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Perioperative blood pressure monitoring

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Arterial blood pressure monitoring is a major part of the decision-making process for every anesthetic. It is important to recognize the advantages, disadvantages, and limitations of available measurement modalities as well as have some understanding of the engineering principles on which these measurements are based. Oscillometry is by far the most common modality used but is limited by its intermittent nature and inaccuracy during hypotension and hypertension. Arterial catheterization is the gold standard for measuring blood pressure but is an invasive procedure that is expensive and not without risk of harm to the patient. Volume clamp and tonometric technologies are relatively new and allow for continuous noninvasive monitoring of the blood arterial waveform, but their accuracy when compared with oscillometry is not well described, and they have not been widely incorporated into standard practice. Additional research is needed to determine whether continuous noninvasive blood pressure monitors can improve outcomes.

Brief history of blood pressure monitoring

Although the concept of qualitatively analyzing cardiac contractions through manual compression of an artery has been in use since the early Egyptians [1,2], the advancement of arterial blood pressure

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measurement techniques has been slow. It was not until 1733 that Stephen Hales first recorded blood pressure by cannulating the crural artery of a mare, observing the increase in blood through a glass tube over 8 feet above the level of the left ventricle [1,3]. His documented rise and fall of blood with each pulse would later be described as pulse pressure. Almost 100 years later, Jean Léonard Marie Poiseuille invented the U-tube mercury manometer that was able to measure blood pressure by attaching one end of the manometer to a cannulated artery. His work with the flow of fluid through capillaries led to the formula currently known as Poiseuille's Law [4].

In 1847, Carl Ludwig designed the kymograph in an effort to improve Poiseuille's manometer. Using a mercury manometer, he was able to attach a float atop the column of mercury. To that float was attached a stylus that made markings onto a sheet of smoked paper revolving around the base of the manometer. This was the first recorded arterial blood pressure waveform [5].

The sphygmomanometer was the first noninvasive means of blood pressure measurement and was developed in 1855 by Karl Vierordt. He postulated that by applying counter-pressure to obliterate the pulse through a weight and lever, one could accurately determine arterial blood pressure when the pulse disappeared [1]. His design was cumbersome and did not gain immediate adoption in the medical community but was improved upon with various modifications by other scientists such as Etienne Jules Marey. In 1860, Marey expanded on the concept of Vierdort's sphygmomanometer to greatly improve the accuracy of blood pressure measurement. Instead of using a clamp to obliterate the radial pulse, he submerged the extremity in a glass chamber filled with water and applied counter pressure. His device was attached to a kymograph and a sphygmograph, which recorded the arterial pulsations, and the pressure of the glass chamber was measured using an attached manometer. Blood pressure was measured by noting the pressure in the manometer when the greatest distance in peaks of the sphygmograph occurred (mean arterial pressure) then, as the pressure was increased, recording the pressure in which the pulsations stopped (systolic blood pressure (SBP)) [6]. Although still too cumbersome for physicians at the time to use routinely, it revolutionized the way researchers studied blood pressure and would build the foundation for developing the oscillometry technique.

In 1896, Italian scientist Riva-Rocci used a pressurized cuff attached to a mercury sphygmomanometer on the upper arm to circumferentially compress the brachial artery. The radial pulse was then palpated distally, and the moment the radial pulse disappeared marked the SBP. It was not until the early 1900s when Nicolai Sergeivich Korotkoff used auscultation distal to the Riva-Rocci cuff that both SBP and diastolic blood pressure (DBP) were appreciated. The appearance and disappearance of turbulent blood as the cuff deflates are known as the Korotkoff sounds. This method is known as the Riva-Rocci/Korotkoff (RRK) measurement and is still one of the most commonly performed procedures throughout the world [7]. The Korotkov technique was eventually automated and, with knowledge from Marey sphygmograph, became the basis for the oscillometric technique, which is the sole blood pressure measurement modality used in approximately 80% of anesthetics at academic medical centers (see below) [8].

Physiology of systemic arterial blood pressure

While a comprehensive review of arterial physiology is beyond the scope of this review (and reviewed in depth elsewhere [2]), a basic conceptual understanding of the creation of the systemic arterial blood pressure waveform is essential to properly use blood pressure measurement technology.

