Pulse wave calibration and implications for blood pressure measurement: systematic review and meta-analysis

Short Title: Pulse wave calibration and central aortic pressure

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Abstract

Central aortic systolic pressure (CASP) can be estimated via filtering of the peripheral pulse wave (PPW) following calibration to brachial blood pressure (brBP). Recent studies suggest PPW calibration to mean arterial pressure (MAP) and diastolic BP (DBP) provides more accurate CASP estimates ($CASP_{MD}$) versus conventional calibration to systolic BP (SBP) and DBP ($CASP_{SD}$). However, the peak of the MAP-DBP calibrated PPW i.e. SBP_{MD}, is rarely reported or used for BP amplification calculations, despite $CASP_{MD}$ being derived from it. We aimed to calculate the unreported SBP_{MD} from studies using MAP-DBP calibration for estimation of $CASP_{MD}$ and compared it with oscillometric brSBP.

Medline database was searched to 18th March 2020. Meta-analysis includes studies reporting non-invasive $CASP_{SD}$, $CASP_{MD}$, brSBP and brDBP. SBP_{MD} was calculated using linear function equations.

Data from 21 studies used 8 different BP monitors (13,460 participants, mean age: 54±10 years, 57% female, brBP: 130±14 / 79±9mmHg). Weighted mean difference between SBP_{MD} and brSBP was 10mmHg (range -2 to 17mmHg) and appeared device-specific. Calibration of brachial vs radial PPWs to brBP, showed greater disparity between SBP_{MD} and brSBP (14 vs 2mmHg). BP amplification was similar comparing SBP-DBP vs MAP-DBP calibrations (brSBP-$CASP_{SD}$ vs SBP_{MD}-$CASP_{MD}$: 9 vs 11mmHg), with no instances of reverse BP amplification.

PPWs calibrated to MAP-DBP, to derive $CASP_{MD}$ generates SBP_{MD} that differs markedly from brSBP with some oscillometric BP monitors. These findings have important implications for BP monitor accuracy, BP amplification, PPW calibration recommendations, and studies of associations between CASP versus SBP and outcomes.

Keywords: Amplification, Blood pressure, Calibration, Central aortic pressure, Pressure wave, Pulse wave.

Abbreviations

ABPM = Ambulatory Blood Pressure Monitoring

br = brachial oscillometric blood pressure measurement

BP = Blood Pressure

CASP = Central Aortic Systolic Pressure

$CASP_{SD}$ = Central Aortic Systolic Pressure calibrated to systolic and diastolic pressures

$CASP_{MD}$ = Central Aortic Systolic Pressure calibrated to mean and diastolic Pressures

DBP = Diastolic Blood Pressure

k = form factor

MAP = Mean Arterial Pressure

PPW = Peripheral Pulse Wave

SBP = Systolic Blood Pressure

SBP_{MD} = Systolic Blood Pressure from the peripheral pulse wave calibrated to mean and diastolic pressures

Introduction

The non-invasive estimation of central aortic systolic pressure (CASP) has generated considerable interest as an alternative index of blood pressure (BP) load when compared to conventional brachial BP measurement[1-4]. Various methods have been developed to estimate CASP which usually involves calibration of a peripheral pulse wave (PPW) to brachial BP. Several recent publications over the last decade have suggested that calibration, and subsequent filtering, of the PPW to brachial mean and diastolic blood pressure (MAP and DBP), yielding $CASP_{MD}$, is superior to conventional brachial systolic and diastolic pressure (SBP and DBP) calibration for $CASP_{SD}$ estimation, based on closer agreement with invasively measured CASP[5-8].

Non-invasive CASP estimation involves three independent processes: (i) acquisition of a PPW, which is measured in mV; (ii) calibration of the PPW with brachial BP, to convert the units from mV to mmHg; and (iii) estimation of CASP (typically achieved via mathematical filtering of the calibrated PPW). The suggestion in recent publications that there are differences in the accuracy of CASP estimation, depending on which two brachial BP readings are used to calibrate the PPW is surprising. This is because the relationship between BP and voltage for the original PPW is linear due to the piezoelectric effect and can be described by a linear function: $f(x) = ax + b$. Thus, in theory, calibration to any two accurate BP readings should generate identical CASP values (Figure 1). Indeed, it can be proven mathematically that either SBP-DBP or MAP-DBP calibrations produce the same CASP value if accurate BP readings are used for calibration (please see http://hyper.ahajournals.org Supplemental Text, Appendix I).

Often overlooked is the fact that when MAP and DBP are used to calibrate the PPW prior to the derivation of $CASP_{MD}$, the calibration process must generate a systolic BP value for the

calibrated PPW, which we have termed SBP_{MD}. Moreover, it is the MAP-DBP calibrated PPW, including SBP_{MD}, and not the brSBP, that is filtered (in studies that utilise filters) to generate $CASP_{MD}$. Remarkably, studies that estimate $CASP_{MD}$[1,2,8-21], with one exception[22], never report the SBP_{MD} which was used for $CASP_{MD}$ derivation. It would be expected that the SBP_{MD} would be very similar to the brSBP, however, this is not known. If brSBP and SBP_{MD} were markedly different, this would have implications with respect to the accuracy of the monitor in measuring brSBP for those BP monitors which produce accurate estimates of invasive CASP using $CASP_{MD}$. Moreover, defining a value for SBP_{MD} is important in the context of the calculation of central-to-peripheral BP amplification because CASP must be related to the SBP value from which it was derived to obtain correct values for BP amplification i.e. $CASP_{MD}$ must be related to SBP_{MD}.

In view of the importance of SBP_{MD}, this study aims to estimate the SBP_{MD} from 21 previous publications reporting different PPW calibration methods and, for the first time, determine the level of agreement between SBP_{MD} and brSBP measured using oscillometric BP monitors.

Methods

The data that support the findings of this study are available from the senior author upon reasonable request.

Study design

A systematic review and meta-analysis was conducted in accordance with PRISMA (Preferred reporting Items for Systematic reviews and Meta-Analyses) guidelines[23]. Ethical committee approval was not required as this study does not use identifiable patient information, it uses summary data published in peer reviewed journals.

