# Arterial Blood Pressure

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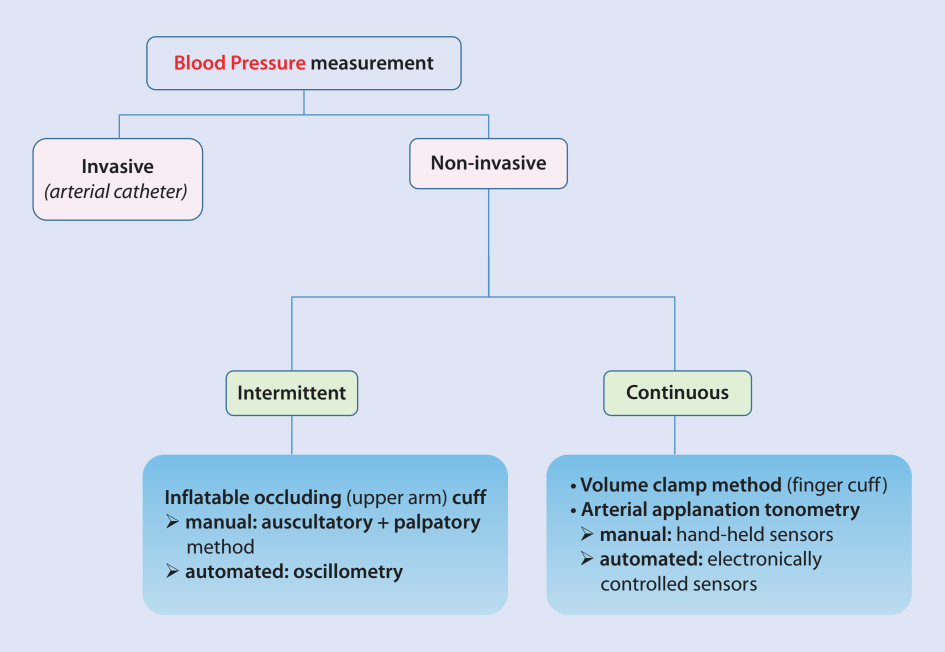
**Learning Objectives**

The measurement of blood pressure (BP) is a key component of hemodynamic monitoring in various fields of medicine, including intensive care medicine, emergency medicine, and anesthesiology. Thus, it is crucial to understand the different technologies available for BP monitoring. This includes understanding the underlying measurement principles of invasive and noninvasive techniques and knowing their advantages and limitations in different clinical settings. In this chapter, we give a brief overview of the history of technologies for BP measurement, and we describe the available technologies for BP monitoring used in intensive care medicine with regard to their measurement principles, advantages, limitations, and clinical applicability.

## 21.1 Introduction

The serial or continuous measurement of arterial BP is a cornerstone of hemodynamic monitoring in intensive care medicine. The measurement of BP is crucial for the timely detection of hemodynamic instability and hypotension (BP monitoring to ensure patient safety) and for individually targeting BP values (BP management). Today, various technologies are available to assess BP either invasively (via an arterial catheter) or noninvasively (■ Fig. 21.1). Noninvasive BP measurements are usually performed in an intermittent manner with an inflatable occluding (upper arm) cuff using the auscultatory method, palpatory method, or automated techniques such as oscillometry. Recently, however, noninvasive BP monitoring technologies that enable the arterial BP waveform to be recorded and displayed continuously have become available for clinical practice. A profound under-



■ **Fig. 21.1** Arterial blood pressure measurement: the different techniques standing of the principles of BP measurement and of the indications and contraindications of each technique in intensive care medicine is important to choose the optimal way to measure BP in the individual patient.

## 21.2 History of Blood Pressure Measurement

BP was first measured directly (i.e., invasively) in the middle of the eighteenth century when Reverend Stephen Hales performed physiologic experiments and aimed to quantify the pressure in the cardiovascular circulation of different animals by measuring the height of the blood column in a long glass tube directly inserted into the animals' arteries [1–3].

In 1828, the French physician Jean Léonard Marie Poiseuille invasively measured BP in animals using a cannula inserted into an artery and a mercury manometer (he called it "hemodynamometer") and coined the unit "centimeters of mercury" to quantify BP readings [1, 3].