The fundamental source of the systemic arterial blood pressure is the left ventricle. During the initial (isovolemic) phase of ventricular systole, the left ventricle is separated from the systemic arterial vasculature by the aortic valve and has no impact on systemic arterial blood pressure. When intraventricular pressure exceeds aortic pressure, the aortic valve opens, placing the ventricular blood in direct contact with the systemic arterial blood. This leads to two things – first, the creation of a pressure wavefront that travels down the systemic arterial vasculature, and second, the movement of blood down a pressure gradient (toward the capillary beds) that lags the pressure wavefront.

The blood pressure wavefront travels down the systemic arterial system at approximately 5–10 m/s [9]. Because blood pressure is oscillatory in nature, resistance to blood flow is best described in terms of vascular *impedance*, which can be affected by vessel diameter as well as compliance. When blood pressure waves travel toward the periphery and pass through areas of changing compliance or diameter, part of these pressure waves is reflected backward toward the left ventricle [10,11]. Similarly, three-dimensional shapes such as branch points can produce reflected waves. The end result of these bi-directional oscillating pressure waveforms is that as the measurement site moves distally from the source, pulse pressure is amplified (although mean arterial pressure must decrease distally to maintain forward movement of blood). The blood pressure tracing at different points along the arterial tree is thus a combination of forward and backward reflective waves and can be quite complex depending on the features of the system [Fig. 1].

Because the systemic arterial system is compliant, i.e., capable of behaving as a capacitor, not all of the blood ejected from the left ventricle will flow toward the capillary beds. Some of this ejected blood will pool in the systemic arterial system as the "capacitance vessels" (e.g., the aorta) expand with rising pressure. Then, as ventricular pressure drops below aortic pressure and the aortic valve closes, these capacitance vessels, which are elastic, begin to contract, ejecting blood downstream during diastole. This model of flow, developed by Otto Frank, is referred to as the Windkessel [12–14] and explains the significant difference between ventricular and aortic pressure waveforms [Fig. 2].

Measurement techniques

Oscillometry

Technological foundation

Oscillometry is similar to the auscultatory method developed by Korotkoff in the sense that a cuff is placed around an extremity and inflated to a suprasystolic pressure. However, as the cuff is deflated to subdiastolic pressure, a pressure sensor detects pressure oscillations in the cuff in contrast to listening to Kortkoff sounds [15]. Marey first introduced oscillometry in the mid-19th century. He discovered that by submerging the forearm into a chamber of water and applying counter pressure, intra-arterial pulsations were transmitted to the water [16]. The magnitude of these pulsations would later be recognized as an indication of blood pressure [6]. At first, it was unclear whether the occluding pressure that resulted in maximum oscillation represented DBP, SBP, or mean arterial pressure, but subsequent studies using both air and liquid as a medium have proven independently that the occluding pressure yielding the maximum oscillations closely approximates mean arterial pressure [16]. Complex algorithms are utilized to extract these data and estimate SBP and DBP, with the Message Authenticator Algorithm (MAA) being the most common. This algorithm uses the assumption that arterial compliance is maximal when cuff pressure matches the arterial pressure when the arterial wall is minimally distended [15]. With this method, mean arterial pressure (MAP) is measured directly

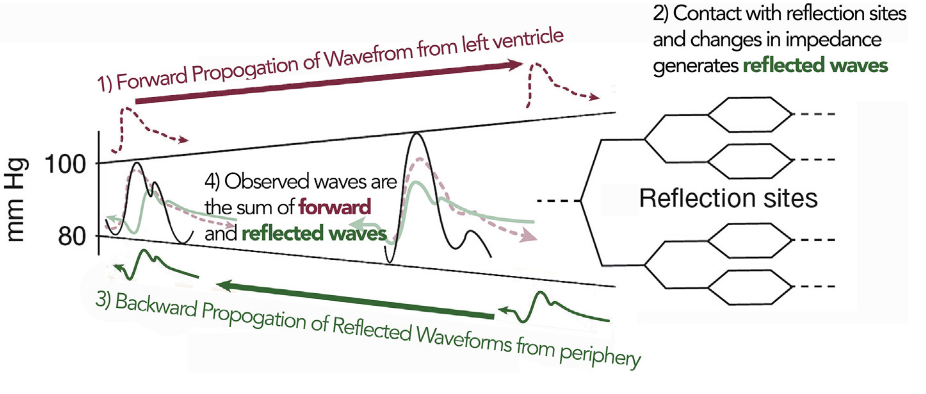

Fig. 1. The arterial waveform is the summation of both forward- and backward-traveling pressure waveforms. The phase difference between these two waveforms, as well as diminution over time, can lead to complex shapes. Note that, in this example, as in many humans, the pulse pressure increases as one moves toward the periphery (the mean arterial pressure, however, must decrease).

