South Afr J Anaesth Analg. 2024;30(4):141-149
https://doi.org/10.36303/SAJAA.3105

South Afr J Anaesth Analg
ISSN 2220-1181 EISSN 2220-1173

ORIGINAL RESEARCH

Comparison between intra-arterial and two non-invasive blood pressure measuring systems: a cross-sectional analytic study employing Bland–Altman and error grid analyses

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Background: We investigated whether invasive and non-invasive blood pressure (NIBP) measurement technique differences were clinically important.

Methods: We compared invasive and two non-invasive measurement techniques (standard automated oscillometry and a mercury sphygmomanometer with flow detection using Doppler ultrasound). Bland–Altman statistical analysis was employed, and clinically important differences were determined using error grid analysis. Natural frequencies (f_n) and damping ratios (ζ) were calculated from monitor photographs of fast flush tests.

Results: Bland–Altman analysis of 195 systolic and 194 mean pressure measurements revealed small mean differences but wide limits of agreement (LOA), which precluded the interchangeability of measurement techniques. However, error grid analysis revealed that 85% and 15% of paired measurements were in the "no risk" and "low risk" zones, respectively. Natural frequencies and damping ratios (mean, range) were 16.5 Hz (4.8–33.0) and 0.38 (0.03–0.74), respectively. Natural frequencies and damping ratios were poorly predictive of error zone location.

Conclusions: This study identified statistically significant differences between invasive and NIBP measurement techniques. Despite the non-interchangeability of techniques, error grid analysis indicated that no patients in our sample would likely have received inappropriate therapy resulting from flawed intra-arterial measurements. In ensuring the accuracy of invasive pressure measurements, fast flush test determination of natural frequencies and damping ratios were unhelpful, mirroring other researchers' findings. Our findings reinforce recommendations that invasive pressures be checked against a reliable NIBP device. A systolic pressure difference > 15 mmHg should prompt an invasive system review. We propose ultrasound-guided systolic pressure measurement as a reliable method for this purpose.

Keywords: blood pressure determination, instrumentation, diagnostic errors, Bland–Altman analysis, ultrasound, natural frequency, damping ratio

Introduction

Arterial blood pressure is a critical physiological variable clinicians use for clinical decision-making and as a guide to therapy.[1-3] Direct intra-arterial blood pressure (invasive blood pressure, invasive-BP) measurements provide continuous, beat-to-beat monitoring and are regarded as a "gold standard", provided there are no artefacts. Many intra-arterial measuring systems have low natural frequencies and inadequate damping, resulting in inaccurate measurements, especially systolic arterial pressures (SAP).[4-7] Resonance artefacts are also greater at faster heart rates.[8] Inaccuracies also result from overdamping due to constrictions in the fluid line, for example, by fibrin deposits. Recommendations include regularly performing the "fast flush" test to determine the system's dynamic responses.[3,9,10] In clinical practice, measuring natural frequencies and damping ratios are seldom feasible because few monitors are equipped with strip chart recorders, and it is inconvenient and time-consuming in a busy clinical setting. Visual inspection of the response to a fast flush, although widely practised, is unreliable, except for identifying attenuation by a severely overdamped system or "ringing" in a recognisably underdamped system.[10]

A pragmatic approach is the comparison of invasive-BP with non-invasive blood pressure (NIBP) measurements by automated oscillometry (oscillometric non-invasive blood pressure, OscNIBP), whereby large discrepancies should prompt careful reassessment of the invasive measurement system.[5] However, studies comparing invasive with automated oscillometry measurements have shown that systematic errors often occur. These systematic errors are that automated oscillometry measurements tend to exceed invasive measurements during hypotension, and vice versa. These discrepancies can have clinical consequences; however, they are contextual, especially in the hypotensive domain.[5] For example, consider a test method that indicates a systolic of 100 mmHg in a patient with a "true" SAP of 85 mmHg. This 15 mmHg difference is more clinically relevant than in a patient with a true systolic of 120 mmHg, measured by the test method as 135 mmHg. Likewise, a test mean arterial pressure (MAP) of 70 mmHg versus a "true" mean of 55 mmHg is much more clinically relevant than means of 90 mmHg versus 105 mmHg.

Bland–Altman analysis is the accepted technique for quantifying statistical agreement between measuring systems.[12] However,

the method does not assess the clinical importance of measurement differences. Note that the clinical importance of the differences between two blood pressure measurement methods depends on both the measurements themselves and the differences. As a method to estimate this clinical importance, Saugel et al.[13] proposed error grid analysis in addition to Bland–Altman analysis. Briefly, 25 anaesthesiology and critical care experts compiled error grids for SAPs and MAPs by plotting a scattergram of a "test" method's measurements on the axis of ordinates against those of a "reference" method on the axis of abscissas. Zones are defined as those that demarcate clinically acceptable and unacceptable errors.[13]

> ***Zone A****: No risk (i.e. no difference in clinical action between the reference and test method).*
>
> ***Zone B****: Low risk (i.e. test method values that deviate from the reference but would probably lead to benign or no treatment).*
>
> ***Zone C:*** *Moderate risk (i.e. test method values that deviate from the reference and would eventually lead to unnecessary treatment with moderate non–life-threatening consequences for the patient).*
>
> ***Zone D****: Significant risk (i.e. test method values that deviate from the reference and would lead to unnecessary treatment with severe non–life-threatening consequences for the patient).*
>
> ***Zone E****: Dangerous risk (i.e. test method values that deviate from the reference and would lead to unnecessary treatment with life-threatening consequences for the patient).*[a]

At least 90% of the data points should lie within Zone A, and no more than 5%, 4%, 2%, and 0% in Zones B, C, D, and E, respectively.[13] Furthermore, the results should be interpreted considering the sample size and the degree of precision as reflected by the standard deviations (SD) or confidence intervals (CI).