In 1847, the German physiologist Carl Ludwig, for the first time, continuously recorded and graphically displayed BP by attaching a floating pen to Poiseuille's mercury manometer and called his invention the "kymograph" [1, 3].

In 1856, the French surgeon Jean Faivre performed the first invasive direct systolic BP measurements in humans using a mercury manometer connected to a cannula inserted in an artery (femoral or brachial) during surgery [1, 3].

Beginning in the middle of the nineteenth century, different physiologists and physicians developed methods to assess BP noninvasively based on the idea to quantify an external counterpressure required to intermittently stop the intra-arterial blood flow.

A noninvasive simple transducer recording the BP waveform at the radial artery using external weights to determine the closing pressure of the artery was developed in 1855 by the German physiologist Karl von Vierordt [1, 3, 4]. This "sphygmograph" was improved by the French physiologist Étienne-Jules Marey in 1860 who invented a brilliant – but very complicated – system combining a water-filled glass chamber enclosing the arm, a sphygmograph, and a kymograph [1, 5].

The British physician Frederick Akbar Mahomed explored the physiology of the radial artery BP waveform and laid the foundation for the science of pulse contour analysis (from 1872 to 1884) [6, 7].

The first modern "sphygmomanometer" was developed in 1881 by the Austrian physician Samuel Siegfried Karl von Basch who placed a water-filled rubber bag surrounding a bulb that was connected to a mercury column over the radial artery [1, 3]. By increasing the amount of water in the bag and thus the pressure on the radial artery, the arterial pulsation was impaired and eventually stopped so that systolic BP could be determined by observing the corresponding height of the mercury column [1]. Interestingly, the *British Medical Journal* back then stated that by the use of a sphygmomanometer to assess BP "we pauperize our senses and weaken clinical acuity" [1].

The French cardiologist Pierre Potain improved von Basch's sphygmomanometer by using air instead of water to compress the artery and a portable aneroid manometer [1].

In 1896, BP assessment using sphygmomanometry with an inflatable non-expanding occluding upper arm cuff (developed by Dunlop) and a mercury manometer was described by the Italian physician Scipione Riva-Rocci [1, 3, 8]. This approach still forms the basis of present-day BP measurement techniques. However, Riva-Rocci used a too narrow cuff with a width of only 5 cm. In 1901, Heinrich von Recklinghausen suggested using a wider cuff (12 cm) [1, 3]. In addition, the palpatory method suggested by Riva-Rocci allowed the assessment of systolic BP but not of diastolic BP.

Due to the advances made by Riva-Rocci and the physicians who came after, the portability and usefulness of the sphygmomanometer became apparent to surgeons and anesthesiologists. In 1897, Leonard Hill and Harold Barnard described a decline in systolic BP after induction of anesthesia with chloroform [9].

The determination of diastolic BP became possible with the discovery of the auscultatory method for BP determination by the Russian army physician Nikolai Sergejewitsch Korotkow [1, 3]. He famously proposed to obtain the "Korotkoff sounds" with the help of a stethoscope placed distally from the cuff over the brachial artery during slow deflation of the upper arm cuff.

Another crucial step toward the routine measurement of both systolic and diastolic BP was the development of oscillometric methods that allowed recording the oscillations within the cuff. In the early twentieth century, the oscillometric method, which had been described by Marey as early as 1876, was further developed and refined by Joseph Erlanger and Victor Pachon who eventually provided a portable "sphygmo-oscillometer" [3, 10].

Since the first description of oscillometry, the technique was further refined and improved and was used for BP measurement in research and clinical routine [3].

However, as late as in 1969, it was demonstrated that the point of maximum oscillation actually corresponds to the mean BP [11–13]. Later, a more detailed understanding of the oscillations observed during cuff deflation allowed defining certain points corresponding to systolic and diastolic BP [12, 14]. In the 1970s, electronic pressure sensors and microprocessors allowed the development of automated oscillometry [12]. The algorithms used to analyze the oscillometric waveforms and the hardware/software of the oscillometric BP monitors were constantly refined since then [12]. Today, automated sphygmomanometers using oscillometry are widely used in all fields of medicine, including medical care sites and home BP monitoring.