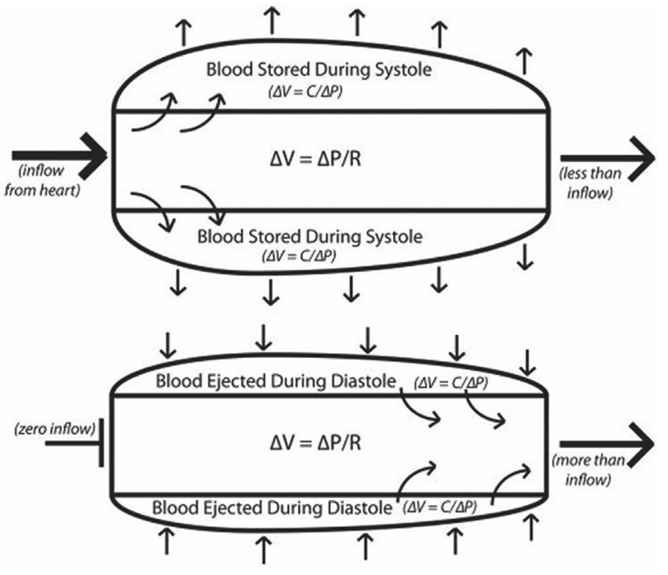

Fig. 2. During systole, some of the left ventricular output "fills" the aorta and other capacitance vessels, which discharge this stored volume downstream (toward the periphery, the rate of which is a function of the pressure gradient and resistance) during diastole. This is the essence of Otto Frank's Windkessel model of systemic arterial blood flow.

(maximum oscillations) while empirically derived coefficients are used to estimate the SBP and DBP. Each manufacturer uses different algorithms to estimate SBP and DBP, and the algorithms are often not available to the public [17].

Accuracy

In 2011, Wax et al. performed a single-center retrospective analysis analyzing 15,310 noncardiac anesthetics for a six-year period in which both arterial blood pressure (ABP) and noninvasive blood pressure (NIBP) were utilized simultaneously. Interestingly, the standard deviation of the MAPs between the two groups was ± 12.5 mmHg (95% confidence intervals of approximately ± 25 mmHg) when the MAP was 75 mmHg, which is where the accuracy of these devices is *highest*. As BP trended toward hypertension or hypotension, the performance of the oscillometric technique decreased substantially [18].

Limitations

The two major limitations of the oscillometric technique are the fact that blood pressure can be measured only intermittently (which may lead to an increased hypotensive burden, see below) and the relatively low accuracy of these devices. Additional disadvantages of the oscillometric technique include the lack of any waveform information (which precludes calculation of pulse pressure variation or estimation of stroke volume), poor performance in obese patients, patients with conditions such as atherosclerosis and vascular insufficiency, and patients who are unable to hold still, such as small children and infants [6]. Sizing of the cuff is also very important in obtaining an accurate blood pressure. The cuff dimensions should be 80% the length and 40% the width of arm circumference (a length-to-width ratio of 2:1) [19]. For very obese patients, the ideal width ratio would not be clinically possible; therefore, a smaller width ratio must be accepted, thus decreasing the accuracy in this population.