Search strategy

As part of this meta-analysis previous publications were searched in order to identify human studies utilising SBP-DBP and MAP-DBP calibrations for subsequent CASP estimation with non-invasively acquired oscillometric BP. Medline database search was performed up to 18th March 2020 by one researcher (DJ). Data from the included studies was independently verified by two researchers (EM, PL). Initially, the following two terms (keywords) were searched and filtered to display results for studies conducted in humans in the last 10 years: "blood pressure calibration" and "blood pressure calibrated". Subsequently, Medline was searched for the BP monitor models identified as eligible in the initial search and filtered to display the results from the last 10 years: "Mobil-O-Graph", "Pulsecor", "Vicorder", "SphygmoCor XCEL", "Omron 705", "Omron HEM-907" and "Omron HEM 9000AI". The references of all studies included in this meta-analysis were also searched to identify any additional eligible studies. Searches were limited to studies published in English and animal studies excluded. Duplicates were discarded.

Data abstraction

The full texts of included studies were reviewed and relevant data was extracted into a prespecified database by one reviewer (DJ) and accuracy of data abstraction was independently verified by the remaining authors. Extracted data included: surname of primary author, year of publication, total number of participants, BP measurement setting (clinic or ambulatory blood pressure measurement (ABPM)), BP monitor model, PPW acquisition site, brSBP, $CASP_{SD}$, $CASP_{MD}$, brDBP and participant characteristics included in Table 1.

Quality assessment

Risk of bias assessment was not undertaken as this meta-analysis is not performed on randomised controlled trials to assess effects of treatment but instead aims to disclose the

unreported SBP_{MD} for past publications regardless of the aims or primary outcomes of the individual studies. Furthermore, the dispersion of SBP_{MD} as well as the difference between SBP_{MD} and brSBP relative to their mean e.g. standard deviation (SD) or 95% confidence intervals (95% CI) are not calculable as patient-level data was not available for this meta-analysis. For the aforementioned reason, heterogeneity tests of SBP_{MD} are not calculable.

Primary outcome

Primary outcome for this study is weighted mean difference between SBP_{MD} and brSBP.

Secondary outcomes

Secondary analyses will compare differences between SBP_{MD} and brSBP for different BP monitors, for fixed form factor derived MAP versus oscillometric MAP, and for brachial versus radial PPWs. BP amplification will be compared between SBP-DBP versus MAP-DBP calibrations.

Definition of form factor

Form factor (k) provides information about the shape of the PPW i.e. the ratio of MAP in relation to pule pressure, and is calculated with the following formula: k = (MAP-DBP)/(SBP-DBP). Fixed form factor formulas with predetermined ratio of MAP in relation to pulse pressure (typically k = 0.33 or 0.4) are often used to calculate MAP (MAP = k × (SBP-DBP) + DBP).

Synthesis of results – calculation of SBP_{MD}

PPWs are captured in mV (Figure 2A) and need to be subsequently converted to mmHg via process of calibration to make the BP values meaningful and comparable. PPW calibration comprises finding the linear function equation ($f(x) = ax + b$) with use of two known BP readings e.g. brSBP and brDBP or brMAP and brDBP (it is irrelevant for the purposes of

mathematical computation of the linear functions and calibrated BP values, whether the values used are oscillometric BP, auscultatory BP or BP calculated with fixed form factor formulas). PPW calibration with any two accurate BP values would generate identical linear functions. In contrast, PPW calibration with inaccurate BP values would generate inaccurate linear functions. This is the only reason why SBP-DBP versus DBP-MAP calibrations produce different linear functions, resulting in inaccurate unit conversion. Thus, accurate peripheral BP measurement is a sine qua non condition for an accurate PPW calibration for subsequent CASP estimation. To illustrate this methodology, Figure 2 shows examples of inaccurate linear functions (due to inaccurately measured BP values) (Figure 2B), which are subsequently used to convert mV (Figure 2A) to mmHg (Figure 2C and 2D). As PPW calibration to either brSBP-brDBP or brMAP-brDBP utilises linear functions ($f(x_{SBP}) = ax + b$ and $f(x_{MAP}) = cx + d$, respectively) to convert units from mV to mmHg (Figure 2), these can be rearranged to calculate the corresponding BP values from the other calibration method.

Appendix II (please see http://hyper.ahajournals.org Supplemental Text, Appendix II) provides formulas that rely on fixed form factors to recalibrate any BP value obtained from SBP-DBP calibration to its equivalent value from MAP-DBP calibration, and vice-versa. Appendix III (please see http://hyper.ahajournals.org Supplemental Text, Appendix III) provides formulas for SBP_{MD} and $CASP_{MD}$ when values in mV are known. SBP_{MD} values for the previous studies included in this meta-analysis were calculated with an equation that does not rely on values in mV nor the frequently unreported MAP values (please see http://hyper.ahajournals.org Supplemental Text, Appendix IV).

Statistical analysis

Data was collated and processed using Microsoft Excel. Average values are reported as mean ± SD. Summary data from 3 studies[16-18] was converted to mean ± SD values using previously

published formulas[24] when needed. Summary data in Tables 1 and 2 were calculated with commonly used weighted mean formula ($\bar{x} = (x_1*n_1+\ldots+x_k*n_k)/(n_1+\ldots+n_k)$) and pooled SD formula ($SD_{pooled} = \sqrt{(((n_1-1)*SD_1^2+\ldots+(n_k-1)*SD_k^2)/(n_1+\ldots+n_k-k))}$). Statistical tests or 95% confidence intervals are not presented because the SBP_{MD} (derived from brBP measurements) has not been reported for any of the studies we analysed and therefore the pooled standard deviations could not be calculated.

Results

Study details

A total of 2,847 records (Figure 3) were initially extracted from the database search from which 2,334 studies were excluded following screening of study titles and a further 102 were excluded following screening of published abstracts. The remaining 411 full text records were then screened, from which a further 300 were excluded for not reporting both $CASP_{SD}$ and $CASP_{MD}$. A further 15 publications were excluded for not reporting brSBP and brDBP, 3 were excluded for measuring brSBP and brDBP with two different BP monitors and a further 72 publications were excluded because of duplicate records. This yielded a total of 21 publications for this meta-analysis[1-4,8,9,11-18,21,22,25-28]. The 21 published reports include 29 sub-group analyses, comprising 15,820 individual comparisons in 13,460 individual participants, as some studies made multiple comparisons in the same participants.

Patient characteristics

The mean age of the analysed population (n = 13,460) was 54 ± 10 years old and a small majority of participants were female (57%) (Table 1). A minority of participants (3%) underwent invasive BP measurements. The full demographics of the study population are presented in Table 1, stratified by oscillometric BP monitor type.