## 21.3 Invasive Arterial Blood Pressure Measurement (Arterial Catheter)

The invasive and continuous recording of the BP waveform and assessment of BP values with a catheter placed in an artery, a fluid-filled tubing system, and an electronic system are also called "direct" measurement and are considered the clinical "gold standard" method for measuring BP.

Arterial cannulation for BP monitoring is routinely performed in critically ill patients. Arteries used for direct BP measurements are the radial, femoral, brachial, and dorsalis pedis artery. The placement of an arterial catheter is usually straightforward when performed by a well-trained operator, but it can be challenging in certain clinical situations, e.g., in pediatric patients or in patients with arteriosclerosis or circulatory shock with peripheral vasoconstriction. Ultrasound guidance has been suggested to improve the success rate and quality of arterial catheter placement [15]. The overall complication rate associated with arterial catheter placement is relatively low, but complications related to the placement or presence of an arterial catheter can be major (embolism, ischemic damage, bleeding, pseudoaneurysm, infection) [16]. In addition, it has been shown that arterial cannulation can decrease blood flow distal to the catheter [17].

It is important to understand the underlying principle of direct BP measurement, which requires an intra-arterial catheter connected to a fluid-filled tubing system and a pressure transducer containing an impermeable diaphragm [18]. The intra-arterial catheter connects the system to the vascular system, picks up BP, and transmits it to the fluid-filled tubing system. The fluid column in the tubing system, in turn, transmits the pressure signal to the diaphragm of the pressure transducer and deforms it physically leading to changes in the electrical resistance of strain gauges attached to the diaphragm and the other side if the diaphragm is open to atmospheric pressure [18]. The pressure-induced changes in electrical resistance show a linear relationship with the intra-arterial pressure and can thus be mathematically translated in a waveform. Thus, the pressure transducer converts the mechanical signal into an electrical signal, which is processed by the monitor and translated into a BP waveform and numeric BP values.

To avoid erroneous BP readings, the tubing system and pressure transducer must be correctly set up and maintained. This includes meticulously priming the tubing system with fluid, referencing (or leveling) the transducer to the level of the patient's right atrium, and zeroing the transducer to atmospheric pressure [18, 19]. Although the correct point for leveling the transducer is a matter of discussion, in clinical practice the phlebostatic axis (located at the fourth intercostal space, halfway between the anterior and posterior chest wall) approximates the location of the right atrium and can be used for referencing the transducer.

For zeroing, the zeroing button of the monitor is pressed after the transducer has been opened to atmospheric pressure. This defines the transducer level as the hydrostatic zero reference point and ensures that the monitor uses atmospheric pressure as the atmospheric zero reference point [18, 19].

In addition, testing the dynamic response of the catheter/tubing system is key for reliable BP readings. The dynamic response is determined by its natural frequency and the damping coefficient. BP readings can be falsely low when the damping properties of the arterial catheter/tubing system are too high (and vice versa) [20].

A fast flush test needs to be performed to verify the natural frequency and damping of the direct BP monitoring system [7, 18, 19, 21]. The flush test consists of inspecting the arterial waveform after flushing the system with 300 mmHg and abruptly terminating the flushing manoeuver.

When deciding whether arterial cannulation is necessary, one should balance the risks (complications associated with catheter placement and maintenance) and the benefits (direct "gold standard" BP readings, blood sampling) of an arterial catheter for each individual patient.

## 21.4 Intermittent Noninvasive Arterial Blood Pressure Measurement

Inflatable air-filled cuffs that occlude the artery at the measurement site are used for intermittent noninvasive (manually or automated) BP measurements. An appropriately sized cuff is a prerequisite for valid measurements [22].

