Best Practice & Research Clinical Anaesthesiology 28 (2014) 309–322

Contents lists available at ScienceDirect

Best Practice & Research Clinical Anaesthesiology

journal homepage: www.elsevier.com/locate/bean

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Measurement of blood pressure

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Keywords:
monitoring
arterial catheter
oscillometry
non-invasive
volume clamp method
radial artery applanation tonometry
tonometry

Blood pressure is overwhelmingly the most commonly measured parameter for the assessment of haemodynamic stability. In clinical routine in the operating theatre and in the intensive care unit, blood pressure measurements are usually obtained intermittently and non-invasively using oscillometry (upper-arm cuff method) or continuously and invasively with an arterial catheter. However, both the oscillometric method and arterial catheter-derived blood pressure measurements have potential limitations. A basic technical understanding of these methods is crucial in order to avoid unreliable blood pressure measurements and consequential treatment errors. In the recent years, technologies for continuous non-invasive blood pressure recording such as the volume clamp method or radial artery applanation tonometry have been developed and validated. The question in which patient groups and clinical settings these technologies should be applied to improve patient safety or outcome has not been definitively answered. In critically ill patients and high-risk surgery patients, further improvement of these technologies is needed before they can be recommended for routine clinical use.

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http://dx.doi.org/10.1016/j.bpa.2014.08.001
1521-6896/

Why and since when do we measure blood pressure?

The first recorded measurement of blood pressure (BP) as a marker of circulation took place in the middle of the 18th century with the experiments of the reverend Stephen Hales in England [1]. He performed direct BP measurements in a horse by inserting a 3-m-high glass tube into an artery and determining the height of the rising blood column. Then he let the horse bleed and repeated the BP measurement. This was performed several times in a row – the BP progressively decreased – until the horse died.

Without a doubt, this physiologic experiment was highly invasive and the applied method impractical for clinical use. Over the course of time, the enthusiastic work and brilliant ideas of a number of great scientists and engineers led to the continuous development of BP measurement devices and BP became the most important vital sign in clinical practice. Nowadays, optimal BP values are targeted during general anaesthesia in the operating theatre, in the treatment of critically ill patients in the intensive care unit (ICU), and for the general prevention of various acute or chronic pathological changes of the human body [2–4]. Retrospective data suggest that a mean BP <55 mmHg, even for a brief duration, increases the risk of acute kidney injury and myocardial injury in patients undergoing general anaesthesia [4], although these findings need to be corroborated prospectively. That said, a prospective randomized controlled trial comparing a mean BP target of 65–70 mmHg to a mean BP target of 80–85 mmHg in septic patients found no difference in the primary outcome although renal replacement therapy was less commonly required in patients with chronic hypertension whose mean BP was maintained at values of ≥80 mmHg [3]. At the same time, several questions concerning BP remain open, for example, the optimal individual BP values during different medical conditions and in different patient groups.

Today, both invasive and non-invasive technologies for BP measurement are available. Understanding the technical basics, advantages, limitations and pitfalls of each method is an essential prerequisite for interpreting BP findings.

The arterial BP waveform

The first device for recording a human pulse wave with a transducer was probably developed in 1855 by the physiologist Karl von Vierordt [5]. A permanent record of pulse curves was obtained by levers on the radial artery and weights to determine the amount of external pressure that was necessary to stop the blood flow in the radial artery. A few years later, Étienne-Jules Marey further developed the method and invented the sphygmograph [6]. The British physician Frederick Akbar Mohamed later described the physiological radial artery BP waveform and laid the foundation for the science of pulse wave analysis (from 1872 to 1884) [7]. Since then, continuous BP recording has progressively improved.

The arterial BP waveform is composed of the different sections of the cardiac cycle. Blood ejection from the left ventricle into the aorta during systole is followed by diastolic distribution of this blood volume towards the periphery. The systolic part of the arterial BP waveform consists of a steep pressure upstroke, peak and decline, representing the phase of left ventricular systolic ejection during the cardiac cycle. The so-called dicrotic notch appears during the downslope of the waveform and is related to aortic valve closure [8]. However, only in cases of direct recording of the waveform from the central aorta, the dicrotic notch agrees timewise with the aortic valve closure while the dicrotic notch of the peripheral arterial BP waveform only approximates the point at which the aortic valve closes and mainly depends on arterial wall properties [9]. The arterial BP waveform then further declines during diastole, finally reaching its lowest point at end diastole.