The primary research question of this prospective, observational, cross-sectional, analytic study of arterial blood pressures in the operating theatres and intensive care units of a large academic hospital was whether observed differences between invasive and two non-invasive techniques were of such clinical importance that they could potentially lead to wrong treatment decisions. The primary outcomes were comparisons between invasive and two non-invasive techniques. The non-invasive techniques are automated oscillometry (OscNIBP) and a mercury sphygmomanometer using flow detection by Doppler ultrasound (ultrasound non-invasive blood pressure, US-NIBP).

The secondary outcome was a pilot study to determine the feasibility of measuring natural frequencies and damping ratios of the invasive measurement systems from photographs of rapid flush tests displayed on a monitor screen, and to what extent these dynamic properties are predictive of the invasive-BP and NIBP differences.

Methods

We investigated arterial blood pressures of patients with radial artery cannulae inserted as part of their routine care in a large tertiary hospital's intensive care units, operating rooms, and post-anaesthesia care units. Before the study's commencement, the Health Research Ethics Committee of Stellenbosch University granted ethical approval and a waiver of written consent (reference 18843). We relied on convenience sampling. Exclusion criteria were age < 18 years, an arrhythmia, haemodynamic instability, body mass index (BMI) ≥ 35 $kg.m^{-2}$, and inability to measure NIBP in the same arm in which the arterial line was present. Investigators obtained verbal consent at the bedside after explaining the study's purpose, with assurance of complete anonymity.

We employed a GE CARESCAPE B450 monitor (GE HealthCare, Chicago, USA), precalibrated by the supplier, for invasive and oscillometric blood pressure measurements. The invasive-BP transducer was fixed at the level of the phlebostatic axis. The transducer intermediate cable was disconnected from the patient's bedside monitor, connected to the CARESCAPE B450 monitor, and "zeroed" to atmospheric pressure. We followed the guidelines of the American Heart Association and conducted OscNIBP measurements with the patient's arm supported at heart level.[14] After measuring arm circumference, an appropriately sized blood pressure cuff was placed on the ipsilateral arm as the arterial line.[b]

We also measured SAPs using a mercury sphygmomanometer with Doppler ultrasound flow detection over the brachial artery in the antecubital fossa. The ultrasound device was a portable, handheld, single-probe, general-purpose, diagnostic ultrasound imaging system (Butterfly iQ+, Butterfly Network, Guilford, USA). The device comprises a battery-powered ultrasound probe connected wirelessly via Bluetooth to a cell phone for image display (https://www.butterflynetwork.com/specs). The NIBP cuff was connected to a free-standing mercury sphygmomanometer. Using the handheld ultrasound probe, the brachial artery in the antecubital fossa was identified in the "out of plane" view. Continuous wave colour Doppler, as close to a zero-degree angle as possible in the midline of the artery, was employed to detect arterial pulsations. The blood pressure cuff was inflated to a supra-systolic pressure and slowly deflated. The pressure reading at which the first Doppler inflection appeared was recorded as the systolic pressure. Heart rates and invasive-BPs were recorded as the average of the three measurements interspersed with pre-randomised NIBP measurements (oscillometric and ultrasound), described in the *Supplementary file*.

The invasive pressure tracing on the monitor screen was set to a speed of 50 $mm.s^{-1}$. Thereafter, a fast flush test was performed

[a] Verbatim quote
[b] A table of recommended cuff sizes is presented in the *Supplementary file*.

by opening the flush valve (pressure bag set to 300 mmHg) for two seconds and then releasing it. This procedure creates a square-wave pressure change that generates a series of pressure oscillations at the system's natural frequency, with amplitudes that decrease exponentially. The screen tracing of this procedure was frozen and photographed, together with a horizontal millimetre scale. At conclusion, participants were reattached to their original monitors and thanked for their participation.

Sample size calculation

We expected that approximately 400 invasive systems (the "population") would have been employed in the hospital during this cross-sectional study. For a 5% margin of error and a 95% confidence level, the required sample size is 197 (https://www.surveysystem.com/sscalc.htm).

Data analysis

We determined statistical agreement between measurement methods using Bland–Altman analysis and employed the Preiss–Fisher procedure to determine whether the data ranges were adequately wide for reliable Bland–Altman analysis.[15,c] We estimated the clinical importance of disparate measurements by error grid analysis using Saugel et al.'s[13] method. Regarding SAPs, we deemed ultrasound-determined non-invasive systolic pressure the reference measurement. Therefore, we compared ultrasound and invasive systolic pressure differences in the various risk zones, using paired t-tests or Wilcoxon signed-rank tests as appropriate. We subjected the systolic pressure differences to multivariate linear regression. Table AI in the Appendix lists the statistical procedures and the software employed.

