Although its reliability is often questioned, non-invasive blood pressure (NIBP) monitoring with an oscillometric arm cuff is widely used, even in shocked critically ill patients. When correctly implemented, modern arm NIBP devices actually can provide accurate and precise measurements of mean blood pressure as well as clinically meaningful information such as identification of hypo- and hypertensive patients and monitoring of response to therapy. Even in specific circumstances such as arrhythmia, hypotension, vasopressor infusion and possibly in obese patients, arm NIBP could be useful, contrary to widespread belief. Hence, postponing the arterial catheter insertion pending the initiation of more urgent diagnostic and therapeutic measures could be a suitable strategy. Given the arterial catheter-related burden, fully managing critically ill patients without any arterial catheter may also be an option. Indeed, the benefit patients may experience from an arterial catheter is questioned in recent studies failing to demonstrate that its use reduces mortality. However, randomized controlled trials to confirm that NIBP can safely fully replace the arterial catheter are yet to be done.
Besides intermittent measurements, continuous NIBP monitoring is a booming field, as illustrated by the release onto the market of user-friendly devices, based on digital volume clamp and applanation tonometry. Their imperfect accuracy and precision would probably benefit from technical refinements but their good ability to track, in real time, the direction of changes in BP is an undeniable asset. Their drawbacks and advantages and whether these devices are, today, ready-to-use in the critically ill patient are discussed in this review.

INTRODUCTION

Arterial blood pressure (BP) is often measured with an automated brachial cuff (arm non-invasive blood pressure [NIBP])[1]. Indeed, intermittent arm NIBP is the first-line monitoring technique during prehospital care, in the emergency department, at intensive care unit (ICU) admission or even during the whole ICU stay[2-4].

Despite the wide use of intermittent NIBP, its fundamental operating principles are not familiar to many physicians. This may partly explain why the reliability of intermittent NIBP is sometimes questioned, in particular in the critically ill, encouraging invasive measurements[5]. However, the superiority of the arterial catheter over NIBP in uncertain[6] and was recently questioned[4,7]. In addition, it is noteworthy that most of the current knowledge about BP cutoffs in patients with hypertension is derived from intermittent NIBP measurements[1]. Similarly, via the analysis of large databases mostly including NIBP measurements, a recent international consensus emphasized that a systolic BP below 100 mmHg represents an alert signal during sepsis[8].

NIBP is a fast-evolving field as illustrated by the development, over the last decade, of several devices displaying continuous measurement of BP now entering the clinical arena. They might soon offer an elegant compromise between noninvasive though intermittent NIBP monitoring and beat-to-beat though invasive intra-arterial monitoring.

The historic auscultatory method, currently nearly abandoned in the setting of critical care, will not be covered in this review. Since several proprietary devices and technologies are discussed in this review, it is important to underscore that none of the authors has or has had any association with the relevant companies or with the development of the devices discussed.

BRACHIAL CUFF OSCILLOMETRIC MEASUREMENTS

How does it work?

The development of oscillometry goes back to the late nineteenth century when it was discovered that the arterial pulse oscillations of the human forearm could be transmitted to a surrounding air-filled cuff[9]. Since then, it took several decades before the physical principles governing the transmission of BP oscillations to the air cuff were understood and before the translation of cuff pressure oscillations into BP values were mathematically modeled[10]. With the arrival of microprocessors, oscillometric devices were released on the market in the late 70's even before recent knowledge and modeling could be fully embedded[11].

Most oscillometric devices measure the amplitude of pressure oscillations in the air-filled arm cuff during gradual deflation, over 30-40 seconds, from a pressure well above systolic BP (collapsing the brachial artery) down to atmospheric pressure (Figure 1). As the cuff deflates below systolic BP, blood flows through the reopening brachial artery and induces arterial wall oscillations that increase until the counterpressure exerted by the cuff allows minimal arterial wall tension and maximal arterial volume change. The cuff pressure at this point of maximal oscillation determines the mean BP (Figure 1). Notwithstanding some artifacts including the imperfect consideration of the slow decrease of pressure in the deflating cuff, mean BP measurements were later found to be accurate to a few

mmHg[12,13].

Systolic and diastolic BP are not directly measured but are mathematically derived[1]. Empirical algorithms, owned by manufacturers, analyze the oscillometry envelope (Figure 1) and determine systolic and diastolic BP either at fixed ratios of maximal oscillation or at varying inflexion points on the ascending and descending parts of the envelope, respectively[14].

How and to what extent oscillometric algorithms evolved over the recent decades while the physics of arterial and air-filled systems became better understood is not known[10]. Ideally, for accurate BP determination, these algorithms should 1) take into account the dynamic compliances of the air-cuff and of the underlying soft tissues, as well as their changes during cuff deflation, 2) operate across a broad range of arterial stiffness levels, 3) sufficiently filter and amplify the BP oscillatory signal, 4) cope with irregular beats during arrhythmia, and 5) recognize artifacts such as patient's movements or vibrations during ambulance or helicopter transport[15,16]. Failure to fulfill one or several of these requirements may account for the observed inaccuracies of some first-generation or even more recent devices, for instance in elderly, hypertensive, or diabetic patients (with increased arterial stiffness), obese patients (with thick soft tissues dissipating pressure waves), and in patients with low flow states or drug-induced vasoconstriction[17].

To what extent can clinicians trust recent devices and use them in everyday critical care practice? Before addressing this practical question, it is worth reminding some basic issues.