It is important to keep in mind the effects of physiology and the measurement site (e.g., radial or femoral artery) on its morphological appearance. In fact, three main points must be considered as the fundamental reasons for the waveform to be the shape it is: the closure of the atrioventricular valves, the differences in compliance/stiffness of the artery and wave reflections. These three characteristics together produce the shape of the arterial BP waveform. Because these characteristics differ depending on physiology and age, the arterial BP waveforms differ accordingly. The corresponding differences and similarities have been described in paediatric and elderly patients [5,10]. In the elderly, an increase in the late

systolic pressure peak can be observed, and the secondary diastolic pressure wave vanishes [11]. The pulse wave of paediatric and elderly patients is very similar. In a paediatric patient, an earlier return of wave reflection can be observed compared with an adult patient. However, in an elderly patient, the stiffness of the central aorta speeds up the pulse wave velocity for a relatively early return of wave reflection, comparable with that in a paediatric patient. At any age, the augmentation of the pulse wave in each artery is greater in short than in tall persons [12]. In addition, the patient's heart rate, cardiovascular disease and specific clinical conditions, for example, heart failure, might influence the pulse wave morphology with regard to the three main points that produce the shape of the arterial BP waveform [13–16].

In addition, the influence of the body site of BP measurement on the above-mentioned three main characteristics for the arterial BP waveform's shape must be taken into account, for example, prior to treatment decisions in critically ill patients. A detailed description of the differences in the waveforms of peripheral and central arteries was provided >50 years ago by McDonald [5]. Specific morphological changes in the arterial BP waveform become obvious from central to peripheral arteries [17]. In summary, peripheral (e.g., radial) arterial pulse waves show a steeper upstroke, a higher systolic peak a later appearing dicrotic notch and lower end-diastolic pressure in comparison with central sites of measurement (e.g., aorta or femoral) [18–21].

It is often assumed that the central arterial BP is most appropriate for estimating organ perfusion. The peripheral, usually radial, BP is considered as a good clinical surrogate for central pressure by the majority of anaesthesiologists and intensivists. However, the accuracy of peripheral arterial BP might be compromised in critically ill patients, for example, during high-risk major surgery or in ICU patients.

While the mean arterial BP gradient under normal physiological conditions has no clinical relevance [21], during exceptional haemodynamic conditions higher and clinically relevant arterial BP gradients from the central to the peripheral arterial tree may be observed – a phenomenon that for instance has been demonstrated in patients undergoing cardiopulmonary bypass surgery [22,23]. The underlying causes for these observations remain poorly understood [23].

Studies demonstrated significantly higher femoral than radial artery systolic and mean BP values in critically ill patients in general and patients with septic shock receiving high doses of vasopressors [17,24]. The question that, therefore, arises is whether the femoral artery should be preferred when monitoring arterial BP in a defined critically ill patient group [25,26].

Invasive BP measurement using an arterial catheter

Continuous direct arterial BP measurement with an invasive catheter has become a standard of care for critically ill patients and for BP monitoring during higher-risk surgical or interventional procedures. Particularly in view of the broad use of invasive BP recordings, usually by placing an arterial catheter in the radial, brachial or femoral artery, every anaesthesiologist and intensivist must be aware of the weaknesses, risks and pitfalls of this widely accepted clinical gold standard. This awareness is of crucial importance in order to avoid misinterpretation of a patient's medical condition and treatment errors due to false high or low BP values.

One potential reason for the measurement of false low BP values is very high damping properties of the arterial catheter system. These might be caused, for instance, by the catheter's occlusion or compression, arterial wall contact by the catheter tip or air bubbles in the tubing system. In addition, false high or low BP values in the presence of a correct arterial BP curve might occur. The potential sources for this error are the lack of or incorrect zero adjustment, wrong transducer position (above or below the reference point), a defective transducer and leakages in the arterial BP measurement system [27]. A very long or very elastic tonometry tubing might cause low natural frequency of the arterial catheter system and therefore high arterial BP waveform harmonics. A missing stable zero line might be due to incorrect cable connections between the transducer and the patient monitor, or due to a defective transducer. The so-called fast-flush test is useful to verify the natural frequency and damping of the arterial BP monitoring system [28]. The pressure in the arterial catheter measurement system is raised by briefly flushing it with 300 mmHg, followed by the abrupt termination of the flushing manoeuvre. Different characteristic types of curves representing correct damping, overdamping or underdamping appear on the patient monitor (Fig. 1).