Characteristics of BP measurement methods

The majority of studies used a Mobil-O-Graph device (n = 12, 57%) and only the studies with Mobil-O-Graph used the oscillometrically derived MAP displayed by the monitor to calibrate the PPW[1-4,8,9,13,14,17,18,21,26]. For all other studies the MAP was calculated with a form factor equation using fixed form factors (k = 0.33 or 0.4)[11,12,15,25,27,29], or using invasive aortic MAP[16,22], or an unusual approach in which MAP was calculated by integration of brachial PPWs calibrated to SBP-DBP for subsequent MAP-DBP calibration of radial PPWs [28]. Four of the 12 Mobil-O-Graph studies used 24-hour ambulatory BP measurement (ABPM) for CASP estimation[1,9,18,21].

Primary outcome

For the primary outcome, the weighted mean difference between SBP_{MD} (139mmHg) and brSBP (129mmHg) was 10mmHg (Table 2, Figure 4, Figure S1), and appeared to be device specific (Mobil-O-Graph: 14mmHg, Omron 705: -1mmHg, Omron HEM 9000AI: 5mmHg, Omron HEM-907: -2mmHg, Pulsecor R6.5: 11mmHg, Riester Champion N: 10mmHg, SphygmoCor XCEL: 17mmHg and Vicorder: 10mmHg).

Device specific comparisons

To further enable device-specific comparisons, data from five studies (participant n = 3,587) that used the same fixed form factor (k = 0.4) for MAP calculation and subsequent MAP-DBP calibration of radial PPWs[12,15,25,27,29] yielded an average weighted mean difference between SBP_{MD} and brSBP of 6mmHg, ranging from 3 to 16mmHg per device (Omron HEM 9000AI: 5mmHg, Omron HEM-907: 3mmHg, Pulsecor R 6.5: 11mmHg, Riester Champion N: 16mmHg and SphygmoCor XCEL: 11mmHg).

Comparing MAP derivation methods

To evaluate the use of oscillometric MAP (only Mobil-O-Graph) versus fixed form factor MAP (all other devices except Vicorder) we compared the weighted mean difference between SBP_{MD} and brSBP, which was 14mmHg (ranging from 11 to 34mmHg per study) versus 2mmHg (ranging from -7 to 23mmHg per study).

Brachial versus radial PPW calibration

A larger disparity in the weighted mean difference between SBP_{MD} and brSBP was also observed in studies using brachial PPWs calibrated to brachial BP (14mmHg, ranging from 11 to 29mmHg per study)[1-4,8,9,13-15,17,18,21,26] versus radial PPWs calibrated to brachial BP (2mmHg, ranging from -7 to 16mmHg per study)[8,11,12,15,16,25,27-29].

Systolic BP amplification

BP amplification was calculated using the corresponding SBP from which CASP was derived for SBP-DBP versus MAP-DBP calibration methods, i.e. brSBP - $CASP_{SD}$ versus SBP_{MD} - $CASP_{MD}$. This demonstrated that systolic pressure amplification was similar between the corresponding PPW calibration methods (9 versus 11mmHg). There was no evidence of reverse BP amplification.

Discussion

The results of this meta-analysis demonstrate for the first time, an unexpectedly large discrepancy between SBP_{MD} and brSBP measured using some clinically validated oscillometric BP monitors i.e. monitors which have successfully passed an internationally recognised validation protocol e.g. Universal Standard Protocol, AAMI, ESH, BHS. On average this amounted to a 10mmHg difference but was highly variable between studies, ranging from -7 to 29mmHg, and appeared to be device-specific (-2 to 17mmHg). Larger differences were also

seen in studies using oscillometric MAP versus MAP derived using a fixed form factor and surprisingly, in studies for which brachial PPWs were calibrated to brachial BP versus studies where radial PPWs were calibrated to brachial BP.

Calibration differences

A key question is why the aforementioned discrepancies occurred? It should be remembered that PPW calibration is simply a unit conversion from mV to mmHg along a linear relationship due to the piezoelectric effect. Thus, discrepancies between SBP_{MD} and brSBP can only arise from differences between the form factor of the PPW and the form factor of the monitor for that particular BP reading. It can be demonstrated mathematically that if the form factors of a PPW and BP monitor are identical for a given measurement, both brSBP and SBP_{MD} as well as $CASP_{SD}$ and $CASP_{MD}$ will be identical (please see http://hyper.ahajournals.org Supplemental Text, Appendix V), even if the brachial BP values used for the calibration were inaccurate (please see http://hyper.ahajournals.org Supplemental Text, Appendix VI). The mismatching of the form factors resulting in differences between SBP-DBP and MAP-DBP calibration of the PPW can be attributed to at least one of the following: (i) inaccuracy of individual BP monitors in measuring at least one of SBP, MAP and DBP, (ii) mismatch between the true form factor of the measured PPWs and the fixed form factor formula used for the calculation of MAP, (iii) poor quality of the PPW acquisition. This is affirmed by invasive data which shows that when invasive PPWs are calibrated to accurate (invasive) BP readings, $CASP_{SD}$ and $CASP_{MD}$ are identical[6]. Our finding of a mismatch in form factors in studies utilising Mobil-O-Graph is particularly surprising, as this device displays the oscillometric MAP and furthermore, the brachial PPWs are captured at the same site and immediately after brachial BP measurements. This finding may also explain the greater disparity between SBP_{MD} and brSBP produced by calibration of brachial vs radial PPWs (14 vs 2mmHg), as most of the brachial PPWs data (98%) used Mobil-O-Graph. Further data from a wider range of monitors

displaying oscillometric MAP is needed for future analysis. The form factor mismatch with the Mobil-O-Graph highlights the importance of a need to review oscillometric monitors pertaining to their accuracy, proprietary algorithms used to derive MAP, SBP and DBP from the oscillometric envelope, device-specific differences, and causes for poorer monitor accuracy in some groups of patients.

Study implications

Given the magnitude of the difference between SBP_{MD} and brSBP, and thus $CASP_{MD}$ and $CASP_{SD}$, our findings have clinical and research implications pertaining to: (i) accuracy of some clinically validated BP monitors, (ii) prognostic value of CASP versus brachial BP with respect to cardiovascular risk stratification and hypertension mediated organ damage, (iii) BP amplification, including BP monitor categorisation as Type I and Type II devices, and (iv) PPW calibration recommendations. These implications are discussed below.

(i) BP monitor accuracy: Proponents of devices reporting big discrepancies in $CASP_{SD}$ vs $CASP_{MD}$, claiming that $CASP_{MD}$ is more accurate relative to invasive CASP, must concede that the large discrepancies between brSBP and SBP_{MD} with these monitors implies that the brSBP is inaccurate despite passing a validation protocol. This is concerning as it is brSBP that is used for clinical decision-making in practice. Alternatively, if brSBP is accurate, this raises concerns about the accuracy of MAP estimation which, interestingly, is never subject to validation studies with any device.