- As existing algorithms best operate within a certain range of cuff compliance, the cuff size is of paramount importance, more specifically the cuff length-to-width ratio (ideally 2:1) and the cuff width-to-arm circumference ratio (ideally 40%)[1,18,19]. Too large cuffs expose to underestimation of BP whereas too small cuffs expose to overestimation[17]. In everyday practice, manufacturer instructions, often printed on the cuff itself, are helpful for a thorough choice of cuff.
- Since mean BP represents the perfusion pressure of most organs, studies not reporting mean BP when testing NIBP devices are of poor value for critical care practitioners.
- Oscillometric systolic BP measurement is the BP component with the poorest agreement with the intra-arterial reference[5,20,21]. Besides drawbacks inherent to empirical algorithms of BP determination, pathophysiological considerations may account for the "error" (bias) observed between systolic NIBP and the invasive reference. Indeed, systolic BP amplifies from the aorta to peripheral arteries[22] and arm NIBP measures BP at the brachial level whereas invasive measurements are mostly taken in the radial artery[23]. Of note, systolic NIBP remains a cornerstone of acutely ill patient triage: for instance, systolic NIBP is one of the 3 criteria of the quick-SOFA, a recently recommended triage tool[8].
- Finally, even invasive BP as displayed by bedside ICU monitors may exhibit inaccurate measurements[24]. Indeed, artifacts due to inappropriate dynamic response of the fluid-filled monitoring systems such as underdamping/resonance phenomena[25] are frequent in the clinical setting[26,27].

Today, does arm NIBP provide acceptable accuracy and precision?

According to the Association for the Advancement of Medical Instrumentation (AAMI), NIBP and intra-arterial BP devices are deemed interchangeable if the mean bias between the two techniques (accuracy) and its standard deviation (precision) do not exceed 5 and 8 mmHg, respectively. In their last update, the so-called ISO Standard 81060-2, the AAMI criteria were slightly refined in order to take into account the variability of the intra-arterial measurements[28,29].

In retrospective analyses of large databases, the ISO Standard was not fulfilled by intermittent arm oscillometric NIBP[5,30]. Mean BP measurements seemed less inaccurate than systolic and diastolic BP. However, paying particular attention to avoid technical factors biasing BP measurements whatever the technique (level of the arterial line pressure transducer, pressure signal over- or underdamping, size of the brachial cuff, cuff placement), recent prospective studies have shown that mean and diastolic BP measurements with arm NIBP fulfilled the ISO Standard[21,31,32], i.e., reported a mean bias of 5 mmHg or less, with sufficient precision. Thus, if correctly applied, the performance of oscillometry can be good.

May we rely on arm NIBP to detect hypotension or hypertension?

Most of the studies have focused on NIBP accuracy and precision via Bland-Altman analysis but few addressed the practical issue of detection of BP values beyond thresholds relevant to patients and clinicians. During the very first hours of critical illness, when invasive BP is not available yet, hypotension, a common trigger for urgent therapy, should be accurately detected. Remarkably, arm NIBP detection of mean BP <65 mmHg was associated with a high diagnostic performance as assessed by the area under the receiver operating characteristics curve (AUC_{ROC})[20,21,31,33]. By plotting the true positive rate (sensitivity) as a function of the false positive rate (1-specificity) of a binary diagnostic tool, those curves enable to globally assess the tool, combining sensitivity and specificity. An AUC_{ROC} of 0.5 indicates a total lack of diagnostic performance whereas an AUC_{ROC} of 1.0 indicates a perfect diagnostic tool. Hence, NIBP assessed as a diagnostic tool to identify hypotensive patients (with invasive mean BP < 65 mmHg) showed very high values of AUC_{ROC} (0.89-0.98)[20,21,31,33].

Generally, detection of chronic hypertension is not a primary concern in critical care. However, pain-, disease- or vasopressor-induced hypertension, for instance, should be reliably diagnosed since it can be harmful during conditions such as arterial hemorrhage or myocardial infarction. The AUC_{ROC} for the identification of patients with a systolic BP >140 mmHg with arm NIBP was of 0.88-0.94[29,33].

Of note, optimal thresholds of NIBP readings that best detect hypotension or hypertension may differ across oscillometric devices, and depend on whether clinicians choose to favor specificity or sensitivity[20]. In this regard, our opinion is that the value of 70 mmHg for mean NIBP as a target when caring for shocked patients may offer a clinically relevant compromise, i.e., allowing ruling out low invasive mean BP (< 65 mmHg) with strong confidence whilst not exposing patients to deleterious high BP levels[20].

What about measurements of changes in BP with arm NIBP?

Changes in arm NIBP have sufficient accuracy to provide good detection of a significant increase in invasive mean BP, enabling identification of BP responders to urgent therapy (AUC_{ROC} of 0.89-0.98 for a 10% mean BP increase cutoff)[20,21,31,33]. When using BP change as a surrogate for cardiac output change during a fluid challenge, arm NIBP was no less performant than intra-arterial BP[34].

Reliability of NIBP in situations frequently encountered in the ICU

Contrary to widespread belief, several studies showed that *vasopressors* have little impact on arm NIBP performance[5,20,21]. In the most recent study, although the authors judged NIBP measurements of insufficient accuracy based on other criteria, diastolic and mean arm NIBP passed the ISO criteria[35].

Hypotension does not appear to cause flawed arm NIBP measurements[5,20,21,31]. During extreme hypotension, arm NIBP may fail to display a value, but along with other signs of shock, this prompts urgent therapy.

In *obese patients*, provided that the cuff is carefully selected and positioned, arm NIBP can be considered reliable to detect hypertension[36]. However, probably depending on the NIBP device used, either poor or fair accuracy were reported in the critically ill obese patient[32,37,38].

Cardiac arrhythmia (atrial fibrillation)-induced beat-to-beat variability of the pulse wave is commonly deemed to hinder the reliability of NIBP measurements[1] but few data support this belief. Cardiac arrhythmia as compared to regular cardiac rhythm in recent studies, does not cause flawed NIBP measurements[31,39,40] provided that one averages 3 consecutive measurements.

In summary, those clinical factors potentially unfavorable to NIBP measurements should not, on their own, refrain clinicians from using brachial cuff NIBP. However, since these potentially unfavorable factors may be encountered concomitantly in the same patient, caution and clinical judgment should always apply.

