusion occurred in 25% of neonates, but the overall rate of infectious complications was only 3.6% in 165 catheterizations and no permanent complications were noted.

Rosenthal and colleagues noted no reduction in leg growth after femoral cannulation. In children under the age of 10 years, prophylactic administration of heparin 100 U/kg has been found to reduce the incidence of thromboembolic events significantly, from 40% to 8%. In the event that thrombotic occlusion occurs in a child, thrombolytic therapy has been found to be successful in 85% of patients, with only 1% requiring surgical embolectomy.

Superficial Temporal Artery. The temporal artery branches off the external carotid artery, which passes anterior to the tragus of the ear. Temporal cannulation may be useful on an emergent basis if there is no access to other sites, or as a primary cannulation site for BP monitoring during thoracic aortic procedures. The superficial temporal artery is often quite tenuous and difficult to cannulate. First, delineating the arterial course with a Doppler probe may facilitate cannula passage by helping to align the vessel with the cannula assembly. Arterial puncture is often performed at the superior edge of the helix of the ear, either percutaneously or through a 3-mm to 2-cm incision (depending on patient size) with the catheter-needle device in a bevel-down position. The bevel-down position has been found to help prevent posterior arterial perforation, and the catheter can then be advanced centrally. Proper positioning of the catheter tip is crucial, with an optimal location in the external carotid artery 1 cm distal to the junction with the external maxillary artery. Risks of superficial temporal cannulation include vessel thrombosis with resultant scalp ischemia and catheter malposition that permits embolic material to pass centrally to the cerebral circulation via the internal carotid artery. Because of the site, it is often difficult to secure the catheter so that it does not become dislodged.

Umbilical Artery. Cannulation of the umbilical artery is used in critically ill newborns, in whom access to more peripheral vessels may prove difficult or tenuous. The umbilical arteries originate from the internal iliac arteries, cross over the ureters, and pass inferiorly on either side of the
dome of the bladder and cephalad in the anterior abdominal wall to the umbilicus. Either a percutaneous or a cutdown technique may be used. With the percutaneous method, a 16-gauge short catheter is initially placed as an introducer and then a longer 3.5F or 5F catheter is guided through the 16-gauge catheter into the aorta. The cutdown method requires placement of a suture at the base of the umbilicus prior to cutting the umbilical cord several millimeters above the skin. An umbilical artery is identified and a probe is inserted to dilate the vessel prior to passage of the catheter (a 3.5F or 5F catheter). After the catheter is successfully inserted, the suture at the umbilical base is tied around the catheter.

Optimal locations for the catheter tip are just above the aortic bifurcation, below the inferior mesenteric artery, or at the mid-dorsal aorta above the diaphragm. Undesirable locations include the celiac plexus and renal or superior mesenteric arteries. Spasm at the junction of hypogastric and iliac arteries is the most common cause of failure to successfully catheterize the aorta via an umbilical artery.

Complications of umbilical arterial cannulation can be catastrophic, including maternal organ ischemia if the catheter becomes dislodged into a specific intra-abdominal vessel, aortic thrombosis, lower extremity ischemia secondary to arterial vasospasm or embolism, vascular perforation causing hemorrhage and paradoxical central nervous system embolism via a patent foramen ovale. Factors contributing to complications include prolonged use and repeated manipulations. Prophylactic low-dose heparin administration has been shown to lower the incidence of thromboembolic complications. Additional methods to avoid complications include radiographic confirmation of catheter tip location, avoidance of catheter manipulation, use of non-thrombogenic catheters, and timely removal of catheters when no longer indicated.

Conclusions

Will indirect measurement of BP ever replace direct intra-arterial BP monitoring? Probably not, because an arterial catheter also functions as a site for drawing multiple blood samples, when needed. On the other hand, the rapid development of noninvasive CO₂ and O₂ analysis, in combination with reliable NIBP measurements, has probably reduced the overall need for arterial catheterization.

It must always be remembered, however, that invasive arterial pressure monitoring and NIBP measurement reflect two different phenomena. When a catheter is placed in a patient’s artery, the systolic, diastolic, and mean pressures can be obtained even when there is no blood flow in the vessel. In contrast, when an occluding cuff is wrapped around the patient’s arm and inflated, detection of the systolic, diastolic, and mean pressure is possible only because of blood flow under the cuff. Thus, one technique measures
pressure directly, whereas the other detects flow and tries to infer pressure indirectly.

Should we resolve these differences? We believe probably not. Attempts to make the direct and indirect methods of BP measurements correspond can lower the accuracy and repeatability of both methods. One should be content with the fact that each method has its particular advantages, and comparisons, except in the most general terms, should be avoided. The important feature of BP monitoring is that the equipment gives a value, which, in turn, should cause the clinician to think about what is happening to the patient and to act accordingly.

REFERENCES