Calculation of natural frequencies and damping ratios of the intra-arterial blood pressure measurement systems

We saved de-anonymised digital photographs of the rapid flush responses to a computer disk in the Joint Photographic Experts Group (jpeg) format and performed measurements on enlarged screen images. We calculated natural frequencies and damping ratios according to standard methods.[10] An example of the methodology appears in the *Supplementary file*.

Table I: Participant and catheter tubing characteristics

Participant characteristics				
	Mean or median	**SD or IQR**	**Range**	***n* (%)**
Age (year)	49	37–61	18–89	195
Weight (kg)	72.8	11.4	46–108	
Height (m)	1.71	0.08	1.48–1.92	
BMI (kg.m^{-1})	24.9	3.1	18.0–33.6	
Gender		Male		108 (55.4)
		Female		87 (44.6)
Receiving vasopressor				17 (8.7)
Participant distribution				***n* (%)**
Post-anaesthesia high-care unit				74 (37.9)
Cardiothoracic ICU				46 (23.6)
Surgical ICU				62 (31.8)
Operating theatre				11 (5.6)
Obstetric critical care unit				1 (0.5)
Medical ICU				1 (0.5)
Invasive-BP systems' dynamic characteristics*				
	Mean or median	**SD or IQR**	**Range**	***n***
f_n (Hz)	16.7	12.5–20.0	4.8–33.0	163
ζ	0.38	0.12	0.30–0.74	152
Catheter tubing configurations				
		Cannula length (mm)	**Tubing length (cm)**	***n* (%)**
System	A	50	174	28 (14.4)
	B	50	153	36 (18.5)
	C	45	174	70 (35.9)
	D	45	153	61 (31.3)
Flush		Heparinised		182
		Unknown		13

* Histograms of the distributions of natural frequencies and damping ratios are presented in the *Supplementary file.*
BMI – body mass index, BP – blood pressure, ICU – intensive care unit, IQR – interquartile range, SD – standard deviation, f_n – natural frequency, ζ – damping ratio