What if the brachial cuff cannot be placed at the arm?

The common practice of a lower limb cuff placement[2] has been only recently evaluated. Possibly for anatomical reasons, NIBP measurements were less accurate if the cuff was placed at the ankle or the thigh rather than at the arm[21]. However, ankle and thigh NIBP still reliably detected hypotensive and therapy-responding patients (AUC_{ROC}=0.93 and 0.96, respectively)[21].

Are there discrepancies from one device to another?

In the same population, accuracy and precision vary significantly from one oscillometric device to another [33] or even, within one device, from an older to a newer software version [41]. This may herald future improvements of NIBP.

What are the risks of arm NIBP?

The wider the interval between 2 intermittent NIBP measurements, the higher the risk of delaying the detection of sudden changes of BP, especially when vasopressors are infused. However, closer intervals expose to discomfort and to cuff inflation–induced injuries of skin, vessels and nerves[42-44].

NONINVASIVE CONTINUOUS MONITORING OF BP

Numerous commercial devices have been developed, relying on two distinct technologies: (1) Finger cuff devices such as CNAP™ (CNSystems, Graz, Austria) and Nexfin™ (recently rebranded as ClearSight™ [Edwards Lifesciences Corporation, Irvine, CA]). The Finapres Nova™ finger cuff system (FMS, Amsterdam, The Netherlands), which recently received clearance from the United States Food & Drugs Administration, is a development of older devices such as the Ohmeda Finapres™ (Ohmeda, Englewood, CO) or the Finometer™ (FMS, Amsterdam, The Netherlands). (2) Tonometers of which the T-line™ system [Tensys Medical, San Diego, CA] being the most studied one[45]. Via beat-to-beat measurements, the promise of these "next-generation" devices is a rapid and reliable detection of acute changes in BP, a detection which could be delayed or even missed with intermittent NIBP. Have these promises been kept?

How does it work?

Finger cuff devices

The volume clamp technique has been described several decades ago. The patient's finger is wrapped in an inflatable cuff including a photoplethysmograph. The finger cuff keeps the finger blood volume constant during each pulse wave by keeping constant the photoplethysmographic absorbance adjusting cuff pressure in real time. Hence, the finger cuff inflates during systole and deflates during diastole (increasing and decreasing pressure in the cuff), using fast electronic retrocontrol loops to keep the photoplethysmographic signal constant[46,47]. Instant changes in the counterpressure exerted by the finger cuff reflect the finger BP waveform (Figure 1). The brachial BP is then mathematically reconstructed and, for the CNAP™ but not the Nexfin™/ClearSight™ system, calibrated against arm oscillometric NIBP[46,47] (Figure 1).

Tonometers

Arterial applanation tonometry consists in placing, over the skin, a pressure transducer that gently compresses, i.e., applanates, the underlying artery. This allows the reconstruction of the BP waveform, using proprietary algorithm taking into account the soft tissues-related signal loss. Hence, a tonometer, through estimating the arterial wall tension, quantifies the arterial pulse physicians otherwise subjectively assess through radial palpation. Contrary to several of its predecessors, the T-line™ device is user-friendly and free of user-bias since the sensor is housed by a wrist bracelet rather than handheld by a healthcare provider (Figure 1). Within the bracelet, the sensor is automatically moved over the radial artery until maximal pulse pressure, i.e., optimal waveform, is recorded. No external calibration is required[48,49].

Do continuous NIBP devices provide acceptable accuracy and precision?

Since the afore-mentioned ISO standard does not cover continuous NIBP[28], acceptability of the accuracy and precision lacks consensual definition. The ISO standard has been proposed for

various settings, from ambulatory to healthcare facility use[28]. In the critically ill, the ISO criteria are not so stringent and could be seen as maximal limits of tolerability[29]. However, even using these rather loose tolerance boundaries (5 mmHg and 8 mmHg for mean bias and its standard deviation, respectively) to compare continuous NIBP with invasive BP, a 2013 systematic review and meta-analysis concluded that continuous NIBP was not sufficiently reliable[45]. More recent reports with the latest hardware and software versions of these devices may slightly nuance this conclusion and refine the current knowledge (detailed information about the numerous recent studies performed with those devices are summarized in the Table).

First, whatever the device, mean and, to a lesser extent, diastolic BP measurements were consistently more accurate and precise than systolic BP measurements. Mean BP readings should therefore be preferred over systolic BP to guide therapy.

Second, in most evaluations of the T-line™, measurements of mean BP fulfilled the ISO criteria. However, the T-line™ has been only studied in small size studies (20-30 patients), often from the same group[48,50-53], during a short observation period of relative hemodynamic stability, mostly with normal BP values. Therefore, the encouraging performance of the T-line™ has to be confirmed in larger studies before drawing any enthusiastic conclusion.

Third, for the Nexfin™/ClearSight™ and CNAP™ devices, the fulfilment of the ISO criteria was inconstant, several studies reporting insufficient accuracy and/or precision (Table).

Fourth, beyond different case mixes, methodological issues may account for the heterogeneous performances reported. Averaging measurements (after data extraction towards a personal computer) and manual elimination of outliers, often subjectively (presumably corresponding to patient motion, arterial line flushing or device calibration), could have artificially improved the agreement between noninvasive and invasive BP in some studies. For the CNAP™ system, BP readings suffer from drifting between two oscillometric calibrations, especially in case of changes in the hemodynamic status[33]. Therefore, the interval to last calibration should have been more often mentioned in study reports since it impacts the accuracy of CNAP™ readings[33,54].

Last, the detection of BP values above or below a critical cut-off, which is one of the clinically relevant questions addressed to those devices, has been assessed in only one study. During the four minutes following calibration, the CNAP™ reliably detected mean BP below 65 mmHg[33].