These inaccuracies are not only device-specific but may also be population specific. For example, Mobil-O-Graph overestimated brSBP by ~12mmHg versus invasive brSBP in children with mean invasive SBP of 84mmHg[26] and underestimated brSBP by ~22mmHg in adults with mean invasive SBP of 164mmHg[13].

(ii) Relationship between CASP versus SBP and clinical outcomes: Studies in the field of central pressure typically investigate whether CASP offers a better stratification for cardiovascular risk or hypertension mediated organ damage than brachial BP to justify its use clinically. In order to correctly evaluate CASP in this context, the corresponding SBP from which CASP was derived should be used i.e. for $CASP_{MD}$ it should be SBP_{MD}. Studies reporting better prediction of cardiac abnormalities[4], left ventricular mass index[1,3] and mortality[2] with $CASP_{MD}$ versus brachial SBP reached such conclusions by failing to compare $CASP_{MD}$ to SBP_{MD}. For example, a study by Díaz[3] concluded that $CASP_{MD}$ correlated better with left ventricular mass index than brachial SBP. However, if the correlation with SBP_{MD} had been reported, which we calculated to be 29mmHg higher than brSBP, their data would likely have shown similar correlations for $CASP_{MD}$ and SBP_{MD} ($CASP_{SD}$ = 109mmHg, r = 0.189 vs brSBP = 119mmHg, r = 0.222; $CASP_{MD}$ = 132mmHg, r = 0.432 vs $SBP_{MD} \approx$ 148mmHg, r = unknown but likely much higher than r for brSBP). Future studies performing analysis on risk stratification with $CASP_{MD}$ must disclose the correlations for SBP_{MD} to correctly evaluate correlations with $CASP_{MD}$.

(iii) Systolic BP amplification: This meta-analysis reports for the first time, the true weighted mean value for BP amplification of 11mmHg for studies using MAP-DBP calibration for non-invasive $CASP_{MD}$ derivation[1-4,8,9,11-18,21,22,25-28], when SBP_{MD} rather than brSBP is appropriately used to calculate amplification. This reveals no instances of reverse BP amplification. Previous studies reporting negative (or reverse) BP amplification[13,17,26,29] incorrectly subtracted $CASP_{MD}$ from brSBP instead of SBP_{MD}. As filters (e.g. moving average or transfer functions, which represent one indirect but most commonly used method for estimating CASP) remove some of the components of the collected PPW signal, it is mathematically impossible to obtain higher CASP than brSBP in studies utilising filters for estimating CASP. Therefore, studies using MAP-DBP calibration must calculate BP amplification by subtracting $CASP_{MD}$ from

SBP_{MD}. This dispels misconceptions about reverse BP amplification and labelling of BP monitors as "Type I" devices (monitors that estimate CASP relative to measured brachial BP) and "Type II" devices (monitors that provide an accurate estimate of CASP), which has been promoted in a recent consensus statement[7] and subsequently adopted by some researchers[30-35]. Interestingly, the authors of the consensus statement[7] did acknowledge the recommendation to relate $CASP_{MD}$ to SBP_{MD} but this has yet to be done in practice.

(iv) PPW calibration recommendations: The debate about how to calibrate PPW to estimate CASP has led some to conclude that calibration to brachial MAP rather than SBP, may yield more accurate estimates of CASP[7]. This is despite the fact that the measurement of MAP has never been formally validated for clinical use. Moreover, in some ~~a~~ studies reporting invasive brachial MAP and SBP with corresponding oscillometric brachial values, oscillometric SBP corresponded more closely with invasive readings when compared to MAP or DBP[36,37]. Furthermore, almost all monitors used in clinical practice don't reveal their oscillometric MAP. Finally, due to the inherent variability in the form factor of each individual PPW, fixed form factor formulas should not be used for MAP calculations[38,39]. Thus, $CASP_{MD}$ should not be used in clinical practice as: (i) MAP is not validated for clinical use, (ii) MAP is typically less accurate than brSBP, and (iii) most monitors don't display the oscillometric MAP and fixed form factor formulas are not a reliable method of estimating MAP. The debate about $CASP_{SD}$ versus $CASP_{MD}$ accuracy has obscured the real concern which is the heretofore unreported large disparity between measured brachial SBP and SBP_{MD} with some monitors, which raises concern about the accuracy of at least one of SBP, DBP and/or MAP. As brachial SBP and DBP are subject to clinical validation it seems likely that errors in MAP lead to disparities between brSBP and SBP_{MD} with some monitors.

Study limitations

Lack of patient-level data is a limitation of this meta-analysis as the SBP_{MD} values could only be calculated based on group averages. Moreover, with respect to statistical analysis, had patient-level data been available we would have been able to calculate standard deviations for SBP_{MD} and present formal statistical testing. However, our necessary use of group averages would typically result in only small and insignificant error (< 1%) in SBP_{MD} calculation, which would not alter the conclusion of this meta-analysis. Only one author (DJ) participated in the database search. However, data extracted from each study was independently validated by two other researchers (EM, PL). Moreover, the study search criteria were very specific, i.e. studies presenting numerical values for CASP derived from two specific calibrations, together with brBP, which substantially limits the potential for systematic search error. As with all meta-analysis, use of weighted means, whilst statistically correct, may have biased our data towards values from studies with larger numbers. Finally, there is always the possibility of publication bias due to negative findings remaining unpublished. However, due to the uniqueness of our analysis in revealing a parameter that hasn't been reported before, any source of bias would have not affected our primary conclusions.

Conclusions

Even though PPW calibration to any two known BP readings should theoretically produce the same calibrated BP values, non-invasive MAP-DBP calibration yields SBP_{MD} values which differ markedly from brSBP with some BP monitors. These differences can only be attributed to form factor mismatch between the PPW and BP monitor, which are likely caused by device-specific inaccuracies of oscillometric monitors and/or limitations of using a fixed form factor for MAP calculations. The lack of reporting of SBP_{MD} in relation to $CASP_{MD}$ in research reports has led to erroneous concepts such as: reverse amplification, $CASP_{MD}$ superiority over brachial SBP for risk prediction, and the illogical classification of BP monitors as type I or II to compensate for obvious deficiencies in the performance of some BP monitors. The continued

acceptance of "black box" technologies for one of the most commonly used measurements in clinical practice must change and the fog that shrouds the inner workings blown away, to allow appropriate levels of scientific scrutiny.