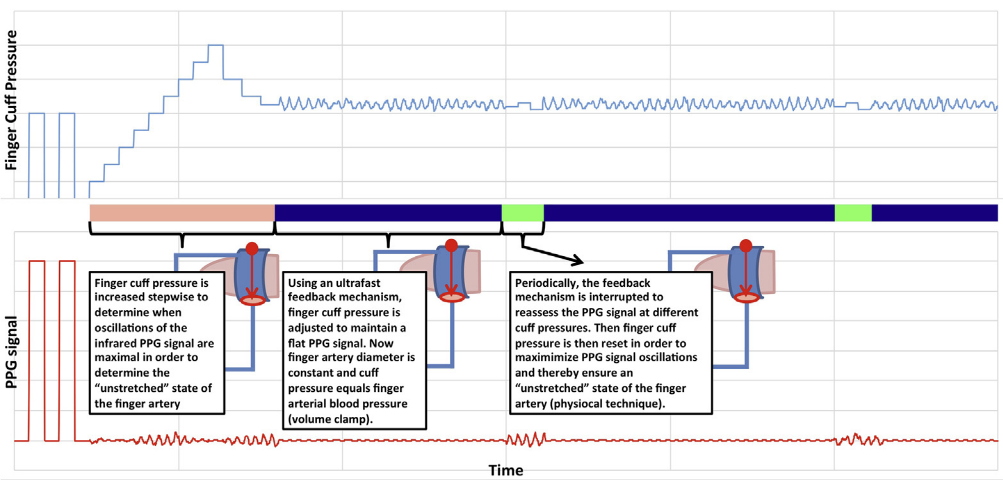

Fig. 3. Graphical depiction of the volume clamp technique utilizing a finger cuff connected to a feedback controller that interprets the PPG signal (in red).

Arterial catheterization

Technological foundation

Arterial catheters are placed directly in systemic arteries, connecting the arterial vasculature to an external pressure monitor through an uninterrupted column of fluid (typically saline). The pressure monitor itself is a Wheatstone bridge strain gauge, which utilizes a 4-element parallel circuit in which the resistance of the elements changes when they are deformed due to mechanical stress [Fig. 4]. After calibration, these devices convert voltage to pressure.

The fluid-filled arterial pressure monitoring system can be characterized by two important features, its *natural frequency* (f_n) and its *damping coefficient* (ζ). f_n is a measure of the frequency at which a pulse applied to the system will oscillate, and ζ is a measure of how long it takes for an oscillating waveform

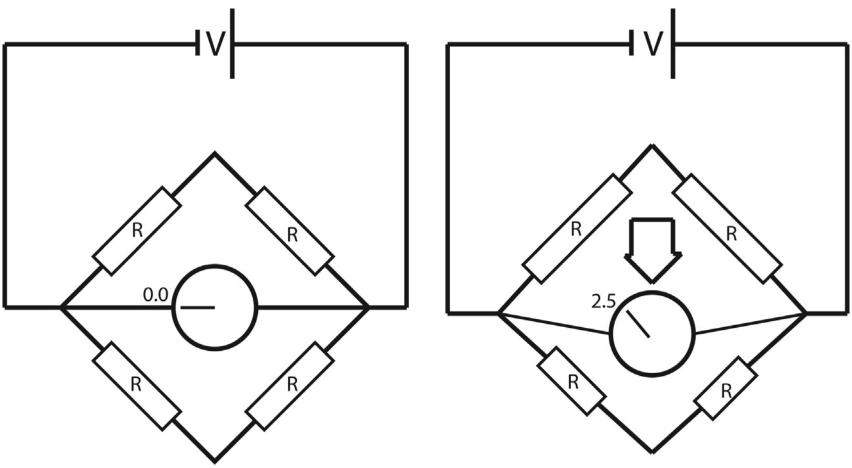

Fig. 4. The Wheatstone bridge is a simple engineering circuit that allows for the accurate measurement of blood pressure. Mechanical forces bend the Wheatstone bridge, changing the resistance of its elements, which, when unmatched, lead to a small voltage differential that can be detected (and converted to units of pressure).

in the system to decay. To measure any oscillating waveform accurately, measurement frequency should be at least twice the frequency of the waveform. In the case of the human arterial blood pressure tracing, which may require up to 10 harmonics (with a frequency as high as 20 Hz for the 10th harmonic [2,20]) to describe accurately, a natural frequency of 40 Hz is needed to reproduce the actual blood pressure tracing with exactitude. This frequency is well in excess of what is typical in clinically available pressure monitoring systems [21].

That said, the exact features of the arterial waveform are not essential to the anesthesiologist and intensivist (although they may be essential to cardiac output monitors based on advanced analysis of the pressure waveform). The primary interest of the anesthesiologist is in the mean pressure, SBP, and DBP − SBP, for instance, can be altered by an improperly damped transduction system [20,22]. Still, in general, anesthesiologists and intensivists should utilize short, rigid tubing to connect an arterial catheter to the pressure monitor and should confirm the adequacy of their system using a flush test, in which the arterial catheter is flushed rapidly (similar to a "square wave"). Flushing the arterial catheter leads to a peak pressure that is the same as the pressure in the pressure bag and then an oscillatory decline back to baseline. f_n is measured by dividing 1 by the time between two peaks in seconds (units s^{-1}), and ζ is calculated by dividing the amplitude of the second peak by the amplitude of the first peak (A_2/A_1) and solving mathematically or graphically. The adequacy of the dynamic response can then be confirmed by plotting f_n and ζ on a dynamic response map [Fig. 5].