Continuous NIBP to track changes in BP

Trending ability denotes the capacity of the device to accurately follow BP changes over time. This implies that the device should be able to detect and take into account major confounders such as disease- or therapy-induced changes in the vasomotor tone of the upper limb. Some devices perform periodical recalibrations of the BP waveform, via changes in finger cuff pressure and contemporaneous analysis of the plethysmogram changes (Nexfin™/ClearSight™)[47] or via upper arm NIBP (CNAP™ system)[46].

The ability of the Nexfin™/ClearSight™ and the CNAP™ devices to indicate the *direction* of changes in actual BP has been often reported to be good[55-60] (Table). In other words, an increase (a decrease) in the BP displayed by a finger cuff system reliably reflects an increase (a decrease) in the

actual BP. Nevertheless, beyond this gross evaluation, firm conclusions about the precise trending ability of these devices cannot yet be drawn for the following reasons.

First, for finger cuff devices, the trending ability has been mostly evaluated during periods of relative hemodynamic stability. Therefore, events of significant changes in BP retained in the analyses were scarce, even among very large datasets[56,58], after exclusion of minimal changes in BP possibly reflecting random noise[61].

Second, the detection of the *magnitude* of changes in BP -rather than the simple increase or decrease- has been scarcely addressed, but encouraging findings were reported[55,56,58-60].

Third, the detection of *abrupt changes* in BP should also be specifically tested. Indeed, in studies reporting good trending ability, recalibrations of the device occurred during the observation period. Thus, these studies tested calibration rather than trending[56,58,60]. In one of the few studies evaluating the trending ability in between calibrations, the effects of a cardiovascular intervention (volume expansion, change in vasopressor dosage, passive leg raising) were poorly detected by the CNAP™ monitor[33]. Similarly, during induction of anesthesia and tracheal intubation, BP changes were detected within a reasonable time lag by the CNAP™ or the Nexfin™/ClearSight™ but the magnitude of these changes was poorly estimated[59,62]. For the detection of a fluid bolus-induced increase in BP, Nexfin™/ClearSight™ tracking ability was only fair[63] or, at best, correct[60].

Likewise, studies addressing the trending ability of the T-line™ investigated the detection of the direction of changes in BP (fair to honorable performance) but not the magnitude of these changes. In addition, disease- or therapy-induced abrupt changes in BP were not studied[48,50,52,53,64-66].

In summary, provided that close recalibrations are automatically or manually performed, these fast-response devices may allow an early and reliable detection of acute changes in BP as alert signals, but may be misleading when considering the magnitude of the BP change in the event of abrupt changes. Specific studies are needed to refine this conclusion.

Limitations to continuous NIBP in ICU patients

Important peripheral *vasoconstriction* (related to hypothermia, to the disease or to high dosage of vasopressor[67]) may account for failure of finger cuff technology to display any measurement, as observed in up to 15-17% of studied ICU patients[33,68,69]. Whether excessive vasoconstriction also alters BP waveform reconstruction by the T-line™ algorithm is unclear.

Movements of the limb equipped by the device hamper the accuracy of BP measurements. This is particularly true for the T-line™ in non-sedated patients, as the optimal placement of the sensor could be lost[48].

The impact of several pathophysiological conditions on continuous NIBP should be better explored: *cardiac arrhythmia*[54] and even *obesity* and upper limbs *edema*[67] which can promote a marked attenuation of the BP signal and yield insufficient precision of the device[65,70]. Some studies excluded patients with obesity[58] or finger edema[54,58,71]. This may also contribute to the between-studies reported differences.

Other applications for continuous NIBP monitors

Prediction of fluid responsiveness. Instant changes in BP waveform are sufficiently well detected to guide fluid management by the noninvasive measurement of respiratory PPV. In the operating room[72-75] or in the ICU[68,76], several works (but one[77]) reported that noninvasive and invasive PPV have similar performance to predict fluid responsiveness. Naturally, all the limitations of invasive PPV (e.g., arrhythmia, spontaneous breathing efforts, limited tidal volume)[78] also apply to noninvasive PPV.

Cardiac output. CNAP™, Nexfin™/ClearSight™ and T-line™ systems, in their latest versions, also provide a noninvasive determination of cardiac output via pulse contour analysis without invasive calibration, an exciting perspective[79]. Discussing the accuracy of these cardiac output measurements is out of the scope of this review.

ARTERIAL LINE, INTERMITTENT NIBP OR CONTINUOUS NIBP?

Can NIBP fully replace the arterial catheter? PROBABLY YES!

NIBP is already widely used in non-severely ill patients, in patients whose critical illness has been partially resolved and even in more severely ill patients, before an arterial line is placed[2]. Postponing the arterial line insertion could be a suitable strategy since arterial catheter insertion may be difficult during hypotension or vasoconstriction. Furthermore, urgent insertion of indwelling devices may not be compatible with appropriate measures to prevent intravascular catheter-related infections. In addition, urgent insertion of an arterial catheter may delay more urgent measures such as patient transfer, imaging and therapeutic invasive procedures, antimicrobials initiation, transfusion. Since NIBP provides rather accurate measurements of mean BP or, at least, a reliable detection of hypotension, hypertension or response to urgent therapy[20,21,31,33], we believe NIBP can be used to postpone the arterial catheter insertion. This attitude can be considered safe as, in case of persistent shock, invasive measurement may correct any inaccuracy in initial management, whereas among patients with improved circulatory status, catheterization may be avoided. Such a strategy of delayed catheter insertion may be prospectively tested to confirm our hypothesis.