Perspectives

It has been suggested that the non-invasive derivation of central aortic systolic pressure (CASP) may be a better measure of true BP load on vital organs and risk. CASP is usually measured by calibrating a peripheral pulse wave (PPW), usually brachial or radial, to brachial BP. It has been suggested by some, that calibration to brachial mean arterial pressure (MAP) and diastolic pressure (DBP) may provide a more accurate estimate of CASP than calibration to systolic blood pressure (SBP) and DBP. However, PPW calibration to MAP and DBP yields a new SBP (SBP_{MD}) value for the calibrated PPW, which until now has not been reported. Without SBP_{MD} reporting, it is impossible to compare CASP with the appropriate brachial BP to evaluate the predictive value of each parameter. We show that for some monitors the SBP_{MD} differs markedly and is much higher than the measured brachial SBP. This disparity which we have noted to be substantial with some monitors, was unexpected and is concerning. Furthermore, it questions the use of these monitors in clinical practice, and has wider implications for the uncritical acceptance of "black box" methodologies for the oscillometric measurement of BP.

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References

1. Protogerou AD, Argyris AA, Papaioannou TG, Kollias GE, Konstantonis GD, Nasothimiou E, Achimastos A, Blacher J, Safar ME, Sfikakis PP. Left-ventricular hypertrophy is associated better with 24-h aortic pressure than 24-h brachial pressure in hypertensive patients: the SAFAR study. *J Hypertens.* 2014;32(9):1805-1814.
2. Wassertheurer S, Baumann M. Assessment of systolic aortic pressure and its association to all cause mortality critically depends on waveform calibration. *Journal of hypertension.* 2015;33(9):1884-1888; discussion 1889.
3. Diaz A, Bia D, Zocalo Y. Impact of Methodological and Calibration Approach on the Association of Central and Peripheral Systolic Blood Pressure with Cardiac Structure and Function in Children, Adolescents and Adults. *High Blood Press Cardiovasc Prev.* 2019;26(6):509-534.
4. Negishi K, Yang H, Wang Y, Nolan MT, Negishi T, Pathan F, Marwick TH, Sharman JE. Importance of Calibration Method in Central Blood Pressure for Cardiac Structural Abnormalities. *American journal of hypertension.* 2016;29(9):1070-1076.
5. Papaioannou TG, Karageorgopoulou TD, Sergentanis TN, Protogerou AD, Psaltopoulou T, Sharman JE, Weber T, Blacher J, Daskalopoulou SS, Wassertheurer S, et al. Accuracy of commercial devices and methods for noninvasive estimation of aortic systolic blood pressure a systematic review and meta-analysis of invasive validation studies. *Journal of hypertension.* 2016;34(7):1237-1248.
6. Picone DS, Schultz MG, Peng X, Black JA, Dwyer N, Roberts-Thomson P, Qasem A, Sharman JE. Intra-arterial analysis of the best calibration methods to estimate aortic blood pressure. *Journal of hypertension.* 2019;37(2):307-315.
7. Sharman JE, Avolio AP, Baulmann J, Benetos A, Blacher J, Blizzard CL, Boutouyrie P, Chen CH, Chowienczyk P, Cockcroft JR, et al. Validation of non-invasive central

blood pressure devices: ARTERY Society task force consensus statement on protocol standardization. *European heart journal.* 2017;38(37):2805-2812.

8. Weber T, Wassertheurer S, Rammer M, Maurer E, Hametner B, Mayer CC, Kropf J, Eber B. Validation of a brachial cuff-based method for estimating central systolic blood pressure. *Hypertension.* 2011;58(5):825-832.
9. Blanch P, Armario P, Oliveras A, Fernandez-Llama P, Vazquez S, Pareja J, Alvarez E, Calero F, Sierra C, de la Sierra A. Association of Either Left Ventricular Hypertrophy or Diastolic Dysfunction With 24-Hour Central and Peripheral Blood Pressure. *American journal of hypertension.* 2018;31(12):1293-1299.
10. Karayiannis C, Moran C, Sharman JE, Beare R, Quinn SJ, Phan TG, Wood AG, Thrift AG, Wang WC, Srikanth V. Blood Pressure, Aortic Stiffness, Hemodynamics, and Cognition in Twin Pairs Discordant for Type 2 Diabetes. *Journal of Alzheimer's disease : JAD.* 2019;71(3):763-773.
11. Kips JG, Schutte AE, Vermeersch SJ, Huisman HW, Van Rooyen JM, Glyn MC, Fourie CM, Malan L, Schutte R, Van Bortel LM, Segers P. Comparison of central pressure estimates obtained from SphygmoCor, Omron HEM-9000AI and carotid applanation tonometry. *Journal of hypertension.* 2011;29(6):1115-1120.
12. Mahieu D, Kips J, Rietzschel ER, De Buyzere ML, Verbeke F, Gillebert TC, De Backer GG, De Bacquer D, Verdonck P, Van Bortel LM, Segers P, Asklepios i. Noninvasive assessment of central and peripheral arterial pressure (waveforms): implications of calibration methods. *J Hypertens.* 2010;28(2):300-305.
13. Nakagomi A, Okada S, Shoji T, Kobayashi Y. Comparison of invasive and brachial cuff-based noninvasive measurements for the assessment of blood pressure amplification. *Hypertension research : official journal of the Japanese Society of Hypertension.* 2017;40(3):237-242.

14. Nakagomi A, Okada S, Shoji T, Kobayashi Y. Crucial Effect of Calibration Methods on the Association Between Central Pulsatile Indices and Coronary Atherosclerosis. *American journal of hypertension.* 2017;30(1):24-27.

15. Peng X, Schultz MG, Abhayaratna WP, Stowasser M, Sharman JE. Comparison of Central Blood Pressure Estimated by a Cuff-Based Device With Radial Tonometry. *Am J Hypertens.* 2016;29(10):1173-1178.

16. Rajani R, Chowienczyk P, Redwood S, Guilcher A, Chambers JB. The noninvasive estimation of central aortic blood pressure in patients with aortic stenosis. *J Hypertens.* 2008;26(12):2381-2388.

17. Wassertheurer S, Hametner B, Mayer CC, Hafez A, Negishi K, Papaioannou TG, Protogerou AD, Sharman JE, Weber T. Aortic systolic pressure derived with different calibration methods: associations to brachial systolic pressure in the general population. *Blood pressure monitoring.* 2018;23(3):134-140.

18. Weber T, Wassertheurer S, Schmidt-Trucksass A, Rodilla E, Ablasser C, Jankowski P, Lorenza Muiesan M, Giannattasio C, Mang C, Wilkinson I, et al. Relationship Between 24-Hour Ambulatory Central Systolic Blood Pressure and Left Ventricular Mass: A Prospective Multicenter Study. *Hypertension.* 2017;70(6):1157-1164.