Accuracy

If the aforementioned technical considerations are adhered to, the intra-arterial catheter is, by definition, the clinical and reference standard for arterial pressure measurement. Occasionally, clinicians will misattribute high pulse pressure to "whip" (an underdamped signal). Without testing f_n and ζ, it is impossible to make this determination, but it should be kept in mind that because of the progressive narrowing of the arteries as well as increasing rigidity in patients with atherosclerosis, it is normal for pulse pressure to widen as the blood pressure wavefront moves distally [see Fig. 1, above].

Limitations

The main limitations of the intra-arterial catheter are the fact that they require a procedure to perform, which both takes time and introduces risk. Although relatively safe, intra-arterial catheterization can lead to nerve injury, pseudoaneurysm formation, hematoma formation, permanent arterial occlusion, and infection (1.7:1000 catheter-days for intra-arterial catheters; by comparison, this rate is 2.7:1000 for nontunneled central venous catheters and 0.5:1000 for peripherally inserted intravenous catheters) [23–25]. This risk can be lowered through the use of chlorhexidine-impregnated sponges [26].

Volume clamp technique

Technological foundation

Marey's work in the 1860s (described above), in which the forearm was submerged in a fluid-filled chamber, formed the intellectual foundation for the volume clamp technique. Marey found that application of counter-pressure that mimicked the arterial pressure waveform would eliminate downstream pulsatility. Marey's experimental apparatus, while scientifically useful, was inadequate for clinical use. Peňáz expanded upon Marey's work with two innovations. First, he utilized the photoplethysmogram (PPG) from the finger to measure the flow of blood into the upper extremity. Second, he connected an ultrafast finger cuff to a feedback loop driven by the PPG signal [Fig. 3] [27–30].

While this feedback loop, if functioning properly, can recreate the *shape* of the arterial blood pressure tracing, it can only approximate blood pressure, and an additional calibration step is required to quantify blood pressure. Prior work demonstrated that when mean arterial pressure was externally applied to a vessel, distal pulsations would be maximal [16]. Thus, volume clamp devices periodically apply constant pressure (as opposed to oscillating pressure) to identify MAP and calibrate their devices. The Continuous Noninvasive Arterial Pressure (CNAP®, CNSystems, Graz, Austria) device moves one step further, using an upper arm blood pressure cuff to further calibrate its device using the oscillometric technique.