To go even farther, critically ill patients may be safely managed completely noninvasively with respect to BP monitoring. The arterial catheter is used for both BP monitoring and blood sampling for laboratory testing. However, despite its wide use for decades, there is no evidence that the arterial catheter is associated with improved outcomes in the ICU[6]. Two recent observational studies addressed this issue. In hemodynamically stable patients who are mechanically ventilated, Hsu et al. reported the lack of association between survival and arterial catheter use[4]. A similar finding has been reported by Gershengorn et al. in a primary cohort of mechanically ventilated patients and in eight of nine secondary cohorts. In the cohort of patients receiving vasopressors (almost 11,000 patients), arterial catheter use was even associated with increased mortality[7].

The wide variation in arterial catheters utilization illustrates the uncertainty around its benefits[2,3]. Indeed, as above-mentioned, even invasive BP monitoring is prone to inaccuracies[26]. Furthermore, arterial lines encourage excessive laboratory blood testing [80], promoting anemia, transfusion and their respective complications whereas the benefit of repeated blood sampling is often questionable[6]. Last,

patient discomfort from repeated percutaneous vascular punctures or frequent BP cuff inflations should be balanced with the life-threatening risks related to arterial catheters (limb ischemia, bloodstream infection for instance[23]). As recently emphasized by Garland, there is an urgent need for rigorous studies assessing the usefulness of arterial catheters in the ICU, as performed earlier for the pulmonary artery catheter [6].

Can continuous NIBP replace intermittent NIBP? POSSIBLY YES!

Only few studies provided comparisons of continuous NIBP with both intermittent NIBP and invasive BP. The Nexfin™/ClearSight[81] and the CNAP™ system[33] were no less accurate than the compared intermittent NIBP while providing beat-to-beat measurements. Again, this may depend on the oscillometer model and on the time to last calibration[33]. To limit the drift and improve the trending ability of the CNAP™ system, setting a shorter between-calibration interval could be proposed. However, this may question the added value of the CNAP™ device over frequent intermittent measurements.

No finger or wrist complications have been reported during the short-term use of continuous NIBP devices[53,82]. Future studies should aim at confirming that replacing intermittent by continuous NIBP is a safe and suitable option. Ideally, the endpoints should be patient-centered outcomes[6].

Some clues may herald future improvements of all NIBP devices since hardware or software updates increase their accuracy[48,83] or were proposed for this purpose[33]. This underscores the ongoing progresses that may render the future of noninvasive monitoring even brighter than the current wide use of intermittent NIBP to resuscitate patients until the placement of an arterial line, if still deemed necessary.

Figure 1: The oscillometric, volume-clamp and applanation tonometry technologies.

Legend: SBP, MBP and DBP: systolic, mean and diastolic arterial blood pressure.

Figure 2: Key messages for clinical practice.

Legend: BP: blood pressure. NIBP: non-invasive blood pressure.

Table: Overview of studies comparing, in adults, Nexfin™/ClearSight™, CNAP™ and T-line™ noninvasive and invasive intra-arterial measurements of arterial blood pressure.

Legend: mean bias = noninvasive minus invasive blood pressure (BP); SBP: systolic blood pressure; MBP: mean blood pressure; DBP: diastolic blood pressure; Concordance rate: percentage of invasive and noninvasive data points with the same direction of change (after excluding central data of the plot which tend to be randomly distributed, i.e., after the application of an exclusion zone). LOA: limits of agreement.

AF: atrial fibrillation; BMI: Body mass index; IABP: intra-arterial blood pressure; ICU: intensive care unit; LVAD: left ventricular assist device; NA: non-available; NIBP: Noninvasive blood pressure; OR: operating room; SD: standard deviation; TAVR: Transcatheter aortic valve replacement.

Mean bias (≤5 mmHg) and SD (≤8 mmHg) validating the ISO standard criteria are provided in green bold characters with underscore whereas red characters are used otherwise.

*: Conflict of interest (COI) with the tested device, as declared by the authors. COI is reported in this table if at least one of the authors received research grants, travel fees and/or is member of the advisory board or is employee of the manufacturer. Simple loan of device is not reported as COI in this table.

¥: Whether bias was calculated as noninvasive minus invasive or *vice versa* is unclear.

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Table: **Overview of studies comparing, in adults, Nexfin™/ClearSight™, CNAP™ and T-line™ noninvasive and invasive intra-arterial measurements of arterial blood pressure.**

Legend: mean bias = non-invasive minus invasive blood pressure (BP); SBP: systolic blood pressure; MBP: mean blood pressure; DBP: diastolic blood pressure; Concordance rate: percentage of invasive and noninvasive data points with the same direction of change (after excluding central data of the plot which tend to be randomly distributed, i.e., after the application of an exclusion zone). LOA: limits of agreement.

AF: atrial fibrillation; BMI: Body mass index; IABP: intra-arterial blood pressure; ICU: intensive care unit; LVAD: left ventricular assist device; NA: non-available; NIBP: Noninvasive blood pressure; OR: operating room; SD: standard deviation; TAVR: Transcatheter aortic valve replacement.

Mean bias (≤5 mmHg) and SD (≤8 mmHg) validating the ISO standard criteria are provided in green bold underlined characters whereas red normal characters are used otherwise.

