Central Blood Pressure/Aortic Stiffness

Validation of a Brachial Cuff-Based Method for Estimating Central Systolic Blood Pressure

Thomas Weber, Siegfried Wassertheurer, Martin Rammer, Edwin Maurer, Bernhard Hametner, Christopher C. Mayer, Johannes Kropf, Bernd Eber

See Editorial Commentary, pp 765–767

Abstract—The prognostic value of central systolic blood pressure has been established recently. At present, its noninvasive assessment is limited by the need of dedicated equipment and trained operators. Moreover, ambulatory and home blood pressure monitoring of central pressures are not feasible. An algorithm enabling conventional automated oscillometric blood pressure monitors to assess central systolic pressure could be of value. We compared central systolic pressure, calculated with a transfer-function like method (ARCSolver algorithm), using waveforms recorded with a regular oscillometric cuff suitable for ambulatory measurements, with simultaneous high-fidelity invasive recordings, and with noninvasive estimations using a validated device, operating with radial tonometry and a generalized transfer function. Both studies revealed a good agreement between the oscillometric cuff-based central systolic pressure and the comparator. In the invasive study, composed of 30 patients, mean difference between oscillometric cuff/ARCSolver-based and invasive central systolic pressures was 3.0 mm Hg (SD: 6.0 mm Hg) with invasive calibration of brachial waveforms and −3.0 mm Hg (SD: 9.5 mm Hg) with noninvasive calibration of brachial waveforms. Results were similar when the reference method (radial tonometry/transfer function) was compared with invasive measurements. In the noninvasive study, composed of 111 patients, mean difference between oscillometric cuff/ARCSolver–derived and radial tonometry/transfer function–derived central systolic pressures was −0.5 mm Hg (SD: 4.7 mm Hg). In conclusion, a novel transfer function-like algorithm, using brachial cuff-based waveform recordings, is suited to provide a realistic estimation of central systolic pressure. (Hypertension. 2011;58:825-832.)

Key Words: central systolic blood pressure ■ oscillometric blood pressure monitor ■ arterial waveforms ■ validation study

Although mean blood pressure (MBP) and diastolic blood pressure (DBP) are relatively constant in the conduit arteries, it has been known for decades that systolic blood pressure (SBP) and pulse pressure are higher in the peripheral than in the central arteries.1 This so-called SBP or pulse pressure amplification is the consequence of the progressive reduction of diameter and increase in stiffness from the proximal to the distal arterial vessels and mostly of the modification in the transit of wave reflections.2 It seems obvious that central pressures are more relevant than peripheral pressures for the pathogenesis of cardiovascular disease: it is central SBP (cSBP) against the heart ejects (afterload), and it is central pulse pressure that distends the large elastic arteries.3 Indeed, cSBP and central pulse pressure have been associated more closely with left ventricular hypertrophy and carotid atherosclerosis as markers of hypertensive end-organ damage than brachial pressures in different populations.4–6 Moreover, it has been documented in a series of studies5,7–9 that central blood pressures are better predictors of cardiovascular outcomes than brachial blood pressures. Finally, antihypertensive drugs can have differential effects on central and peripheral blood pressures,10 and this may be a major determinant of outcomes with different antihypertensive drug classes.11

For these various reasons, the estimation of cSBP in clinical routine may be advantageous. The relationship between central and peripheral pressures depends, among others, on age, sex, height, heart rate, and cardiovascular risk factors and is driven mainly by differences in vessel stiffness and wave reflections. Thus, while being highly correlated, central pressures cannot be reliably inferred from peripheral cuff pressures by mathematical formula.12 For obvious reasons, invasive measurement of cSBP is not feasible during routine care as well. In recent years, noninvasive methods for...
the estimation of cSBP have been introduced.\textsuperscript{13,14} However, these methods require pressure waveforms and have, in the main, been either confined to the research area or necessitate dedicated equipment and trained operators, which may hinder their implementation into routine clinical practice or large-scale clinical trials. We recently introduced a novel method (the ARCSolver method, Austrian Institute of Technology) for estimating central aortic pressures based on brachial pulse waves recorded with a regular brachial oscillometric blood pressure cuff. The method considers the influence of arterial impedance using a generalized transfer function (TF), as well as aortic hemodynamics by the means of a mathematical model,\textsuperscript{15} and has already been successfully validated against a common tonometric method.\textsuperscript{16} The aim of the presented work was the prospective validation of the cSBP provided by the ARCSolver algorithm implemented into a commercially available, oscillometric brachial cuff–based sphygmomanometer that has been validated for automated blood pressure monitoring\textsuperscript{17} against invasive recordings using gold standard solid-state pressure sensor-tipped catheters (Millar Instruments, Houston, TX) and against a validated, Food and Drug Administration–approved noninvasive system (SphygmoCor, AtCor Medical Inc, West Ryde, Australia).