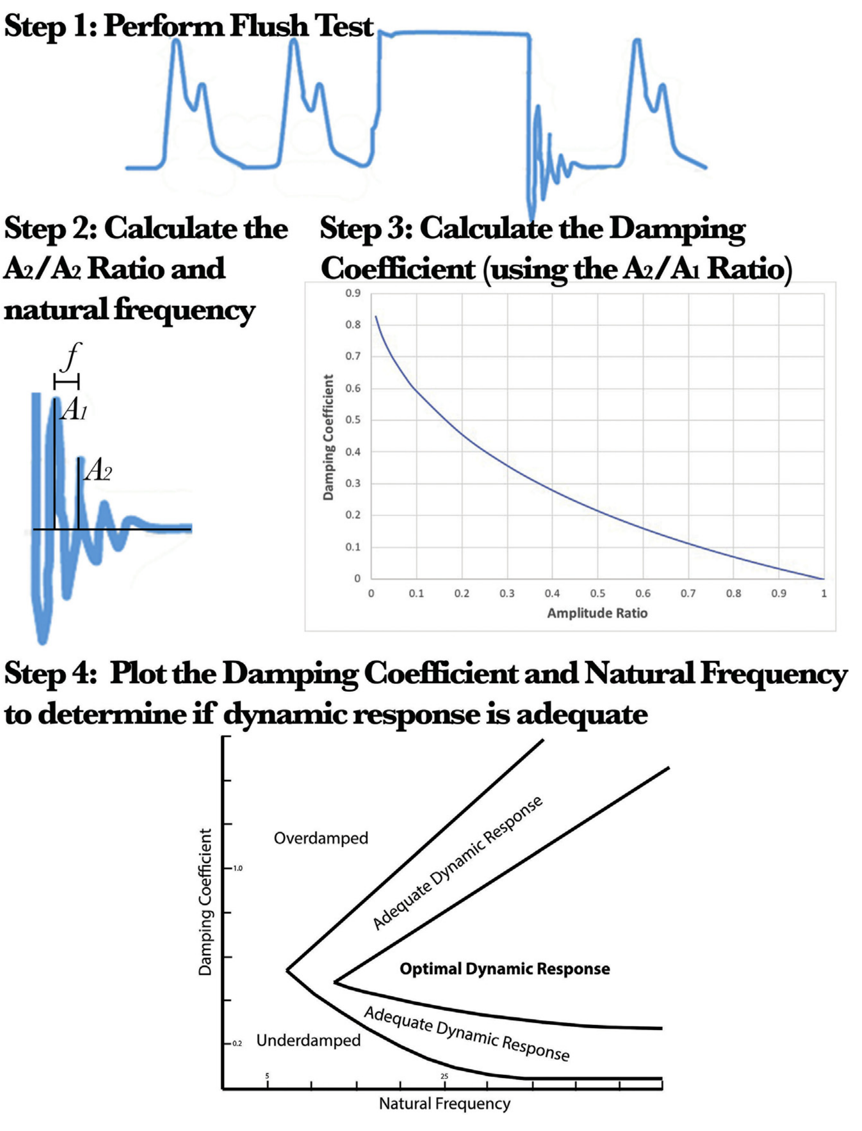

Fig. 5. Technique for ensuring the fidelity of a blood pressure transduction system.

Accuracy

A previous report including 24 studies from 2009 to 2014 including 1116 subjects demonstrated a weighted average of −15.4 mmHg (lower limit) and 21.9 mmHg (upper limit) for 95% confidence intervals between volume clamp estimates of mean arterial pressure and invasive measurements [6]. More recent work has not demonstrated a meaningful improvement in reported accuracy [31–34]. There is one published three-way study in which blood pressure is measured using oscillometry, the volume clamp technique, and intra-arterial catheterization (the reference standard). Lakhal et al. found that the 95% confidence interval surrounding both oscillometric and volume clamp measurements was identical, but the oscillometric technique introduced significantly less bias (−2 vs. 7 mmHg) [33].

Limitations

Volume clamp devices, regardless of the manufacturer, require a photoplethysmographic signal. Thus, any condition that might alter the PPG signal (e.g., hypothermia, high-dose vasopressors) may also compromise the accuracy of this class of devices. Because they apply pressure externally (through skin, fat, and other tissues), they may also lose accuracy in obese patients [34]. It is important to note that the volume clamp technique is relatively new, and improvements in both the devices themselves and their algorithms may lead to increased accuracy over time.

Applanation tonometry

Technological foundation

The aforementioned limitations of peripherally obtained blood pressure, combined with the risks associated with arterial cannulation, led to interest in the development of noninvasive techniques for continuous arterial blood pressure measurement. Tonometry can overcome many of these limitations and estimates central pressure in a peripheral artery [35]. *Applanation* means "to flatten," and *tonometry* translates to "measuring of pressure." Radial artery applanation tonometry (RAAT) is performed by compressing the radial artery with a tonometer, allowing the arterial pressure to be transmitted through the tonometer to a strain gauge. A mathematical formula (transfer function) then estimates central pressure by analyzing the radial pressure waveform as well as the brachial blood pressure measured simultaneously [35]. Early research utilized a handheld "pen-like" tonometer, which required user intervention to identify the optimal signal location of the radial artery. The development of the T-line® by Tensys Medical (Irvine, CA) eliminated the need for user intervention, allowing for this technology to be used in the operating room. Unlike the research tonometer, the T-line clamps above the radial artery and is able to identify the point of maximal impulse automatically.

Accuracy

Initial, laboratory-based work using a handheld tonometer was promising [35,36]. Subsequent studies in the operating room and ICU environments, which utilized automated devices, have been mixed, with some authors reporting clinically acceptable agreement when compared with invasive arterial BP measurement [37–39] and others reporting unacceptable agreement [40,41]. Direct analysis of published data reveals that the 95% confidence interval surrounding estimates of mean arterial pressure was remarkably consistent in four of the studies, ranging from −11 to −10 mmHg (lower bound) and from 14 to 16 mmHg (upper bound) [37–40]. A fifth study, which focused on ICU patients with known, severe cardiovascular disease (ejection fraction less than 30%, severe aortic stenosis, or atrial fibrillation) found that the 95% confidence interval for mean arterial pressure ranged from −16 to 46 mmHg [41]. Whether or not these reported levels of agreement are "clinically acceptable" will likely be a patient-specific decision.