19. Weberruss H, Maucher J, Oberhoffer R, Muller J. Recovery of the cardiac autonomic nervous and vascular system after maximal cardiopulmonary exercise testing in recreational athletes. *European journal of applied physiology.* 2018;118(1):205-211.

20. Zeng X, Jia N, Liu D, Wang L, Xu Z, Zhang Y, Wang H, Zhang R, Zhou J, Pan C, Gan Y, Qiao W. A cross-sectional study of the ambulatory central artery stiffness index in patients with hypertension. *Medicine.* 2019;98(26):e16053.

21. Zhang Y, Kollias G, Argyris AA, Papaioannou TG, Tountas C, Konstantonis GD, Achimastos A, Blacher J, Safar ME, Sfikakis PP, Protogerou AD. Association of left

ventricular diastolic dysfunction with 24-h aortic ambulatory blood pressure: the SAFAR study. *Journal of human hypertension.* 2015;29(7):442-448.

22. Guilcher A, Brett S, Munir S, Clapp B, Chowienczyk PJ. Estimating central SBP from the peripheral pulse: influence of waveform analysis and calibration error. *Journal of hypertension.* 2011;29(7):1357-1366.

23. Shamseer L, Moher D, Clarke M, Ghersi D, Liberati A, Petticrew M, Shekelle P, Stewart LA. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015: elaboration and explanation. *Br Med Journal.* 2015;350(1756-1833 (Electronic)).

24. Hozo SP, Djulbegovic B, Hozo I. Estimating the mean and variance from the median, range, and the size of a sample. *BMC medical research methodology.* 2005;5:13.

25. Laugesen E, Rossen NB, Peters CD, Maeng M, Ebbehoj E, Knudsen ST, Hansen KW, Botker HE, Poulsen PL. Assessment of central blood pressure in patients with type 2 diabetes: a comparison between SphygmoCor and invasively measured values. *American journal of hypertension.* 2014;27(2):169-176.

26. Mynard JP, Goldsmith G, Springall G, Eastaugh L, Lane GK, Zannino D, Smolich JJ, Avolio A, Cheung MMH. Central aortic blood pressure estimation in children and adolescents: results of the KidCoreBP study. *J Hypertens.* 2019;38(5):821-828.

27. Park CM, Korolkova O, Davies JE, Parker KH, Siggers JH, March K, Tillin T, Chaturvedi N, Hughes AD. Arterial pressure: agreement between a brachial cuff-based device and radial tonometry. *Journal of hypertension.* 2014;32(4):865-872.

28. Pucci G, Cheriyan J, Hubsch A, Hickson SS, Gajendragadkar PR, Watson T, O'Sullivan M, Woodcock-Smith J, Schillaci G, Wilkinson IB, McEniery CM. Evaluation of the Vicorder, a novel cuff-based device for the noninvasive estimation of central blood pressure. *Journal of hypertension.* 2013;31(1):77-85.

29. Wohlfahrt P, Krajcoviechova A, Seidlerova J, Mayer O, Filipovsky J, Cifkova R. Comparison of noninvasive assessments of central blood pressure using general transfer function and late systolic shoulder of the radial pressure wave. *American journal of hypertension.* 2014;27(2):162-168.

30. Cheng HM, Chuang SY, Sung SH, Wu CC, Wang JJ, Hsu PF, Chao CL, Hwang JJ, Wang TD, Chen CH. 2019 Consensus of the Taiwan Hypertension Society and Taiwan Society of Cardiology on the Clinical Application of Central Blood Pressure in the Management of Hypertension. *Acta Cardiologica Sinica.* 2019;35(3):234-243.

31. Cheng HM, Sung SH, Chen CH, Yu WC, Yang SM, Guo CY, Chuang SY, Chiang CE. Guiding Hypertension Management Using Different Blood Pressure Monitoring Strategies (GYMNs study): comparison of three different blood pressure measurement methods: study protocol for a randomized controlled trial. *Trials.* 2019;20(1):265.

32. Chuang SY, Chang HY, Cheng HM, Pan WH, Chen CH. Prevalence of Hypertension Defined by Central Blood Pressure Measured Using a Type II Device in a Nationally Representative Cohort. *American journal of hypertension.* 2018;31(3):346-354.

33. Chuang SY, Chang HY, Cheng HM, Pan WH, Chen CH. Impacts of the New 2017 ACC/AHA Hypertension Guideline on the Prevalence of Brachial Hypertension and Its Concordance with Central Hypertension. *American journal of hypertension.* 2019;32(4):409-417.

34. Dorr M, Richter S, Eckert S, Ohlow MA, Hammer F, Hummel A, Dornberger V, Genzel E, Baulmann J. Invasive Validation of Antares, a New Algorithm to Calculate Central Blood Pressure from Oscillometric Upper Arm Pulse Waves. *Journal of clinical medicine.* 2019;8(7).

35. Yu S, Xiong J, Lu Y, Chi C, Teliewubai J, Bai B, Ji H, Zhou Y, Fan X, Blacher J, Li J, Zhang Y, Xu Y. The prevalence of central hypertension defined by a central blood

pressure type I device and its association with target organ damage in the community-dwelling elderly Chinese: The Northern Shanghai Study. *Journal of the American Society of Hypertension : JASH.* 2018;12(3):211-219.

36. Shih YT, Cheng HM, Sung SH, Hu WC, Chen CH. Quantification of the calibration error in the transfer function-derived central aortic blood pressures. *Am J Hypertens.* 2011;24(12):1312-1317.

37. Gravlee GP, Brockschmidt JK. Accuracy of four indirect methods of blood pressure measurement, with hemodynamic correlations. *J Clin Monit.* 1990;6(4):284-298.

38. Schultz MG, Picone DS, Armstrong MK, Black JA, Dwyer N, Roberts-Thomson P, Sturgess D, Sharman JE. The influence of SBP amplification on the accuracy of form-factor-derived mean arterial pressure. *J Hypertens.* 2020;38(6):1033-1039.

39. Grillo A, Salvi P, Furlanis G, Baldi C, Rovina M, Salvi L, Faini A, Bilo G, Fabris B, Carretta R, Benetos A, Parati G. Mean arterial pressure estimated by brachial pulse wave analysis and comparison with currently used algorithms. *J Hypertens.* 2020;38(11):2161-2168.

Novelty and significance

What is new?