Manual intermittent noninvasive BP measurements obtained during gradual deflation of the occluding cuff (with a manometer indicating the applied pressure) can be performed by the palpatory or auscultatory method [14]. The palpatory method, i.e., palpating the pulse distal to the occluding cuff during slow cuff deflation, only allows assessing systolic BP. The auscultatory method (auscultation of Korotkoff sounds distal to the cuff with a stethoscope) yields systolic (onset of the sounds) and diastolic pressures (disappearance of sounds).

Different technologies for automated intermittent noninvasive assessment of BP with an occluding cuff are available, with "oscillometry," a technique detecting oscillations of the arterial wall, being the most widely used [13]. Small oscillations occur when the cuff pressure is higher than the systolic BP. During cuff deflation, the oscillations increase until they reach a maximum at mean BP [23] and then again decrease toward the diastolic BP. From the pressure with maximal oscillations (mean BP), algorithms help deriving systolic and diastolic pressures. The cuff pressure at the time of the initial occurrence of oscillations corresponds to the maximum systolic BP, and the lowest cuff pressure just prior to the time that oscillations stop decreasing in amplitude corresponds to the diastolic BP [4, 7]. Today, automatic oscillometry is widely used in intensive care medicine and anesthesiology but also in physician offices, on hospital wards, for 24-h ambulatory BP monitoring, and for home BP monitoring. It needs to be stressed, however, that oscillometry is not a standardized technique. There are numerous different proprietary algorithms to derive BP that are not made publicly available by the manufacturers [12, 24, 25]. Although oscillometry can basically be applied easily and rapidly and provides BP readings in an automated way without the need for trained personnel, the choice of the appropriate cuff size is key in order to avoid erroneously low (too large cuff size) or high (too small cuff size) BP measurements [26]. In addition, oscillometric BP measurements are prone to artifacts (potentially resulting in false BP values) caused by active or passive movement at the measurement site [12]. Oscillometry tends to underestimate the systolic BP and overestimate the diastolic BP compared with invasively measured BP [27]. Data on the measurement performance of oscillometry in critically ill patients are – in part – conflicting. On the one hand, it has been proposed that oscillometry can be used in intensive care unit patients with hypotension or vasopressor infusion [28]. In addition, it has been shown that oscillometry provides accurate BP measurements compared with invasive reference measurements in critically ill patients with cardiac arrhythmia [29, 30]. On the other hand, Lehman et al. [31] analyzed a database of intensive care unit patients and compared oscillometric BP values with direct BP measurements (arterial catheter) and observed marked and clinically relevant discrepancies between the methods. In noncardiac surgery patients, Wax et al. [32] demonstrated that oscillometric BP measurements were generally higher compared with invasive BP measurements during hypotension and lower during hypertension.

## 21.5 Continuous Noninvasive Arterial Blood Pressure Measurement

Two different technologies for automated continuous noninvasive assessment and analysis of the BP waveform are now available, namely, the volume clamp method (also called vascular unloading technology or "finger cuff technology") and radial artery applanation tonometry [7]. Although these technologies are often referred to as "new and innovative" technologies, the basic principles of both measurement techniques have been described many years ago [33, 34].

The volume clamp method uses an inflatable single- or double-finger cuff (with an integrated infrared light and an infrared transmission plethysmograph) that adjusts its pressure multiple times per second to keep the volume in the finger artery constant. From this pressure a BP curve can be derived. This method was described by the Czech physiologist Peňáz in 1973 [33]. Further technical developments and refinements of this method [35–38] led to monitoring systems that are now commercially available for bedside use. The ClearSight system (Edwards Lifesciences, Irvine, California, USA) uses a transfer function, an algorithm called "Physiocal" that adjusts for finger BP changes related to changes in the vasomotor tone, and a "heart reference system" that automatically adjusts for the hydrostatic difference between the level of the finger sensor and the level of the heart [35, 39–41]. In contrast, the CNAP system (CNSystems Medizintechnik AG, Graz, Austria) calibrates the systolic and diastolic BP values obtained with the finger cuff to oscillometric BP measurements assessed with an integrated upper arm cuff using a proprietary algorithm. To adjust and correct for long-term tracking of the finger BP, the CNAP system uses concentrically interlocking control loops [38].