[c] The Preiss–Fisher procedure is explained in the *Supplementary file.*

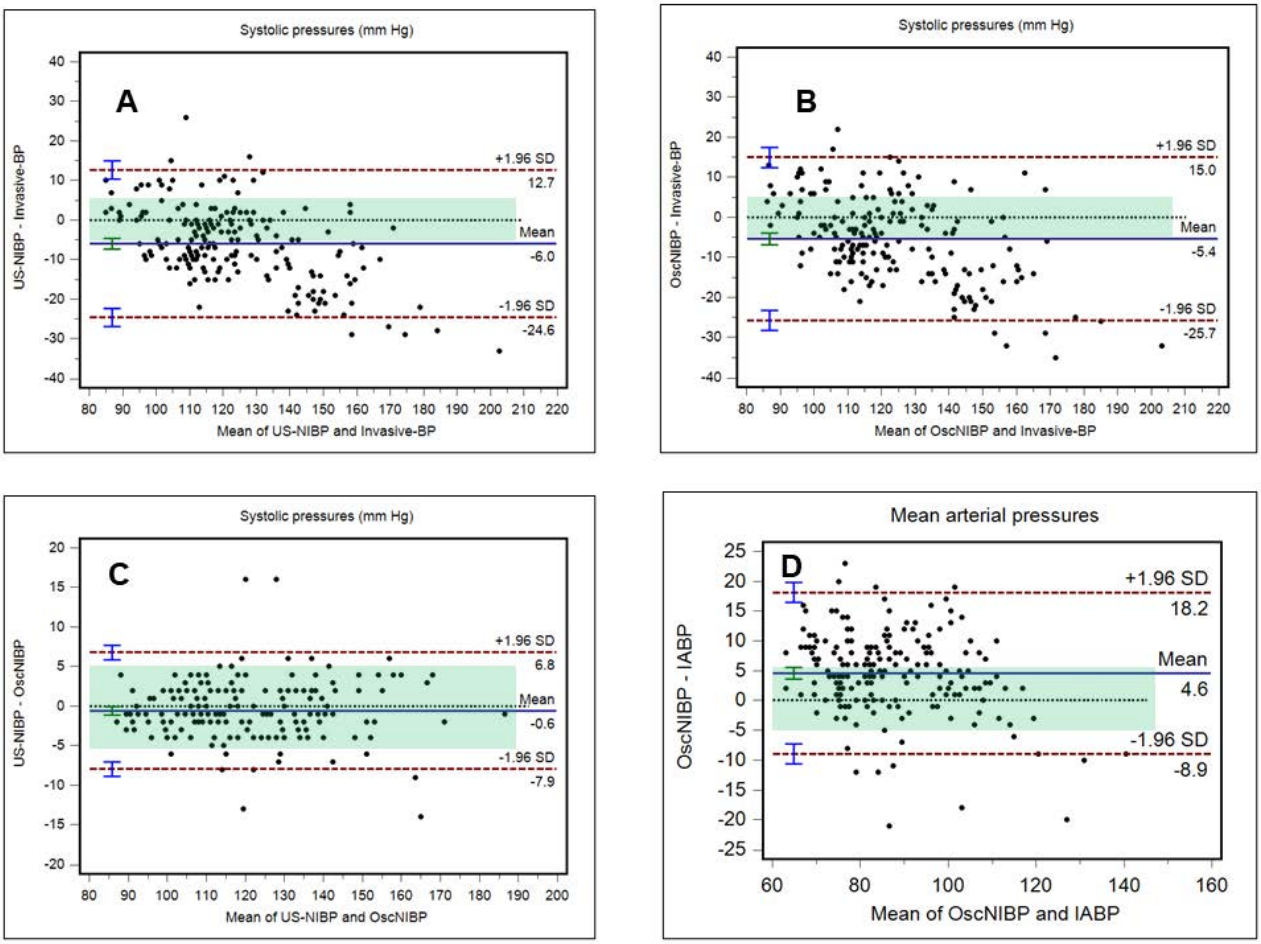
Results

We recruited 198 participants, and three participants' data were lost. Thus, we recorded 195 SAPs and 194 MAPs concurrently. Table I displays the characteristics of the participants and the invasive arterial measurement systems. Of the 195 screen photographs of the flush test, 17 (8.8%) systems were overdamped. Natural frequencies and damping ratios could be measured in 163 (98.8%) and 152 (92.1%) subjects, respectively.

All transducers were Sembu TR disposable pressure transducers supplied with 2 mm internal diameter connecting tubing (SSEM Mthembu Medical [Pty] Ltd., Johannesburg, South Africa, http://www.ssemmthembu.co.za/product/vascular-access/pressure-transducers). All cannulae were 20G (131 were BD® [BD Company, Franklin Lakes, USA] and 63 were Arrow® [Arrow Medical Ltd., Kington, UK]).

Bland–Altman analysis[d] (Table II, Figure 1)

The data met the Preiss–Fisher criteria regarding adequate measurement ranges for reliable Bland–Altman analysis.[e] Histograms of the measurement differences exhibited approximately normal distributions. The means of the between technique biases were small but differences were statistically significant with wide LOA. Green shaded areas in the Bland–Altman graphs indicate a mean (acceptable) bias of 5 mmHg, per the American National Standards Institute/Association for the Advancement of Medical Instrumentation/International Organisation for Standardisation 81060-2:2013 protocol



Legend
Invasive-BP: Intra-arterial blood pressure measurements.
OscNIBP: Non-invasive blood pressure measurements by automated oscillometry.
US-NIBP: Non-invasive blood pressure measurements by ultrasound.

Graph A: Systolic arterial pressures: Invasive-BP vs. US-NIBP.
Graph B: Systolic arterial pressures: Invasive-BP vs. OscNIBP.
Graph C: Systolic arterial pressures: OscNIBP vs. US-NIBP.
Graph D: Mean arterial pressures: Invasive-BP vs. OscNIBP.

Units are mm Hg.
Solid blue line indicates the mean difference between measurements;
Brown dotted lines indicate the limits of agreement (1.96 standard deviations (SD) from the mean value) .
Error bars indicate 95% confidence intervals.
Boundaries of the green shaded area indicate the ± 5 mmHg maximum allowed differences, wherein the 95% confidence intervals of the limits of agreement should be included, in order to declare the two methods of measurement to be interchangeable.

Figure 1: Bland-Altman plots comparing arterial blood pressure measurements employing three techniques: intra-arterial, automated oscillometry and ultrasound.

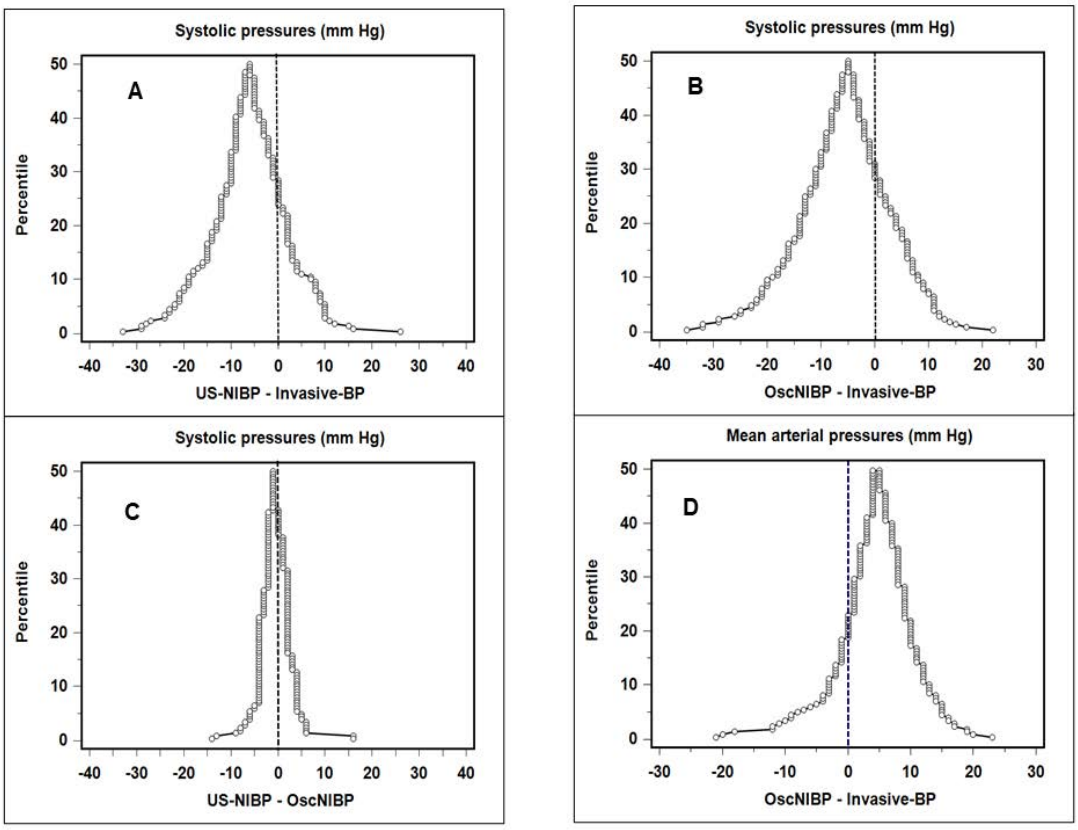
[d] See histograms in the *Supplementary file.* A checklist regarding reporting standards for Bland–Altman analyses can be downloaded from the journal website.
[e] See *Supplementary file.*