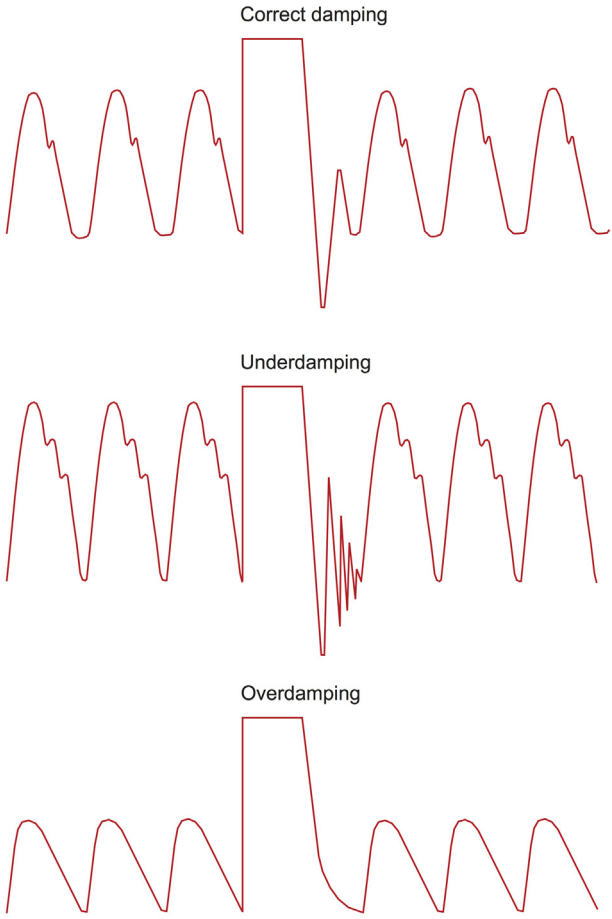

Fig. 1. Evaluation of damping properties of an arterial blood pressure monitoring system using a fast-flush test. This figure schematically illustrates different arterial blood pressure waveforms and the response to a fast-flush test according to different damping properties of the arterial blood pressure monitoring system.

The placement of arterial catheters is associated with potential complications. When the radial site is used, temporary occlusion of the artery might occur from wrist flexion, external compression or positioning restraint. Rarer but potentially severe complications are permanent ischaemic damage, pseudoaneurysm, infection of the insertion site, catheter-related blood stream infections (sepsis) and haematoma/bleeding [29]. Although these severe complications are rare, they nevertheless become relevant in regard to the millions of arterial catheters that are placed perioperatively and in the ICUs in the United States and Europe each year [29]. Expressed in figures, in the United States for instance, about 80,000 blood stream infections caused by an arterial catheter are observed annually [30]. This results in a significant cost of health care [31].

On the other hand, the placement of an arterial catheter allows regular blood sampling for laboratory testing and blood gas analysis and therefore increases patient safety in the ICU or during lengthy surgical procedures.

Balancing these risks and benefits of the placement of an arterial catheter is therefore essential for each individual patient. In addition, when comparing new BP measurement technologies with the invasive arterial catheter (clinical gold standard), we must also consider the above-mentioned potential pitfalls of the clinical gold standard method.

Intermittent non-invasive BP measurement: the oscillometric method

Over 30 years ago, the first devices for oscillometric arterial BP measurement became commercially available. BP measurement using an upper-arm cuff dates back to 1896 when Riva-Rocci introduced it into clinical sphygmomanometry [32]. Since then, arterial BP was determined by an upper-arm cuff and palpation and later (1905) by detecting the Korotkoff sounds. The principle of oscillometry was first described by Marey in 1875 and further established by Erlanger [33]. Oscillations of the arterial wall are detected by the upper-arm cuff. When the cuff pressure exceeds systolic BP, small-amplitude oscillations can be detected. With decreasing cuff pressure, the amplitudes increase and the maximum occurs when the cuff pressure level corresponds to the mean BP. The arterial wall oscillations decrease below a cuff pressure equivalent to the diastolic BP resulting in a continuous reduction of the amplitudes. The cuff pressure at the time of the initial increase in arterial oscillations corresponds to maximum systolic BP, and the lowest cuff pressure just prior to the time that oscillations stop decreasing in amplitude corresponds to the diastolic BP [5].

Today, automatic oscillometric BP measurement devices have almost completely replaced the auscultatory method. Avoiding the inconvenience of auscultation and introducing automation made oscillometry highly preferable. As a consequence, the oscillometric method is broadly and confidently used in physicians' offices, emergency departments and hospital wards, and for perioperative monitoring and treatment in the majority of general anaesthesia cases. However, oscillometry must detect small pressure changes within the cuff despite a relatively rapid reduction in cuff inflation pressure. A standardized algorithm for detecting the oscillometric systolic or diastolic BP is not available. Instead, multiple proprietary algorithms exist – depending on the manufacturer and often not reliably validated by comparison with direct invasive arterial BP [34,35].