A 2014 meta-analysis including 919 patients (from 28 studies) found that the overall random-effects pooled bias and SD for all noninvasive techniques was 3.2 ± 8.4 mmHg, whereas the overall random-effects pooled bias and SDs for the tonometric device (T-line) was 1.3 ± 5.7 mmHg, suggesting that tonometric devices were superior to volume clamp devices (see below) [42]. Unfortunately, there are no known three-way studies analyzing the accuracy of oscillometry *and* tonometry using intra-arterial catheterization as a reference standard. Thus, while tonometry has an advantage over oscillometry in terms of response time, its relative accuracy can only be inferred due to the absence of any head-to-head comparisons.

Limitations

RAAT is a relatively new technique for monitoring blood pressure and has not gained widespread traction in clinical practice. The earlier designs such as the SphygmoCor device utilized a handheld tonometer, which required continuous access to the wrist; hence, although it has been validated in clinical trials, it remains primarily useful for research [6]. Individual cardiovascular properties vary substantially; hence, it is unclear whether a generalized algorithm may be used to accurately estimate central pressures, or a more individualized approach needs to account for variables such as age, sex, and disease state [36]. It is also necessary for improvements to be made regarding motion artifacts and noise dilution [37].

Blood pressure control: feedback and automation

Whether or not they know it, anesthesiologists taking care of patients are an integral part of a feedback loop, a well-established engineering concept [43]. At its simplest, a feedback loop consists of a measured variable (e.g., blood pressure), a measuring device (e.g., intra-arterial catheter), and an intervention that affects the measured variable (e.g., phenylephrine). The ability to control the measured variable is a function of the characteristics of all elements of the system. Key elements include the time delay of the measurement, the response-time of the intervention, and the magnitude of the intervention. A system can be optimally controlled when there is minimal time delay in the measurement or in the response variable, and the magnitude of the response (referred to as gain) is optimal.

The practical realities of feedback loops were recently demonstrated by the Department of Outcomes Research at the Cleveland Clinic, which tested whether or not the use of a continuous, noninvasive blood pressure monitor could reduce the burden of hypotension during noncardiac anesthesia. After randomizing 360 subjects to blinded versus nonblinded continuous pressure monitoring with the ClearSight® (Edwards LifeSciences, Irvine, CA) volume clamp device, they found that use of the device reduced the time-weighted average time below 65 mmHg from 11% to 5% ($p = 0.03$) [44]. Smaller studies have consistently demonstrated that the use of continuous noninvasive blood pressure monitoring can increase detection frequency and reduce the hypotensive burden during both surgical [45,46] and nonsurgical procedures requiring general anesthesia [47].

This body of work highlights a key argument in favor of using continuous, noninvasive blood pressure technology that patients who would not traditionally receive an intra-arterial catheter still experience hypotension that might be missed by a blood pressure cuff that only measures blood pressure every 5 min.

Eventually, blood pressure management may become either fully or partially automated. The feasibility of using a closed-loop fluid management system to manage blood pressure in human patients undergoing both abdominal and vascular surgery was recently demonstrated [48,49]. For additional details on closed loop management of hemodynamics, see Alexander et al. [58].

Clinical outcomes data

While understanding the technological basis of various blood pressure monitoring devices is important, ultimately what matters is that the knowledge gained from the use of these measuring devices can be employed to improve relevant patient outcomes. An even more modern approach to equipment adoption puts these potential benefits into the context of cost, which is particularly important given the proliferation of noninvasive devices available for the continuous measurement of blood pressure.