Table II: Results of the Bland–Altman analyses (bracketed values are 95% CI)

Pressure differences expressed in mmHg				
SAP differences				**MAPs**
	US-NIBP minus invasive-BP	**OscNIBP minus invasive-BP**	**US-NIBP minus OscNIBP**	**OscNIBP minus invasive-BP**
Mean difference	-6.0 (-7.3 to -4.6)	-5.4 (-3.9 to -6.8)	-0.6 (-1.0 to -0.5)	4.6 (3.6 to 5.6)
Lower LOA	-24.6 (-26.9 to -22.3)	-25.7 (-28.2 to -23.2)	-7.9 (-8.9 to -7.0)	-8.9 (-10.6 to -7.3)
Upper LOA	12.7 (10.4 to 15)	15.0 (12.4 to 19.5)	6.8 (5.9 to 7.7)	18.2 (16.5 to 19.8)
Slope	-0.24 (-0.29 to -0.19)	-0.25 (-0.31 to -0.19)	0.01 (-0.02 to 0.01)	0.13 (0.06 to 0.20)
Pressure differences expressed as percentages*				
SAPs				**MAPs**
	US-NIBP minus invasive-BP	**OscNIBP minus invasive-BP**	**US-NIBP minus OscNIBP**	**OscNIBP minus invasive-BP**
Mean difference	-4.3% (-5.3 to -3.3)	-3.8% (-4.9 to -2.7)	-0.5% (-0.9 to -0.09)	5.7% (4.6 to 6.9)
Lower LOA	-18.6% (-20.3 to -16.8)	-19.4% (-21.3 to -17.5)	-6.5% (-7.2 to -5.8)	-10.1% (-12.1 to -8.2)
Upper LOA	10.0% (8.2 to 11.8)	11.8% (9.9 to 13.7)	5.5% (4.7 to 6.2)	21.5% (19.6 to 23.5)
Slope	-0.15 (-0.19 to -0.10)	-0.16 (-0.21 to -0.11)	-0.01 (-0.01 to 0.03)	-0.18 (-0.26 to -0.10)

invasive-BP – intra-arterial blood pressure, LOA – limits of agreement (1.96 standard deviations from the mean difference), MAP – mean arterial pressure, OscNIBP – oscillometric non-invasive blood pressure, SAP – systolic arterial pressure, slope – slope of linear regression of pressure differences on means of two measurements, US-NIBP – ultrasound method of measuring systolic blood pressure

* See the *Supplementary file* for Bland–Altman plots, where the pressure differences are expressed as percentage differences.



Legend

Differences between measurement methods are plotted on the abscissa and percentiles on the ordinate. Percentiles greater than 50% are converted to 100-50%; thus displaying a "folded" plot of the distribution of the differences. See the online Supplementary file for a more detailed explanation.

Invasive-BP: Intra-arterial blood pressure measurements.
OscNIBP: Non-invasive blood pressure measurements by automated oscillometry.
US-NIBP: Non-invasive systolic blood pressure measurements by ultrasound.
Graph A: Systolic arterial pressures: distribution of the differences between Invasive-BP and OscNIBP.
Graph B: Systolic arterial pressures: distribution of the differences between Invasive-BP and US-NIBP.
Graph C: Systolic arterial pressures - distribution of the differences between US-NIBP and OscNIBP.
Graph D: Mean arterial pressures; distribution of the differences between Invasive-BP and OscNIBP
Dotted vertical lines indicate zero difference. Units are mm Hg.