The volume clamp method has some limitations due to the distal BP measurement site. In clinical circumstances with altered or impaired finger perfusion, such as finger edema, peripheral vasoconstriction, peripheral vascular disease, or marked hypothermia, the quality of the BP signal recorded with the finger cuff might be not good enough. Moreover, BP measurements with a finger cuff technology can be influenced and disturbed by excessive active or passive movement of the patient (especially of the arm or hand used for the measurements). When used in awake patients, the finger cuff technologies can cause discomfort or pain because the cuff impairs venous return from the finger and causes venous congestion. In addition to these general limitations of the vascular unloading technology, a specific limitation of the CNAP system might be the calibration of the BP values to brachial BP values assessed with oscillometry because, as discussed above, oscillometry also has some limitations with regard to the measurement performance and the clinical applicability.

A different technology for continuous noninvasive BP monitoring is the radial artery applanation tonometry that uses a pressure sensor applied over the radial artery based on the principle first described by Pressman and Newgard in the 1960s [34] and further developed by other researchers [42, 43]. The basic principle of arterial tonometry is that external flattening (applanation) of the arterial wall causes the pulse pressure amplitude (that is assessed with a sensor over this artery) to be maximal. To be able to flatten an artery with an external sensor, the artery must be superficial and supported by a bony structure (e.g., radial artery supported by styloid bone). The technology enables the mean arterial BP to be measured directly and the systolic and diastolic BP values to be calculated (e.g., using population-based algorithms) [44]. Nonautomatic systems using handheld sensors have been used for many years by cardiologists to estimate central vascular pressures [45]. Automatic radial artery applanation tonometry systems using a sensor attached to the patient's wrist have been developed for BP monitoring in the intensive care unit or the operating room [46]. Automatic artery applanation tonometry systems need to constantly adjust the pressure of the sensor flattening the underlying artery to obtain the optimal contact pressure and thus the optimal BP signal. One device for automatic radial artery applanation tonometry is the T-Line system (Tensys Medical, San Diego, CA, USA) that uses a disposable wrist splint for optimal positioning (slight extension) of the hand

and a “bracelet” housing the sensor and two motors that electromechanically drive the sensor over the artery to achieve the optimal sensor position and applanation pressure [7, 47]. The mean BP can be obtained from the maximal pulse pressure; systolic and diastolic BP is derived after scaling of the BP waveform using a proprietary algorithm that considers biometric data and a large invasive radial artery reference database [47, 48].

The main limitation of radial artery applanation tonometry is its high sensitivity to motion artifacts caused by movement of the measurement site. The system has been evaluated in a variety of clinical settings [44, 47, 49–52].

Numerous validation studies have been carried out to evaluate the measurement performance of these innovative noninvasive technologies for continuous BP monitoring in comparison with invasive reference measurements [53–55]. For all the technologies and devices described above, the validation studies revealed contradicting results. Some studies showed good agreement between the test and the reference method and recommended the use of noninvasive technologies as an alternative to invasive BP monitoring. Other studies reported a poor agreement with reference methods and concluded that these technologies should not be used in clinical routine to guide BP management. A meta-analysis on the accuracy and precision of different continuous noninvasive BP monitoring technologies including 28 studies revealed an overall random effect pooled mean of the differences of 3.2 mmHg, with a standard deviation of ±8.4 mmHg and 95% limits of agreement −13.4 to 19.7 mmHg for mean BP [54]. The authors stratified the results according to the different devices and reported a mean of the differences ± standard deviation of 3.5 ± 6.8 mmHg, 5.5 ± 9.3 mmHg, and 1.3 ± 5.7 mmHg, for the ClearSight (volume clamp method), CNAP (volume clamp method), and T-Line system (radial artery applanation tonometry), respectively [54].

However, how to define clinically acceptable agreement between noninvasive test methods and reference methods remains a matter of debate [56]. In addition, innovative noninvasive technologies should probably not only be tested against an invasive reference method but also against intermittent noninvasive BP monitoring techniques (such as oscillometry). Vos et al. [57] recently concluded that noninvasive continuous BP monitoring with the ClearSight system was interchangeable with monitoring by an oscillometric technique.