Oscillometric BP may overestimate systolic arterial BP and underestimate diastolic arterial BP and be less reliable in patients with atrial fibrillation [36–38]. In addition, oscillometry results in an erroneously high BP reading when the cuff is too small and vice versa [39]. Furthermore, studies demonstrated several shortcomings of the oscillometric method compared with invasive arterial BP monitoring. Bur and colleagues revealed a significant underestimation of BP by the oscillometric method compared with invasive arterial BP monitoring in critically ill patients mainly due to a mismatch between upper-arm circumference and cuff size [40,41], especially in overweight critically ill patients [42]. Lehman and colleagues recently used a large ICU database to compare invasive arterial and oscillometric BP and demonstrated clinically significant discrepancies between the methods [43]. Of note, non-invasive systolic BP in the $\leq$70 mmHg range was associated with a significantly higher acute kidney injury prevalence and ICU mortality than invasive systolic BP readings in this BP range, indicating clinically relevant discrepancies between invasive and non-invasive systolic BP measurements during hypotension. Wax and colleagues demonstrated a generally higher oscillometric than invasive BP during periods of hypotension and vice versa during periods of hypertension [44] (Fig. 2). They also demonstrated a difference in therapeutic interventions (e.g., blood transfusions and vasopressor infusions) depending on the BP monitoring method used. Besides these inaccuracies concerning BP measurements, the treating physician should be aware that clinically relevant hypotensive episodes might be missed or detected late by oscillometric versus continuous beat-to-beat BP [45]. The lack of adequate oscillometric BP validation studies and the demonstrated shortcomings of the method should lead to reconsidering the confidence in oscillometrically assessed BP.

Continuous non-invasive BP measurements

Continuous non-invasive BP monitoring systems are now available in the operating theatre or at the bedside. They are based on either the volume clamp method or radial artery applanation tonometry. Both systems provide a continuous arterial BP waveform without the risks of an arterial catheter [46]. With regard to a consensus statement on haemodynamic monitoring that declared an 'ideal haemodynamic monitoring technique provides accurate and reproducible measurements, is easy to use, is readily available, causes no harm, and should provide information that is able to guide therapy' [47], the non-invasive devices for continuous BP monitoring potentially fulfil these criteria. The clinical use

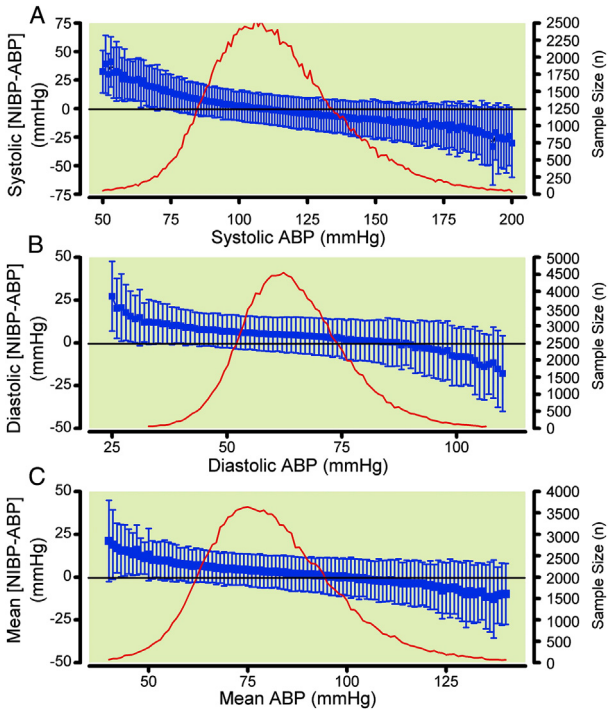

Fig. 2. Difference between oscillometric cuff and radial artery catheter measurements of blood pressure. Average difference (±SD) between simultaneous non-invasive (NIBP) and invasive radial artery (ABP) systolic (A), diastolic (B), and mean (C) blood pressure measurements in 24,225 adult patients during noncardiac surgery and anaesthesia, as well as total sample size of data pairs for each ABP value (bell-shaped curve and right-side *Y*-axis). Figure and figure legend reprinted from Wax et al. [44], with permission.

of continuous non-invasive BP measurement technologies is currently increasing which makes gaining and deepening knowledge about these technologies very important for the practising physician.

The volume clamp method

The Czech physiologist Jan *Peňáz* was the first to describe in 1973 a new approach to continuously and non-invasively measure BP using the finger arteries – the so-called volume clamp method (also named the vascular unloading technique) [48]. In the following years, the method was continuously developed further and improved by *Peňáz* himself and other scientists [49–52]. The volume clamp method basically functions as follows: an inflatable finger cuff containing an infrared transmission plethysmograph to measure the finger artery's diameter is used. An increase in artery size because of an increase in blood volume (and subsequently pressure) automatically leads to an increase in cuff pressure in order to keep the artery diameter constant (and the arterial wall 'unloaded'). The BP can be derived from the cuff pressure that is required to achieve a constant artery diameter (Fig. 3).