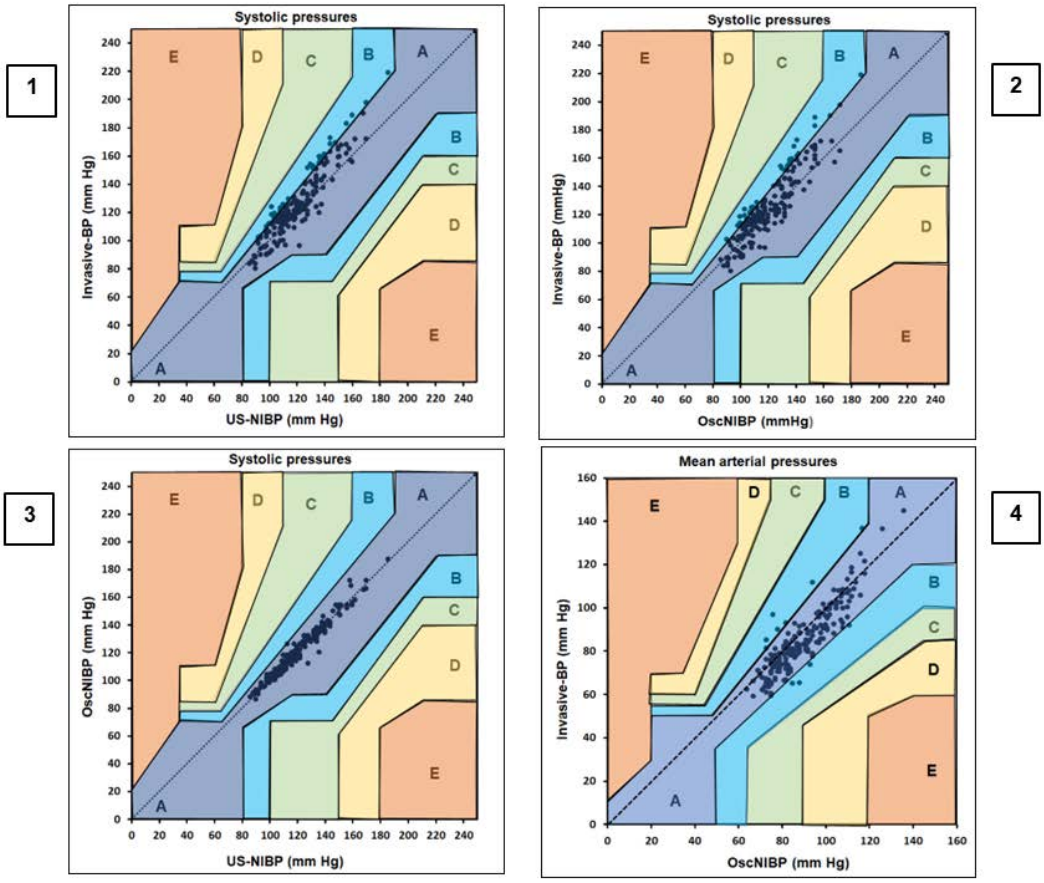
Figure 2: Folded empirical cumulative distribution plots (mountain plots) depicting distributions of arterial blood pressure measurement differences employing three techniques: intra-arterial, automated oscillometry and ultrasound.

Table III: Results of the error grid analyses (bracketed values are 95% CI)

Proportions of paired blood pressure measurements within the five risk zones				
		Systolic pressures *n* = 195		**MAPs *n* = 194**
Test vs. reference	**Invasive-BP vs. US-NIBP**	**Invasive-BP vs. OscNIBP**	**OscNIBP vs. US-NIBP**	**Invasive-BP vs. OscNIBP**
Zone A	85.6% (79.8 to 90.2)	87.7% (82.3 to 92)	100% (98.1 to 100)	94.3% (90.1 to 97.1)
Zone B	14.4% (9.8 to 20.1)	12.3% (8.0 to 17.7)	0.0%	5.7% (2.9 to 9.9)
Zone C	0.0%	0.0%	0.0%	0.0%
Zone D	0.0%	0.0%	0.0%	0.0%
Zone E	0.0%	0.0%	0.0%	0.0%

Properties of the invasive-BP systems with systolic pressures in Zones A and B (invasive-BP vs. US-NIBP)				
		n	**Median (95% CI)**	**H-L median difference (95% CI)**
Natural frequency, f_n (Hz)	Zone A	142	16.7 (16.7 to 16.7)	3.2 (4.2 to 0.0) $p = 0.008$
	Zone B	21	12.5 (12.5 to 16.7)	
Damping ratio, ζ	Zone A	136	0.38 (0.36 to 0.41)	-0.03 (-0.08 to 0.02) $p = 0.309$
	Zone B	16	0.38 (0.31 to 0.40)	
Difference in SAP (mmHg)	Zone A	164	5.0 (2.0 to 6.0)	16.0 (13.0 to 19.0) $p < 0.0001$
	Zone B	31	20 (15.0 to 22.4)	

CI – confidence interval, H-L median difference – Hodges–Lehmann median difference, invasive-BP – intra-arterial pressure measurements, MAP – mean arterial pressure, OscNIBP – oscillometric non-invasive blood pressure, SAP – systolic arterial pressure, US-NIBP – ultrasound method of measuring systolic blood pressure



Legend
Invasive-BP: Intra-arterial blood pressure measurements.
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Units are mm Hg.

Graph 1: Systolic arterial pressures: Invasive-BP vs. US-NIBP.
Graph 2: Systolic arterial pressures: Invasive-BP vs. OscNIBP.
Graph 3: Systolic arterial pressures: OscNIBP vs. US-NIBP.
Graph 4: Mean arterial pressures: Invasive-BP vs. OscNIBP.