Unfortunately, there are scarce high-quality prospective data on the use of specific blood pressure targets in patients undergoing anesthesia and surgery, or even to suggest that blood pressure itself should be measured at all. In 2012, a retrospective study designed to examine the impact of mean arterial pressure and sensitivity to anesthesia (through a combination of bispectral index and minimum alveolar concentration) on mortality found a trend toward increased risk of death in patients with MAP < 82 mmHg [50]. However, in a follow-up, prospective randomized controlled trial of 7569 patients, patients randomized to the “triple low” alert group experienced no mortality benefit [51]. The multivariate nature of this study makes it difficult to interpret. Another larger, retrospective study of 33,330 patients undergoing noncardiac surgery and anesthesia found that hypotension (MAP < 55 mmHg) for 1–5 min was associated with an increased risk of both renal and myocardial injury [52]. This study has not repeated in prospective, interventional fashion.

More recently, a prospective, randomized controlled trial focused exclusively on intraoperative blood pressure was performed in 298 adult patients undergoing major surgery and anesthesia. The results suggested that keeping SBP to within 10% of baseline (and always above 80 mmHg) could reduce the incidence of a composite measure of organ dysfunction [53]. Unfortunately, this study had several shortcomings, including its small size, the relatively small difference in blood pressure between groups (6.5 mmHg), and the fact that blood pressure indexed to baseline was not actually reported [54]. A larger trial of 776 septic patients randomized to MAP of 65–70 versus 80–85 mmHg found no difference in mortality or serious adverse events between groups [55]. This study was not focused on patients undergoing anesthesia and general surgery, and thus, it must be interpreted with caution.

It is known that not all interventions can be studied in a prospective, randomized fashion. There are, for instance, no published randomized controlled trials testing the use of parachutes while jumping out of planes at altitude [56]. Similarly, it can be extremely difficult, even with large studies, to demonstrate improved outcomes through the use of monitoring equipment – a Cochrane analysis of pulse oximetry including 22,992 patients in 5 trials found "*no evidence that pulse oximetry affects the outcome of anesthesia for patients*." [57] This does not mean that we should not measure blood pressure or that we should not strive to measure it accurately. It means that individuals and their institutions need to make informed decisions based on device performance, cost, and local knowledge of their patient populations to provide the safest and most efficient healthcare possible.

Summary

Oscillometry is used as an exclusive measure of blood pressure in more than 80% of anesthetic cases but has two major shortcomings – its intermittent nature and its inaccuracy, particularly during episodes of hypotension and hypertension. Arterial catheterization is the gold standard for measuring blood pressure but is an invasive procedure that is expensive and may lead to infectious or vascular complications. Two new classes of blood pressure monitoring devices have been developed to provide anesthesiologists with real-time, continuous blood pressure waveform data without incurring the risks associated with intra-arterial catheters. Tonometric devices are clamped above the radial artery and measure the pressure transmitted to them through the overlying tissue. Volume clamp devices rely on the use of finger cuffs, photoplethysmographic signals from the fingers, and a rapid feedback loop that attempts to keep the photoplethysmographic signals flat by altering the pressure in the finger cuff. Both the volume clamp and tonometric technologies are relatively new, and while they allow for continuous noninvasive monitoring of the blood arterial waveform, their accuracy in comparison with oscillometry is not well described and they have not been widely incorporated into standard practice. Recently, closed-loop algorithms for the automated management of blood pressure have been developed and tested in humans. Additional research is needed to better understand the accuracy of continuous noninvasive blood pressure monitors, determine the role of specific blood pressure targets (global or individualized) on outcomes, and assess the safety and impact of closed loop hemodynamic monitoring algorithms.

Conflicts of interest

None.

Practice points

- Oscillometry is most accurate around a mean arterial pressure of 75 mmHg (95% confidence intervals of approximately ± 25 mmHg as compared to direct arterial measurements).
- The accuracy of oscillometric blood pressure measurements degrades significantly during extreme hypotension or hypertension.
- The use of continuous noninvasive blood pressure monitor appears to reduce the hypotension burden (time-weighted average) during anesthesia and surgery.
- Continuous noninvasive monitors provide an arterial waveform, but lack of agreement with intra-arterial catheters may preclude their use in some patient populations.
- The correct use of an arterial catheter requires knowledge of its natural frequency (f_n) and its damping coefficient (ζ).

Research agenda

- Three-way comparisons of oscillometry, intra-arterial catheters, and continuous noninvasive blood pressure monitors are needed to fully understand the marginal benefit of this new class of devices.
- The impact of perioperative blood pressure targets (either global or individualized) on patient outcomes needs to be better understood.
- The safety and impact of closed loop hemodynamic management systems on the anesthesiologist's workflow, hypotensive burden, and relevant clinical outcomes should be assessed.

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