Because of the dependence of reliable volume clamp method-derived BP values on a sufficient BP signal from the finger artery, certain clinical conditions make BP recording with the volume clamp method difficult or even impossible. For instance, finger oedema, impaired peripheral blood perfusion (e.g., in shock or vascular diseases) or marked hypothermia might severely disturb BP recording at the finger arteries. The fact that these conditions mainly occur in critically ill patients explains that in 2–17% of patients in this population, depending on the device used, BP data recording is impossible using the volume clamp method [53,54].

Considering these contraindications for non-invasive BP measurements using the volume clamp method, selecting the patient group that benefits the most from the volume clamp method for non-

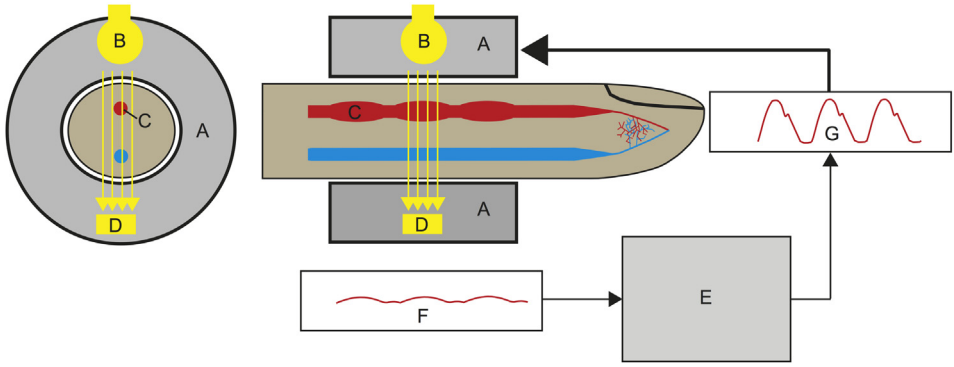

Fig. 3. Schematic illustration showing the theoretical principle of the volume clamp method (also called vascular unloading technique). An inflatable finger cuff (A) applies pressure to the finger and contains an infrared transmission plethysmograph (B) to measure the finger artery's (C) diameter (i.e., blood volume). A light detector (D) that is also integrated in the finger cuff measures the absorption of the infrared light. An increase in artery size because of an increase in blood volume (and subsequently pressure) automatically leads to an increase in cuff pressure with the help of a photo-plethysmographic control system (E) in order to keep the artery diameter constant (and the arterial wall 'unloaded'). Thus, from the pressure needed to keep the volume in the finger artery constant (F) throughout the cardiac cycle, the arterial blood pressure waveform can be derived indirectly (G).

invasive continuous BP monitoring is of paramount importance. Continuously monitoring BP in acutely ill patients on hospital admission, during general anaesthesia or during the first days after larger surgical interventions are conceivable application possibilities.

Today, two non-invasive BP measurement technologies based on the volume clamp method are available, and they are introduced and discussed in the following.

The CNAP technology

The continuous non-invasive arterial pressure (CNAP) system (CNSystems Medizintechnik AG, Graz, Austria) is one of two commercially available BP-recording technologies based on the volume clamp method. The CNAP system is composed of the CNAP Monitor 500, the reusable CNAP double-finger cuff (available in three sizes), the CNAP controller, which is attached to the patient's forearm and connects the finger cuff, and an upper-arm cuff for oscillometric BP measurements at the brachial artery used for calibration of the finger cuff-derived values. In order to achieve a constant volume in the finger arteries, the controller on the forearm makes multiple adjustments per second. The systolic BP and diastolic BP values measured at the finger artery are calibrated to the BP values obtained by oscillometric upper-arm cuff measurements using a proprietary transfer function, and the mean BP is adjusted accordingly. The CNAP system further incorporates concentrically interlocking control loops for correct long-term tracing of the finger BP [52]. Several validation studies were performed, especially in the operating theatre during general anaesthesia [55,56]. Jeleazcov and co-workers, for example, found the CNAP technology to provide reasonable BP values compared with invasive BP measurement [55]. In addition, the ability of the CNAP system to detect rapid BP changes and intraoperative hypotension was generally good in patients undergoing major surgical procedures [55]. Less data are available for the performance of the CNAP technology in critically ill patients admitted to the ICU [53,57].