Note that the risk zones expand at the hypotension and hypertension extremes, the rationale being that at these blood pressures, patients would receive appropriate therapy in spite of large differences between measurement methods.

Figure 3: Error grid pairwise comparisons of three arterial blood pressure measurement techniques: intra-arterial, automated oscillometry and ultrasound. See text for a description of the risk zones.

(≤ 5 mmHg with standard deviation ≤ 8 mmHg for systolic and diastolic blood pressures).[16] For two methods of measurement to be regarded as statistically interchangeable, the lower bound of the 95% CI of the lower LOA and the upper bound of the 95% CI of the upper LOA should fit within the green shaded area. This was not the case in any of the four analyses. Thus, the various methods could not be regarded as interchangeable regarding systolic and mean pressure measurements.

Folded empirical cumulative distribution plots ("mountain plots", Figure 2) illustrate the distributions of the differences between measurement methods.[17] Median systolic US-NIBP and OscNIBP differences were acceptably small with a narrow distribution (graph C). However, differences between systolic blood pressures determined invasively and using the two non-invasive methods were widely distributed, ranging from -40 to 40 mmHg. The MAP determined invasively and by automated oscillotonometry also exhibited a small median difference, albeit also exhibiting a wide between-methods distribution (graph D).

The mean differences are all statistically significant (the 95% CIs do not include zero).

Error grid analysis (Table III, Figure 3)

SAP pairwise comparisons:

The two non-invasive systolic measurement techniques met the criteria for clinically acceptable agreement, with 100% of the data being in Zone A. The comparison of systolic measurements using the invasive versus the two non-invasive techniques showed that > 85% of the data were in Zone A, with 95% CIs including 90%. The remaining comparisons were in Zone B. Thus, no systolic measurements were located in Zones C, D, or E.

In Zones A and B, there was a significant difference between the invasive versus the ultrasound-determined systolic pressures. The natural frequencies were significantly smaller in Zone B, and the damping ratios did not differ. Participants' mean heart rates in Zones A and B were similar (89.2 vs. 89.1 bpm).

MAP pairwise comparisons (invasive-BP vs. OscNIBP):

With OscNIBP as the reference measurement, all comparisons were in Zones A and B (94.3% and 5.7%, respectively).

In a least squares, backward entry, multiple regression analysis, the difference in systolic pressure measurements between invasive-BP and US-NIBP was the dependent variable and the following were entered as independent variables: catheter tubing combination (Systems A to D in Table I), natural frequency, damping ratio, age, BMI, heart rate, and vasopressor administration. The following were retained within the model: use of System A, (i.e. the system with the longest cannula [50 mm] and the longest tubing [174 mm]), natural frequencies, and damping ratios. The regression equation was:

*Difference = 15. + (3.9 * System A) - (0.3 * f_n) - (12 * ζ)*

However, the associations were weak (adjusted R^2 = 0.06). A detailed report of the regression analysis is presented in the *Supplementary file*.

Discussion

We compared 195 invasive-BP measurements concurrently with two non-invasive measurement techniques. Bland–Altman analyses of systolic and mean arterial blood pressure revealed small mean differences between the invasive and the two non-invasive techniques. However, despite the small mean differences and narrow CIs, the LOA were wide. Consequently, the systems could not be regarded as interchangeable. Nevertheless, error grid analyses showed that none of the paired measurements were in the "dangerous" zones. Thus, our results indicate that it is likely that none of the patients in our sample would have received inappropriate therapy resulting from flawed intra-arterial SAP or MAP measurements.

Automated oscillometric measurements are influenced by several factors, such as cuff size, cuff fit, rate of cuff deflation, and the proprietary algorithms employed by different device brands. Regarding MAP measurements, the measurement method is usually by means of the maximum amplitude algorithm (i.e. determination of the maximum amplitude of a pressure waveform "envelope" constructed around the peaks and troughs of the pressure pulsations during cuff deflation). Systolic and diastolic pressures are determined by proprietary algorithms exemplified by the fixed ratio method. For example, the systolic and diastolic pressures are measured at the points where the waveform envelope approximates 50% and 70% of the maximum amplitude.[18] Thus, our findings apply only to the non-invasive measurement devices and the invasive-BP configurations we studied under static conditions.

Regarding the invasive-BP configurations, the only physical dissimilarities were minor differences in cannula length (45 vs. 50 mm) and connecting tubing length (153 vs. 174 cm). Similar intra-arterial cannulae and connecting tubing internal diameters (20G and 2 mm) and the same brand of transducer were used throughout. Nonetheless, the invasive pressure dynamic responses ranged widely, with natural frequencies and damping ratios similar to those reported by previous investigators.[3,7] Regression analysis revealed that these measurements were poor predictors of invasive versus non-invasive measurement differences. This could have been due to flawed measurement techniques, considering that some fast flush responses were difficult to analyse when the damping ratios were high, and others were poorly photographed. Furthermore, our technique has not been validated against a standard sine wave pressure generator method.[7]