- It has been suggested that peripheral pulse waves (PPW) should preferentially be calibrated to mean arterial pressure (MAP) and diastolic blood pressure (MAP-DBP) (rather than to systolic and diastolic blood pressure (SBP-DBP) for the derivation of central aortic systolic pressure. However, MAP-DBP calibration must also generate a SBP value for the peak of the PPW (i.e. SBP_{MD}), which should be equivalent to the measured brachial SBP (brSBP) if the brachial BP indexes are all accurate. For the first time, we calculate and report SBP_{MD} and compare it to the original brSBP.
- We report that the SBP_{MD} shows a substantial and clinically important difference from the oscillometric brSBP for some BP monitors.

What is relevant?

- The marked difference between the original brSBP and SBP_{MD} explains why a common finding of reverse aortic-brachial systolic pressure amplification with some BP monitors is erroneous, due to the incorrect SBP indexes being used in the calculation of amplification.
- Likewise, our findings suggest that when assessing the relative risk predictive value of aortic pressure versus brachial pressure, the appropriate SBP must be used.
- These findings highlight potentially important inaccuracies in BP measurement with some oscillometric BP monitors.

Summary:

- The study highlights a clear need for transparency and scientific scrutiny of the proprietary methodologies used for oscillometric BP measurement and the derivation of additional parameters, e.g. central aortic pressure.

Figure 1. **The Piezoelectric Effect**.

Peripheral pulse wave (A) acquired with a device utilising the piezoelectric effect where changes in voltage are directly proportional to changes in BP (B).

BP = Blood Pressure, BP_1 = Blood Pressure at time point 1, BP_2 = Blood Pressure at time point 2, BP_3 = Blood Pressure at time point 3, BP_4 = Blood Pressure at time point 4, BP_5 = Blood Pressure at time point 5, DBP = Diastolic Blood Pressure, MAP = Mean Arterial Pressure, SBP = Systolic Blood Pressure.

Figure 2. **Pulse Wave Calibration for Non-Invasive CASP Estimation.**

In this example of pulse wave calibration to brachial BP, uncalibrated brachial (dashed line) and derived aortic (dotted line) pulse waves in mV (panel A) are calibrated to SBP-DBP (dash-dot line) or MAP-DBP (solid line) using linear functions (panel B) to convert all data from mV to mmHg. PPW calibration to inaccurate BP values results in an inaccurate calculation of linear functions (hence why the linear functions differ between calibration methods) and thus inaccurate unit conversion from mV to mmHg. This subsequently produces different values in mmHg between SBP-DBP (panel C) and MAP-DBP (panel D) calibration methods. As a consequence, in the example presented, the SBP_{MD} and $CASP_{MD}$ are markedly higher than the measured brSBP and $CASP_{SD}$.

BP = Blood Pressure, brDBP = Diastolic Blood Pressure displayed by the BP monitor, brMAP = Mean Arterial Pressure displayed by the BP monitor, MAP = Mean Arterial Pressure, MAP_{SD} = Mean Arterial Pressure obtained from SBP-DBP calibration, brSBP = Systolic Blood Pressure displayed by the BP monitor, CASP = Central Aortic Systolic Pressure, $CASP_{MD}$ = Central Aortic Systolic Pressure obtained from MAP-DBP calibration, $CASP_{SD}$ = Central Aortic Systolic Pressure obtained from SBP-DBP calibration, DBP =

Diastolic Blood Pressure, SBP = Systolic Blood Pressure, SBP_{MD} = Systolic Blood Pressure obtained from MAP-DBP calibration.

Figure 3. Search Strategy Flow Chart.

Results of the database screening. n = number of publications.

Figure 4. Primary Outcome.

The weighted mean (vertical dashed line) and individual study (horizontal lines) differences between SBP_{MD} and brSBP (different BP monitors are represented with different symbols). A colour version of this figure is available in the Online Data Supplement (http://hyper.ahajournals.org – Figure S1).

Y- axis label: first author (reference number) - sub-analysis or group. BPW = Brachial Pulse Wave, brSBP = Systolic Blood Pressure, FF = Form Factor, LVH = Left Ventricular Hypertrophy, n = number of study participants, RPW = Radial Pulse Wave, SBP_{MD} = Systolic Blood Pressure after MAP and DBP calibration.

Table 1. Participant demographics summary table

Variable (units)	MOG	Omron	Pulsecor	RCN	SXCEL	Vicorder	Total	Studies used in the calculations
Age (years)	54 ± 11 (9536)	48 ± 8 (2461)	70 ± 6 (1107)	65 ± 11 (34)	61 ± 7 (182)	49 ± 17 (140)	54 ± 10 (13460)	1-4,8,9,11-18,21,22,25-29
Female (%)	63% (9536)	49% (2461)	24% (1107)	15% (34)	52% (182)	44% (140)	57% (13460)	1-4,8,9,11-18,21,22,25-29
Current smoker (%)	25% (1255)	10% (40)		24% (34)			25% (1329)	1,3,8,9,18,21,22,25
BMI ($kg.m^{-2}$)	27.6 ± 4.7 (1519)	25.1 ± 3.9 (2056)	27.4 ± 4.5 (1107)	31.0 ± 4.0 (34)		26.2 ± 5.4 (140)	26.5 ± 4.3 (4856)	1-4,8,9,11-13,21,22,25,27,28
Treated hypertension (%)	65% (982)	30% (391)	67% (1107)	100% (34)	100% (182)	12.2 (90)	62% (2786)	1,9,13,15,18,21,25,27-29
CKD (%)	26% (722)						26% (722)	1,2,13,18
Diabetes (%)	21% (2058)	8% (431)	31% (1107)	100 (34)	14% (182)		23% (3812)	1-4,8,9,13-15,18,21,22,25,27,29
Participants Requiring Catheterisation (%)	3% (9536)	2% (2461)	0% (1107)	100% (34)	0% (182)	36% (140)	3% (13460)	1-4,8,9,11-18,21,22,25-29
brSBP (mmHg)	127 ± 12 (9225)	132 ± 16 (2461)	142 ± 16 (1107)	148 ± 21 (34)	128 ± 13 (182)	134 ± 16 (140)	130 ± 14 (13149)	1-4,8,9,11-17,21,22,25-29

brDBP (mmHg)	79 ± 8 (9225)	77 ± 11 (2461)	84 ± 10 (1107)	84 ± 13 (34)	77 ± 9 (182)	74 ± 10 (140)	79 ± 9 (13149)	1-4,8,9,11-17,21,22,25-29
HR (beats.min^{-1})	75 ± 8 (7948)	64 ± 10 (2407)	68 ± 2 (1107)	67 ± 11 (34)	68 ± 11 (182)	65 ± 11 (140)	72 ± 8 (11818)	2,3,8,11,12,15,17,25,27-29
24-hour brSBP (mmHg)	128 ± 13 (726)						128 ± 13 (726)	1,9,18
24-hour brDBP (mmHg)	82 ± 10 (726)						82 ± 10 (726)	1,9,18
Values are reported as mean ± SD or %, with sample size reported as (n). BMI = Body Mass Index; CKD = Chronic Kidney Disease; brDBP = brachial Diastolic Blood Pressure; brSBP = brachial Systolic Blood Pressure; HR = Heart Rate; n = sample size; MOG = Mobil-O-Graph; Omron = combined data for Omron 705, Omron HEM 9000AI and Omron HEM-907; RCN = Riester Champion N; SD = Standard Deviation; SXCEL = SphygmoCor XCEL. Studies used in the analysis are numbered accordingly.								