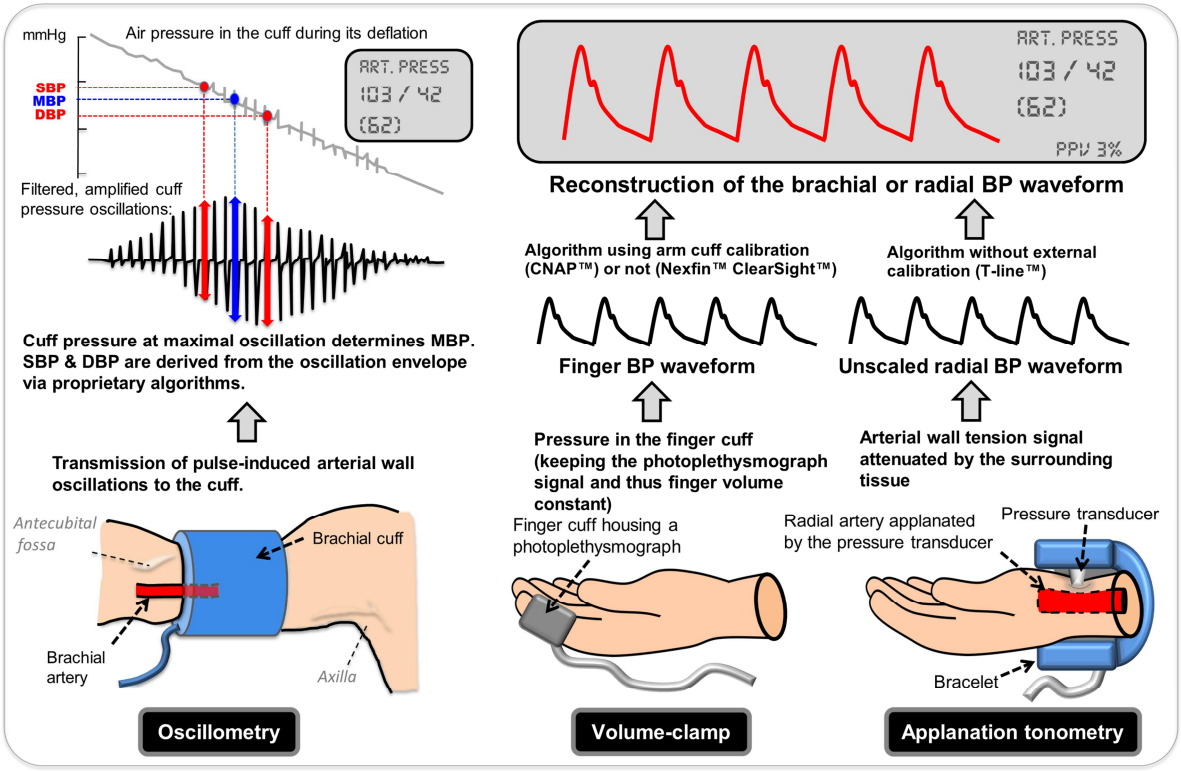
*: Conflict of interest (COI) with the tested device, as declared by the authors. COI is reported in this table if at least one of the authors received research grants, travel fees and/or is member of the advisory board or is employee of the manufacturer. Simple loan of device is not reported as COI in this table.

¥: Whether bias was calculated as noninvasive minus invasive or *vice versa* is unclear.

	1st author & journal	Year of publication	Device & version	Setting	Cardiac arrhythmia	Patients	Pairs	Mean bias±SD SBP	Mean bias±SD DBP	Mean bias±SD MBP	Trending	Comment
Nexfin™ / ClearSight™	**Schramm** [63] *J Anesthesiol Neurosurg*	2017	***Nexfin™**	**OR** (neurosurgery)	NA	35	280.	¥14±19	¥25±15	¥23±16	Concordance rate for MBP: 84% fluid bolus 41% sitting up (exclusion zone 10%)	. Recordings made in supine & in sitting position . Norepinephrine in 33 patients (0.017 µg/kg/min [IQR 0.0-0.04])
	Balzer [55] *J Int Med Res*	2016	**ClearSight™**	**OR** (orthopedic)	0%	20	120	-5.2±16	5.07±12	0.8±13	Polar plot: within the accepted range of angle/angular bias ±30°	. Measurements at the beginning and end of surgery . Vasopressors NA
	Heusdens [84] *Brit J Anaesth*	2016	**ClearSight™**	**OR** (carotid)	NA	25	3782	-3.3±10.8	6.1±5.7	3.5±5.2	NA	Ephedrine, phenylephrine, and/or norepinephrine in all patients.
	Vos [81] *Brit J Anaesth*	2014	**ClearSight™**	**OR** (general)	NA	112	758	NA	NA	2±9	NA	. Vasopressors NA
	Ameloot [56] *Minerva Anesth*	2014	**Nexfin™**	**ICU** (medico-surgical)	NA	45	675	8.3±13.8	-9.4±6.9	-1.8±5.1	. Concordance rate 85% (10% exclusion zone) . Polar plot : 97% of the data points lie within the 10% lines	. Trending analysis with mean of 3 measurements . Norepinephrine in 78% (0.20±0.17 µg/kg/min)
	Martina [85] *ASAIO J*	2014	***Nexfin™**	**ICU** (surgical)	NA	29	8700	−7.6 ± 5.8	−7.0 ± 5.2	−6.9 ± 5.1	NA	. Continuous flow LVAD in all patients . Norepinephrine in 14% (dosage NA)
	Weiss [59] *Brit J Anaesth*	2014	**Nexfin™**	**OR** (general)	0%	31	3479	+3.8±16.5	+8.8±10.8	+5±12 to -9±15	. Concordance rate (SBP & DBP) 100% (no exclusion zone). . High bias and/or LOA for changes in SBP or DBP.	. Recordings from 1 min before the induction to 10 min after tracheal intubation . 58% ephedrine and 9.7% phenylephrine
	Hofhuizen [60] *J Crit Care*	2014	**ClearSight™**	**ICU** (after cardiac surgery)	0%	20	54	2.7 ± 11.5	4.9 ± 6.9	4.2 ± 7.0	. Concordance Rate 100% (exclusion zone 5%) . Mean polar angle 10.4°, SD of 10.3°. 100% between the 30° radial limits.	. 28 fluid challenges in 19 patients . Norepinephrine in 40% (0.03 µg/kg/min [0.01-0.08])
	Hohn [67] *Brit J Anaesth*	2013	**Nexfin™**	**ICU** (surgical)	0%	25	117	-9±25	NA	6±12	NA	Norepinephrine in 72% (0.13±0.11 µg/kg/min)
	Broch [57] *Minerva Anesth*	2013	***Nexfin™**	**OR** (elective coronary)	0%	50	514	6.5±17.5 to 15.1±17.9	6.2±11.7 to 13.5±11.3	9.3±15.8 to 13.7±12.1	Concordance rate MBP 86 to 94% (15% exclusion zone).	. Recordings during "off-pump" periods. Body temperature 35.5-35.9°C . Agreement with IABP differed according to IABP site (femoral or radial) and to timing of measurements (before or after cardiopulmonary bypass). . Vasopressors NA
	Martina [47] *Anesthesiology*	2012	***Nexfin™**	**OR** (cardiothoracic)	NA	50	9000	-0.5±6.7	2.8±6.4	2.2±6.4	NA	Recordings during "off-pump" periods. . Vasopressors NA.
	Fischer [86] *Brit J Anaesth*	2012	**Nexfin™**	**ICU** (after cardiac surgery)	0%	44	220	-5.7±14.7	8.9±6.9	4.6±6.5	NA	Norepinephrine in 44% (0.01 to 0.1 µg/kg/min)
	Monnet [69] *Crit Care*	2012	**Nexfin™**	**ICU** (medical & surgical)	13%	38	76	NA	NA	-2±11	NA	All patients had signs of acute circulatory failure. Norepinephrine in 45% (0.4 µg/kg/min [0.21-0.60])
	Stover [87] *BMC Anesth*	2010	**Nexfin™**	**ICU** (surgical)	0%	10	80	NA	NA	¥-2±8	NA	Norepinephrine in all patients (12 ± 12 µg/min)