The fast flush test has been criticised as unable to correctly evaluate the dynamic responses of clinically employed invasive-BP measurement systems.[19,20] Watanabe et al. indicated that the fast flush test cannot characterise the true amplitude versus frequency response of the arterial pressure wave harmonics because it derives the damping ratio only at the system's natural

frequency.[21] They patented a method for creating frequency-amplitude response curves in the clinical situation without requiring a sine wave pressure generator. Termed "clinical impulse response analysis", the method involves computer analysis of the fast flush square wave response at the proximal and distal ends of the connecting tubing simultaneously. They subsequently demonstrated how two systems with differing connecting tubing lengths can have similar natural frequencies and damping ratios but differing flat frequency response characteristics. They have also provided a mathematical explanation for the inadequacies of the conventional fast flush test.[20]

To achieve an adequate flat frequency response, it is necessary to faithfully reproduce 6–10 harmonics of the fundamental frequency (the heart rate). For heart rates up to 120 bpm, this requires a natural frequency > 20 Hz.[22] However, most clinical systems have lower natural frequencies, despite assiduous efforts to eliminate air bubbles.[20] The GE-B450 monitor incorporates a 12 Hz first-order (one pole) low-pass filter in series with a -3 dB 40 Hz first-order low-pass filter,[f] intended to prevent resonance at the higher pulse wave frequency components. However, in evaluating various filtering methods for obtaining high-fidelity invasive pressure waveforms, Hersh et al.[4] point out that this can only succeed if the natural frequency is considerably greater than 12 Hz. They conclude that a damping ratio of 0.6–0.7 is required to prevent resonance but is seldom achievable without special filters. In our sample, 75% of natural frequencies were < 20 Hz and 83% of damping ratios were < 0.5.

An elegant solution for achieving optimal damping without reducing natural frequency is the incorporation of the Resonance OverShoot Eliminator (R.O.S.E.), an indwelling damping device.[23] The R.O.S.E. is not available in South Africa, and even if it were, its routine use would contribute significantly to healthcare costs. Since a considerable proportion of clinically employed invasive pressure monitoring systems exhibit resonance artefacts, and determining natural frequencies and damping ratios is cumbersome and mostly unhelpful, the clinical conundrum is which method clinicians should use to evaluate the acceptability of their invasive-BP measurements.[5,7]

In a study involving 300 patients and 1 200 invasive versus non-invasive measurements, Romagnoli et al.[5] reported that comparing systolic pressures is strongly predictive of invasive pressure resonance artefacts. They suggested that systolic pressure differences > 15–20 mmHg are clinically important, requiring revision of the invasive-BP monitoring system. In our study, the median difference between invasive and ultrasound-determined systolic pressures in Zone B was 20 mmHg (95% CI 15 to 24) (Table III). We suggest that a straightforward clinical solution is to utilise error grid analysis. For that purpose, we have created an Excel® spreadsheet using the coordinates of Saugel et al.,[13] whereby one can conveniently plot an invasive versus non-invasive measurement on an error grid.[9] Measurements located outside of Zone B should prompt revision of the invasive-BP system for sources of resonance or overdamping.

Invasive blood pressure measurements should be compared with a well-maintained and calibrated oscillometric device using correctly sized cuffs. Alternatively, Korotkoff sound detection using a mercury sphygmomanometer or calibrated aneroid manometer can be used. However, the auscultatory method suffers from inter-observer variation.[24] We postulate that ultrasound-derived systolic pressure is a reliable technique for verifying invasive systolic pressure measurements, the parameter most susceptible to measurement errors. The ultrasound-based technique, first developed in 1968, has demonstrated good agreement between invasive and auscultatory methods in small studies.[25-27] However, the ultrasound-based technique has never gained popularity, apart from recent interest in critically ill paediatric patients.[28] Validation employing a standardised protocol is required.[29]

Conclusion

We conclude that error grid comparisons are useful for routinely evaluating the clinical importance of differences between invasive and non-invasive techniques. Despite statistically significant observed differences, error grid analysis indicated that no patients in our sample would likely have received inappropriate therapy resulting from flawed intra-arterial measurements. Our findings reinforce recommendations that invasive pressures be checked against a reliable, non-invasive device. A systolic pressure difference > 15 mmHg should prompt an invasive system review. We propose ultrasound-guided systolic pressure measurements as a reliable method for this purpose. It is perhaps feasible to determine natural frequencies and damping ratios from monitor screen photographs of the fast flush test, but the method is cumbersome, and the measurements were unhelpful.

Acknowledgements

We wish to thank Seugnet Vervey of the Department of Clinical Technology at Tygerberg Hospital for making available a calibrated, oscillometric, non-invasive blood pressure measuring device.

Conflict of interest

The authors declare no conflict of interest.

Funding source

No external funding was received by the investigators.

Ethical approval

Before the study commenced, ethical approval was obtained from the Health Research Ethics Committee of Stellenbosch University, which granted a waiver of informed consent (reference 18843). The protocol was registered with the National Health Research Database of the Western Cape (reference WC_202104_037). Tygerberg Hospital management granted

[f] Personal communication by the supplier.

[9] The spreadsheet can be downloaded from the journal website.

permission to perform the study, which we conducted per the World Medical Association's Declaration of Helsinki and the Western Cape Department of Health Guidelines for Good Clinical Practice.

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Supplementary material available online