## 21.6 The Future of Arterial Blood Pressure Measurement

In the future, innovative, sophisticated, tiny sensors able to record biosignals such as BP and heart rate might change the way we perform clinical, ambulatory, and home BP monitoring.

For instance, it has been shown that flexible pressure-sensitive organic thin film transistors can be used for noninvasive continuous recording of the radial artery BP waveform [58]. In addition, thin conformable piezoelectric pressure sensors placed on the skin enable BP signals to be registered and analyzed [59]. Recently, it was demonstrated that nanocomposites (graphene added to polysilicon) can be used as highly sensitive electromechanical sensors that can measure pulse and BP [60].

These innovative materials might be used to develop flexible and wearable sensors that allow noninvasive transcutaneous recording of BP signals. Wireless and wearable sensors might offer intriguing possibilities for long-time continuous monitoring of BP, other vital signs, and the cardiovascular status (“mobile health monitoring,” “mobile biomonitoring”) [61–64]. Innovative sensor technologies might thus improve ambulatory and clinic BP monitoring and might be used in a variety of clinical applications in critical care, anesthesiology, emergency medicine, and cardiology [62–64].

### Practical Implications

In clinical practice, the choice of the type of BP monitoring device is based on a variety of factors, with patient-specific factors being the most important ones. Considering the specific advantages and limitations of each technology and the clinical circumstances, the optimal BP monitoring device needs to be selected for the individual patient.

For critically ill patients with circulatory shock, invasive direct BP monitoring with an arterial catheter is required and recommended [65]. Besides the direct measurement of BP, an arterial catheter allows regular blood sampling for laboratory testing and blood gas analysis.

Patients undergoing high-risk surgery (e.g., cardiothoracic surgery, major abdominal surgery) and high-risk patients undergoing low- or intermediate-risk surgery also require invasive BP monitoring with an arterial catheter.

In the perioperative setting, the majority of the remaining patients will be monitored using noninvasive BP monitoring techniques. In certain groups of surgical patients, the continuous noninvasive BP monitoring allows a better stability of BP compared with intermittent BP measurements [66–68]. Future research needs to identify specific clinical settings in which continuous noninvasive BP monitoring can improve the quality of care or patient safety compared with intermittent noninvasive BP measurements. Because even short periods of intraoperative hypotension are associated with postoperative organ failure [69], continuous BP monitoring or the use of closed-loop systems might in the future help to avoid hypotension-related postoperative complications.

In acutely ill patients treated in the emergency department or patients undergoing complex diagnostic or therapeutic interventions [70–72], continuous noninvasive BP monitoring might enable BP instability to be detected earlier compared with serial intermittent BP measurements.

## Conclusion

BP is a crucial hemodynamic variable in critically ill patients. The understanding of BP monitoring technologies is key to choose the optimal BP monitoring method for the individual patient and to avoid erroneous BP measurements. In critically ill patients, the direct invasive continuous BP measurement with an arterial catheter remains the reference method. In hemodynamically stable patients, BP monitoring can be performed in an intermittent manner using oscillometry. Noninvasive technologies that enable BP to be monitored continuously are now available for routine clinical use. Current research aims to evaluate whether these technologies for continuous noninvasive BP monitoring can improve patient outcome or the quality of care in certain clinical settings (perioperative medicine, emergency medicine).

### Take-Home Messages

- BP monitoring is a mainstay of hemodynamic monitoring in various fields of medicine, including intensive care medicine, anesthesiology, and emergency medicine.
- Different technologies for invasive and noninvasive BP monitoring are available.
- An arterial catheter connected to a fluid-filled tubing system and a pressure transducer is the clinical reference method for invasive continuous BP monitoring.
- Noninvasive BP measurements are usually performed in an intermittent manner with an inflatable occluding cuff using the auscultatory method, palpatory method, or automated techniques such as oscillometry.
- Noninvasive BP monitoring technologies that enable the arterial BP waveform to be recorded and displayed continuously are now available for clinical practice.
- It is important to know the principles, the advantages, and the limitations of each BP measurement technique to be able to choose the optimal method to measure BP in the individual patient.

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