CNAP™	**Lakhal** [33] *Anesth Analg*	2016	Infinity SmartPod **CNAP™**	**ICU** (surgical & medical)	37%	182	546	-4.3±13.8	-9.7±7.8	7.2±6.4	. Concordance rate 67% (exclusion zone 10%) . Cardiovascular intervention: Important drift	. Agreement reported in this table has been analyzed during the 3 min following calibration . Trending was analyzed between 2 calibrations . Norepinephrine in 61% (0.3 [0.1–0.4] µg/kg/min)
	Wagner [71] *J Clin Monit Comput*	2015	***CNAP™**	**ICU** (medical)	AF 7%	55	4891	-10±16	+7±9	1±9	NA	Mechanical ventilation 47%, Norepinephrine 35% (dosage NA)
	Smolle [58] *Anesth Analg*	2015	***CNAP™** 500	**ICU** (medical)	AF15%	40	7200	-3.2±10.1	7.0±6.7	4.6±6.7	. Concordance rate 95% (exclusion zone 10%) .Polar concordance rate of 99.5% within 10% limits.	. All patients sedated and under mechanical ventilation . Norepinephrine in 70% (0.16 µg/kg/min [0.08–0.25])
	Kumar [88] *Indian J Anesth*	2015	Infinity SmartPod **CNAP™**	**OR** (cardiac)	0%	60	1200	-6.0±10.4	3.7±6.1	0.0±5.7	NA	. Recordings during anesthesia induction . Vasopressors NA
	Ilies [54] *Eur J Anaesth*	2014	***CNAP™** 500 v3.5	**ICU** (after cardio-vasc. surg)	15%	104	11222	-4.3±11.6	9.4±8.0	6.1±7.6	NA	. Epinephrine or Norepinephrine in some patients (n NA)
	Tobias [70] *J Anesth*	2014	**CNAP™** 500	**OR** (bariatric)	NA	18	2159	-0.3±14.2	1.3±9.5	0.6±8.6	NA	. Obese patients (BMI 38-75 kg/m2). . Cuff, for calibration against oscillometry NIBP, was placed around the upper arm (n=9) or the forearm (n= 9) . Vasopressors NA
	Schramm [89] *Anesth Analg*	2013	**CNAP™** 500 v3.5 R01 (hardware revision R06)	**OR** (TAVR)	27%	33	152 000	Overall: −6.3±18.9 Severe hypotension: 11.8±14.5	Overall: 7.4±10.5 Severe hypotension: 13.8±12.4	Overall: 4.0±11.3 Severe hypotension: 12.9±12.4	NA	Episodes of severe hypotension were induced by rapid pacing.
	Hahn [83] *Brit J Anaesth*	2012	**CNAP™** 500 V3.0 & V3.5	**OR** (orthoped)	6%	100	524 878	V3.0: -3.4±16 V3.5: -0.9±13	V3.0: 4.4±10.8 V3.5: 2.8±8.6	V3.0: 2.9±10.6 V3.5: 3.1±9.5	NA	. 2 software versions were tested (3.0 & 3.5) . Vasopressors NA
	Jagadeesh [90] *Ann Card Anesth*	2012	Infinity SmartPod **CNAP™**	**ICU** (cardiac)	NA	30	3600	10.4±5.8	-5.3±3.0	0.04±2.0	NA	. Vasopressors NA
	Ilies [91] *Brit J Anaesth*	2012	***CNAP™** 500	**OR** (major abdo., vascul, or thoracic)	NA	85	16 843	Induction: 3.3±20.3 Maintenance: -4.2±16.5	Induction: 10.8±12.6 Maintenance: 5.8±6	Induction: 10.2±13.1 Maintenance: 4.3±10.4	NA	. Separate analysis of recording during induction and maintenance of anesthesia. . Vasopressor in some patients (n NA and dosage NA).
	Monnet [68] *Brit J Anaesth*	2012	**CNAP™** 500	**ICU** (medical)	0%	39	195	2±14.8	-11±12.8	4.8±11	NA	All patients had signs of acute circulatory failure. Norepinephrine in 64% (0.7 [0.1–2.4] to 1.1 [0.6–2.0] µg/kg/min)
	Gayat [62] *Acta Anesth Scand*	2012	**CNAP™** 500	**OR** (general)	0%	52	5174	2±22	11±12	8±13	NA	. Recordings from before the induction to 5–10 min after tracheal intubation. . Vasopressors NA
	Schramm [92] *Blood Press Monit*	2011	**CNAP™** v2.94	**OR** (TAVR)	NA	29	48691	−11±18	6±16	−0.8±15	NA	. Vasopressors NA
	Biais [93] *Ann Fr Anesth Rea*	2010	Infinity SmartPod **CNAP™**	**OR** (vascular)	0%	25	1452	7.2±12.7	-7.5±10.1	-1.8±10.3	Concordance rate 80% (exclusion zone NA)	Ephedrine used in 756 measurements.