Table 2. Calculated SBP_{MD} and SBP_{MD}-brSBP for previously conducted studies

First Author	Year	N	BP Type	BP Device	PPW Site	brSBP	$CASP_{SD}$	SBP_{MD}	$CASP_{MD}$	brDBP	SBP_{MD}-brSBP	Additional Details
Blanch [9]	2018	77	ABPM	Mobil-O-Graph	BPW	135.1	124.3	155.8	140.9	81.0	20.7	Non-invasive Sub-group - Participants with LVH
		131	ABPM	Mobil-O-Graph	BPW	126.0	116.2	144.3	130.6	79.8	18.3	Non-invasive Sub-group - Participants without LVH
Díaz [3]	2019	269	Clinic	Mobil-O-Graph	BPW	119	109	148	132	70	29	Non-invasive All participants
		147	Clinic	Mobil-O-Graph	BPW	116	104	150	130	64	34	Non-invasive Sub-group - Children, adolescents and young adults
Mynard [26]	2019	52	Clinic	Mobil-O-Graph	BPW	96	87	113	101	44	17	Invasive study in Children (only 52 of 69 patients had Mobil-O-Graph data)
Nakagomi [13]	2017	45	Clinic	Mobil-O-Graph	BPW	141.9	130.0	167.2	149.5	89.7	25.3	Invasive
Nakagomi [14]	2017	139	Clinic	Mobil-O-Graph	BPW	140.8	127.9	169.2	149.5	87.0	28.4	Invasive

Negishi [4]	2016	349	Clinic	Mobil-O-Graph	BPW	140	128	166	149	81	26	Non-invasive
Protogerou [1]	2014	229	ABPM	Mobil-O-Graph	BPW	127	118	142	130	82	15	Non-invasive
Wassertheurer [2]	2015	159	Clinic	Mobil-O-Graph	BPW	132.5	121.2	150.4	134.9	84.6	17.9	Non-invasive
Wassertheurer [17]	2018	7409	Clinic	Mobil-O-Graph	BPW	126	117	138	127	79	12	Non-invasive
Weber [8]	2011	111	Clinic	Mobil-O-Graph	BPW	128.0	118.5	144.9	131.7	84.6	16.9	Non-invasive
		111	Clinic	Mobil-O-Graph	RPW	128.0	119.0	143.6	131.4	84.6	15.6	Non-invasive
		30	Clinic	Mobil-O-Graph	BPW	129.1	123.4	142.1	134.9	81.1	13.0	Invasive
		30	Clinic	Mobil-O-Graph	RPW	129.1	119.7	143.9	131.6	81.1	14.8	Invasive
Weber [18]	2017	289	ABPM	Mobil-O-Graph	BPW	127	119	138	128	83	11	Non-invasive
Zhang [21]	2015	230	ABPM	Mobil-O-Graph	BPW	126.6	117.8	141.8	130.1	80.2	15.2	Non-invasive
Guilcher [22]	2011	40	Clinic	Omron 705	DPW	145	138	141	134	67	-4	Baseline data, Invasive aortic pressures used for PPW calibration

Rajani [16]	2008	14	Clinic	Omron 705	RPW	148	137	155	143	77	7	Invasive aortic pressures used for PPW calibration
Kips [11]	2011	143	Clinic	Omron HEM 9000AI	RPW	137.7	129.1	142.6	133.2	82.1	4.9	Non-invasive Unclear whether fixed form factor MAP was used in the calculations
Wohlfahrt [29]	2014	391	Clinic	Omron HEM 9000AI	RPW	130	120	135	124	78	5	Non-invasive Fixed form factor MAP (k = 0.4)
Mahieu [12]	2010	1873	Clinic	Omron HEM-907	RPW	131.5	123.5	124.8	117.8	76.6	-6.7	Non-invasive Fixed form factor MAP (k = 0.33)
		1873	Clinic	Omron HEM-907	RPW	131.5	123.5	134.4	126	76.6	2.9	Non-invasive Fixed form factor MAP (k = 0.4)
Park [27]	2014	1107	Clinic	Pulsecor R6.5	RPW	142	132	153	141	84	11	Non-invasive Fixed form factor MAP (k = 0.4)
Laugesen [25]	2014	34	Clinic	Riester Champion N	RPW	148	133.6	151	135.7	84	3	Non-invasive Fixed form factor MAP (k = 0.33)

		34	Clinic	Riester Champion N	RPW	148	133.6	164	146.0	84	16	Non-invasive Fixed form factor MAP (k = 0.4)
Peng [15]	2016	182	Clinic	SphygmoCor XCEL	BPW	128	115	151	132	77	23	Non-invasive Fixed form factor MAP (k = 0.4)
		182	Clinic	SphygmoCor XCEL	RPW	128	116	139	124	77	11	Non-invasive Fixed form factor MAP (k = 0.4)
Pucci [28]	2013	90	Clinic	Vicorder	RPW	129	115	137	121	72	8	Non-invasive
		50	Clinic	Vicorder	RPW	143	129	156	139	78	13	Invasive study

ABPM = Ambulatory Blood Pressure Monitoring, BP = Blood Pressure, BPW = Brachial Pulse Wave, br = brachial, $CASP_{SD}$ = Central Aortic Systolic Pressure from SBP-DBP calibration, $CASP_{MD}$ = Central Aortic Systolic Pressure from MAP-DBP calibration, DBP = brachial Diastolic Blood Pressure, DPW = Digital Pulse Wave, k = form factor, LVH = Left Ventricular Hypertrophy, MAP = Mean Arterial Pressure, n = sample size, PPW = Peripheral Pulse Wave, RPW = Radial Pulse Wave, SBP = brachial Systolic Blood Pressure, SBP_{MD} = Systolic Blood Pressure from MAP-DBP calibration