One specific limitation of the CNAP system might be that it calibrates finger BP values to oscillometric BP values using an upper-arm cuff. The sources of error during oscillometry (e.g., atrial fibrillation or an inadequate cuff size) might consequently influence the reliability of the obtained CNAP BP values. However, regarding the simplicity of use and the absence of risks, certain patients might benefit from continuous non-invasive BP monitoring using the CNAP system compared with intermittent oscillometric measurements, as recent studies have shown. A randomized controlled trial showed that the time spent in hypotension was significantly shorter using continuous CNAP monitoring compared with oscillometry in patients undergoing thyroid surgery in an upright position [58]. The CNAP system improved the detection of fast BP changes in patients receiving sedating agents during interventional

endoscopy [59]. Further, it has high potential to improve patient safety during a caesarean section [60] and in acutely ill patients admitted to the emergency room [45] – clinical scenarios in which arterial cannulation is not clearly indicated or challenging.

The ClearSight technology

The ClearSight system (Edwards Lifesciences, Irvine, CA, USA) (formerly named Nexfin; BMEye, Amsterdam, the Netherlands) is also based on the volume clamp method. The main difference lies in the method used for calibration of the obtained finger BP values. While the CNAP system uses external calibration measurements (upper-arm cuff oscillometry), the finger BP values obtained by the ClearSight system are automatically calibrated during BP measurement with an algorithm called 'Physiocal' [49]. Because the finger arteries are affected by contraction and dilatation related to psychological and physical (e.g., blood loss) stress, the Physiocal algorithm compensates for these vasomotor-related effects [61]. In order to maintain a constant ('unloaded') diameter of the finger artery, calibrations with Physiocal take place at regular intervals. Additionally, a 'heart reference system' corrects for changes in the height of the fingers in relation to the heart level by measuring the hydrostatic difference between both [54]. The BP waveform that is displayed to the operator on the ClearSight monitor corresponds to that of the brachial artery. Because the finger and brachial artery waveforms physiologically differ in shape and absolute levels, a transfer function and waveform filtering are applied [62]. Martina and colleagues found that BP changes are adequately followed by the Nexfin technology and that BP values are comparable to those obtained by an arterial catheter [54]. However, this technology also has some limitations in certain clinical scenarios. The application of the Nexfin system in critically ill patients in an ICU did not result in clinically acceptable non-invasively obtained BP values in comparison with invasive BP monitoring [63]. Hohn and colleagues described high differences between both techniques in critically ill patients suffering from oedema and in patients with impaired peripheral blood flow, receiving high continuous doses of norepinephrine [63].

Radial artery applanation tonometry

The first approaches to measure arterial BP non-invasively by applanation tonometry date back to the 1960s when Pressman and Newgard published their findings about transducers used to measure BP at large superficial arteries [64]. They described an artery wall flattening as essential for maximum pulse amplitude sensing. Later, this newly developed method was further supported by the work of Stein and Blick [65] as well as by Drzewiecki and Nordergraaf [66]. The applanation tonometry required that the superficial artery (e.g., radial) be flattened (applanated) underneath a sensor and be supported by a bony structure (e.g., the styloid bone). Continuous non-invasive beat-to-beat recording of the arterial BP waveform thereby became possible.

The very first available beat-to-beat arterial tonometer for clinical use was the Colin CBM-30002 device [67]. In the years that followed, several applanation tonometry devices became available and disappeared again from the market. The method itself continuously advanced in its measurement accuracy and feasibility since it was invented in the early 1960s. Today, the T-Line system (Tensys Medical Inc., San Diego, CA, USA) is available for continuous non-invasive BP measurement using radial artery applanation tonometry [68]. In order to measure reliable BP values using radial artery applanation tonometry, the optimal contact pressure between the radial artery and the bone must be achieved and continuously adjusted. The T-Line system incorporates an automated tracking system to continuously identify the optimal applanation of the artery. The T-Line system consists of the following main components: a disposable wrist splint for optimal positioning (slight extension), a bracelet (including the sensor that is applied over the distal radial artery pulse and the sensor positioning mechanisms), and a patient monitor for BP waveform display. The bracelet holds two motors to move the pressure sensor laterally for identifying the site of maximum pulsation and up and down for achieving optimal artery applanation. Comparable to the oscillometric BP measurements using a cuff, the maximum pulse pressure (equivalent to the mean BP) can be obtained when the transmural pressure is zero (representing the maximum compliance of the arterial wall) [69]. The arterial BP waveform is scaled using proprietary signal processing algorithms based on the patient's body mass

index according to a large invasive radial artery reference database. Thus, an external calibration is not needed [68] (Fig. 4).