	Jeleazcov [94] *Brit J Anaesth*	2010	* Infinity SmartPod **CNAP**™ (V2.9.14)	**OR**	0%	78	156 000	6.7±13.9	-5.6±11.4	-1.6±11.0	NA	. Vasopressors NA
T-line™	**Lin** [95] *J Neurosurg Anesthesiol*	2017	TL-300™	**OR** (Neurosurgery)	NA	23	4381	1.3±5.9	2.8±6.4	1.8±4.2	NA	. *Retrospective* study . Vasopressors NA
	Sun [66] *J Clin Monit Comput*	2017	TL-300™	**OR** (Colic)	NA	30	1538	−0.9±7.6	4.3±7.4	3.1±6.5	Concordance rate MBP 85% (exclusion zone 4 mmHg)	
	Greiwe [65] *Brit J Anaesth*	2016	TL-200pro™	**OR** (bariatric surgery)	NA	28	201 907	3.4±13.0	3.7±9.9	4.0±9.4	Concordance rate MBP 74% (exclusion zone 3 mmHg)	. BMI 49.4±9.7 kg/m² . Norepinephrine in all patients (maximal dose 0.05±0.03 µg/kg/min
	Landwieser [50] *Clin Res Cardiol*	2015	*TL-200pro™	**ICU** (cardiac)	AF 20%	30	7304	-6±11	4±7	2±6	Concordance rate MBP 88% (exclusion zone 3 mmHg)	. Mechanical ventilation in 63% . Norepinephrine in 23% (0.29 [0.03–0.45]) µg/kg/min ; Epinephrine in 33% (0.13 [0.09–0.21]) µg/kg/min
	Meidert [51] *Brit J Anaesth*	2014	*TL-200™ or TL-200pro™	**ICU** (medical)	AF 25%	24	2993	-3±15	5±7	2±6	NA	Mechanical ventilation in 46%; Norepinephrine in 25% (dosage NA).
	Meidert [52] *J Crit Care*	2013	*TL-200pro™	**ICU** (medical)	AF 4%	23	2879	-3.3±11.2	4.9±7.0	1.0±5.5	Concordance rate MBP 85% (exclusion zone 3 mmHg)	Mechanical ventilation in 50%; Norepinephrine in 39% (dosage NA).
	Colquhoun [64] *J Med Eng Tech*	2013	TL-200™	**OR** (spine surgery)	NA	21	NA	3.1 to 7.1 **SD NA**	4.9 to 7.0 **SD NA**	3.5 to 6.4 **SD NA**	Concordance rate MBP: 82-90% (exclusion zones 2.5-12.5 mmHg)	. Bias varied according to applied filters. . Vasopressors NA
	Saugel [48] *Brit J Anaesth*	2013	*TL-200pro™	**ICU** (medical)	AF 18%	34	4502	-1.4±8.8	4.4±6.6	0.7±5.1	Concordance rate MBP 88% (exclusion zone 3 mmHg)	Mechanical ventilation in 50%; Norepinephrine in 32% (0.09 µg/kg/min [0.02–0.20])
	Saugel [53] *Intensive Care Med*	2012	TL-200™	**ICU** (medical)	AF 32%	28	76826	-9.0±14.5	5.2±9.5	0.5±8.7	Concordance rate MBP 67% (exclusion. zone 3 mmHg)	Mechanical ventilation in 54%; Norepinephrine in 50% (0.11 µg/kg/min [0.04–0.16]).
	Dueck [49] *J Clin Monit Comput*	2012	*TL-200™	**OR** (general)	NA	19	4747	2.3±7.8	1.7±6.2	2.3±5.9	NA	. Vasopressors NA
	Szmuk [96] *Anaesthesia*	2008	*TL-100™	**OR** (Spine surgery)	NA	22	5450	0.0±7.9	1.6±5.6	1.6±5.3	NA	. Vasopressors NA
	Janelle [97] *Anesth Analg*	2006	*TL-100™	**OR** (general)	NA	25	17009	1.7±7.0	2.3±6.9	1.7±5.3	NA	. Vasopressors NA



Intermittent NIBP

- Mean and diastolic BP measurements are often accurate and precise with modern NIBP devices. Mean BP readings should be preferred over systolic BP to guide therapy.
- NIBP reliably identifies hypotensive (mean BP <65 mmHg or systolic BP <90mmHg) and hypertensive patients (mean BP >140 mmHg).
- Arm NIBP reliably tracks therapy-induced changes in BP (>10% increase in mean BP).
- Even in specific circumstances such as arrhythmia (provided that triplicates are averaged), hypotension, vasopressor infusion and possibly in obese patients (provided that the cuff is carefully selected), arm NIBP could be useful.
- NIBP measurements are less accurate if the cuff is placed at the ankle or the thigh rather than at the arm.

Continuous NIBP

- Mean and diastolic BP measurements are consistently more accurate than systolic BP measurements. Mean BP readings should therefore be preferred over systolic BP to guide therapy.
- Whether continuous NIBP measurements are accurate & precise is uncertain.
- Provided that close recalibrations are automatically or manually performed, these fast-response devices may allow an early and reliable detection of acute changes in BP as alert signals, but may be misleading when considering the magnitude of the BP change in the event of abrupt changes.