Several studies recently investigated the ability of the T-Line system to measure BP accurately and precisely compared with the arterial catheter (gold standard) in different clinical settings. Janelle and colleagues showed an acceptable agreement between radial artery applanation tonometry using the T-Line system and contralateral BP values derived from an arterial catheter in surgical patients during general anaesthesia [70]. In addition, when hypotension was induced in another study by Szmuck and colleagues, the T-Line readings were comparable to those measured contralaterally by an arterial catheter during general anaesthesia [71]. In addition, the T-Line system was also evaluated in critically ill patients admitted to the ICU. In the setting of clinical studies, radial artery applanation tonometry is basically feasible in this patient group. Several studies revealed a good accuracy and precision for mean BP compared with invasively obtained BP values [72–75]. However, not all studies have found acceptable accuracy and precision [76]. In order to serve as a reliable BP measurement device in both the ICU and surgical patients, further technical developments and advances are needed especially to improve the accuracy and precision of radial artery applanation tonometry-derived systolic and diastolic BP values.

When applying radial artery applanation tonometry, specific limitations of this method that have not yet been overcome must be kept in mind. In general, adequate training of the operator in handling the T-Line system, theoretic knowledge of radial artery applanation tonometry and knowledge of normal BP waveforms are necessary to avoid suboptimal sensor positioning over the artery and to obtain reliable BP values. The major limitation of radial artery applanation tonometry is that the system is highly sensitive to motion, for example, caused by the patient or a medical professional bumping against the patient's arm, dislodgement by changes in the patient's position or the necessity for tight arm tucking against the patient's body during surgery. After a loss of signal due to bracelet movement, the T-Line system provides BP values again after a period of 'motion recovery'. Bearing this specific major limitation of radial artery applanation tonometry in mind, it is crucial to select the right target patient population that will have the maximum benefit of continuous non-invasive BP monitoring using this system. For instance, patients undergoing elective surgical procedures who are usually monitored using intermittent oscillometric measurements might benefit from continuous non-invasive BP monitoring using the T-Line system.

In contrast to the volume clamp method, radial artery applanation tonometry provides reliable BP values despite the presence of moderate to severe oedema due to its favourable application on the patient's wrist and does not need upper-arm cuff oscillometric calibration [52,54].

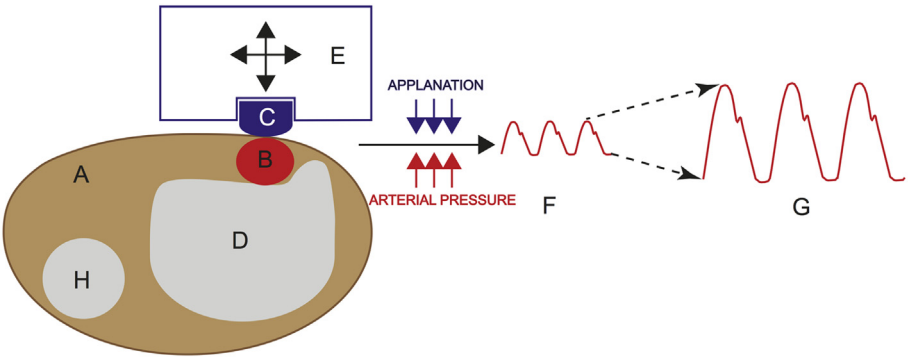

Fig. 4. Cross section of the wrist (A) with a schematic illustration showing the radial artery applanation tonometry technology. The applanation tonometry requires that the radial artery (B) be flattened (applanated) underneath a sensor (C) and be supported by a bony structure (e.g., the radius (D)). The sensor is integrated in a bracelet (E) that also holds the motors to move the pressure sensor laterally for identifying the site of maximum pulsation and up and down for achieving the optimal artery applanation. The maximum pulse pressure (equivalent to the mean blood pressure) can be obtained when the transmural pressure is zero (representing the maximum compliance of the arterial wall). Continuous non-invasive beat-to-beat recording of the arterial blood pressure waveform can thereby be derived (F). Subsequently, the arterial blood pressure waveform is scaled using proprietary signal processing algorithms based on biometric data (G). The ulnar bone is indicated by H.

Considering the fact that radial artery applanation tonometry measures mean BP and derives systolic and diastolic BP, the measurement performance of the T-Line system might be improved by further improvement of the algorithms used for the scaling of the waveform based on the raw BP signal and the transfer function used to derive systolic and diastolic BP. While the T-Line system allows mean BP determination with high accuracy and precision compared with invasive BP measurements, further improvements regarding the assessment of systolic and diastolic BP are necessary [72,75]. In addition, technical improvements (e.g., a reduction of the bracelet size) to make the measurements less sensitive to interferences like the motion of the patient's limb might result in a great progress for the technology's clinical applicability.

Finally, further clinical data are needed to identify the right target patient group for the beneficial and potential outcome-improving application of radial artery applanation tonometry.

Non-invasive continuous BP measurement devices – the future?

The non-invasive continuous BP monitoring devices available today are promising considering the potential improvement of patient safety in a variety of clinical settings. Particularly with regard to the shortcomings of the widely used and well-accepted oscillometric method, the non-invasive technologies deserve the practising physician's attention as a valid alternative. Non-invasive continuous BP monitoring technologies can improve patient monitoring during interventions and in the operating theatre [58–60]. In order to raise acceptance and application in clinical routine, the next most important step – in parallel to improving the measurement performance of the non-invasive technologies – is to prove a benefit from continuous non-invasive BP monitoring in terms of patient safety or outcome. Studies evaluating the effect of goal-directed therapy algorithms based on continuous non-invasive BP monitoring on patient outcome are therefore needed. A large number of validation studies for continuous non-invasive BP monitoring technologies already exist. In order to adequately estimate the measurement performance of such technologies, defined cut-off values to determine whether a non-invasive device measures BP well, acceptably, or poorly compared with a gold standard (e.g., arterial catheter) are required. In this context, appropriate statistical methods and cut-off values for evaluating the BP monitoring technology's ability to measure absolute BP values and detect changes reliably are still a matter of debate.

A complete replacement of continuous invasive BP monitoring by continuous non-invasive technologies in ICU and high-risk surgery patients is not possible with regard to the need for regular arterial blood gas analyses and the current measurement performance of the innovative technologies.

Nevertheless, we should evaluate the non-invasive technologies as a potential alternative to intermittent oscillometric BP measurements and invasive arterial catheter-derived BP measurements in certain groups of patients that need to be clearly defined in future clinical studies.

In addition, continuously and non-invasively recorded BP waveforms allow the monitoring of respiratory variation of systolic BP and pulse pressure (stroke volume variation and pulse pressure variation) for testing fluid responsiveness in mechanically ventilated patients and further advanced haemodynamic variables such as continuous non-invasive cardiac output.

Summary

In clinical routine in the operating theatre and the ICU, BP measurements are usually obtained intermittently and non-invasively using oscillometry (upper-arm cuff method) or continuously and invasively with an arterial catheter. Although the oscillometric method and invasive arterial catheters are both routinely used and well accepted for BP measurement, they have potential limitations. Every anaesthesiologist and intensivist must understand the underlying technology basics in order to reliably measure a patient's BP and recognize measurement errors due to inherent limitations. Innovative technologies allowing for continuous non-invasive BP monitoring such as the volume clamp method and radial artery applanation tonometry are available. Despite encouraging validation data, the question of which patient groups and clinical settings these technologies should be applied to improve patient safety or outcome has not been sufficiently addressed. In critically ill ICU and high-risk surgical patients, further improvements of these technologies with regard to data recording and processing are needed before they can be recommended for routine clinical use.

Practice points

- Understanding the basic principles, limitations and pitfalls of intermittent non-invasive (oscillometry) and continuous invasive (arterial catheter) BP measurements is crucial in anaesthesiology and intensive care.
- The benefits of placing an arterial catheter for continuous invasive BP monitoring must be carefully weighed against potential harm.
- Innovative technologies for continuous non-invasive BP monitoring might be an alternative to intermittent oscillometric or arterial catheter-derived BP measurements in certain defined patient groups.
- The exclusion criteria for the use of non-invasive technologies and their specific limitations must be regarded in order to obtain reliable BP readings.
- The sole use of continuous non-invasive technologies outside of clinical studies in critically ill ICU patients and during high-risk surgical interventions can currently not be recommended.

Research agenda

- Additional work comparing intermittent non-invasive with continuous non-invasive BP monitoring with regard to patient safety and outcome with special regard to shortcomings and specific limitations of the methods would be useful.
- Further technical improvement of the technologies for continuous non-invasive BP monitoring is needed in order to reduce artefacts due to motion of the patient's extremity or finger oedema.
- Regarding technologies for continuous non-invasive BP monitoring, the further development of calibration methods and algorithms used for BP determination is essential.
- In order to exactly evaluate a new non-invasive method's ability to reliably measure BP, we need appropriate statistical approaches, especially when it comes to tracking rapid BP changes.
- We need well-designed clinical trials in order to determine the specific patient groups or clinical settings that benefit most from the new technologies for continuous non-invasive BP monitoring.

Conflict of interest statement

BS received unrestricted research grants from Tensys Medical, Inc. (San Diego, CA, USA) and refunds of travel expenses from CNSystems Medizintechnik AG (Graz, Austria). BS collaborates with Pulsion Medical Systems SE (Feldkirchen, Germany) as member of the Medical Advisory Board.

RD has received research funding from Tensys Medical, Inc. (San Diego, CA, USA), via contract with Veterans Medical Research Foundation, San Diego, CA, and currently serves as a member of the Medical Advisory Board of Tensys Medical, Inc.

JYW received refunds of travel expenses from CNSystems Medizintechnik AG (Graz, Austria).

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