Methods

Patients

For the invasive study, we included patients undergoing elective coronary angiography for suspected coronary artery disease at our institution, a large tertiary care cardiology department in a university teaching hospital in Austria. For the noninvasive comparison, we recruited inpatients of our department, as well as healthy volunteers. Exclusion criteria for both studies were unstable clinical conditions, arrhythmias that would disturb the regular rhythm required during pulse recordings, and significant ($\geq 2+$) valvular heart disease. Both studies were approved by our regional ethics committee, and all of the participants gave written informed consent.

Brachial Blood Pressure Measurement and ARCSolver Algorithm

To perform the noninvasive data capturing at the brachial artery, the Mobil-O-Graph NG (IEM, Stolberg, Germany) with inbuilt ARCSolver algorithm was used. This device is a commercially available brachial oscillometric 24-hour ambulatory blood pressure monitor with Food and Drug Administration and Conformité Européenne approval. Its blood pressure detection unit is validated according to the British Hypertension Society and European Society of Hypertension recommendations.\textsuperscript{17,18} In addition to brachial SBP and DBP, MBP can be displayed as well, which is a logical extension of the underlying working principle of the oscillometric method: MBP is the lowest cuff pressure at which the oscillations are maximal.\textsuperscript{19} The algorithm for the generation of cSBP and aortic blood pressure curves, using the oscillometric method, has been reported previously.\textsuperscript{16} Briefly, after the conventional oscillometric blood pressure measurement, the pulse waves are recorded, using the brachial cuff, at DBP level for $\sim 10$ seconds. After digitalization, a 3-step algorithm is applied. In a first step, the single pressure waves are verified for their plausibility by testing the position of minima and the corresponding wavelengths. Minima were detected by means of an iterative procedure evaluating higher order time derivatives of the pressure signal. During the second stage, all of the single pressure waves are compared with each other to recognize artifacts. Thereafter, an aortic pulse wave is generated by the means of a generalized TF. The idea behind a TF is the modification of a certain frequency range within the acquired pulse signal to derive the aortic pressure wave. Modulus and phase characteristics of the ARCSolver TF have been published.\textsuperscript{16} Finally, the coherence of the measured parameters is verified.

Invasive Study

The 5F Millar SPC-454D catheters (Millar Instruments) were adjusted to baseline electronically, calibrated under saline, connected to a Millar PCU-2000 U, inserted from a femoral sheet along a guide wire, carefully adjusted for thermal drift, and located in the ascending aorta $\sim 1$ cm above the aortic valve. High-fidelity pressure waveforms were recorded for 3 to 4 minutes, using the Millar pressure sensor located at the tip of the catheter and a customized software, written in Matlab 7.5 (The Mathworks Inc, Natick, MA). Brachial waveforms were acquired simultaneously in the left arm, using the Mobil-O-Graph NG, in the supine position, with the arm supported at heart level, using appropriate cuff sizes. All of the measurements were performed in duplicate in 26 patients (with results averaged) and as single measurements in 4 patients. Invasively recorded pressure signals were continuously analyzed for their extrema (SBP and DBP) and for MBP during the 3- to 4-minute recording period and averaged to get a single value for SBP, MBP, and DBP per reading. MBP was measured continuously using the "area-under-the-curve" method. The final analysis included all of the measurements as recorded (we did not exclude any measurements because of suspected inaccuracy) and consisted of the following 2 steps. First, the brachial pulse waves were calibrated with invasive MBP and DBP to blind out the potential systematic influence of oscillometric calibration and to validate the ARCSolver algorithm, per se. This approach is well established and has also been used to validate the SphygmoCor TF.\textsuperscript{13} Then, we tested the absolute performance of the noninvasive system against invasive measurements, and, therefore, the brachial pressure waveforms were calibrated with the brachial SBP and DBP and the brachial MBP and DBP, all provided by Mobil-O-Graph NG, manipulated by the ARCSolver algorithm and then compared against invasive values.

In addition, simultaneously with invasive and brachial measurements, radial waveforms were acquired by a single operator at the right wrist, using a validated, commonly used tonometric method (SphygmoCor, AtCor Medical Inc; software version 8.2), in duplicate with results averaged per patient, with high-quality recordings available in all of the patients. cSBP was calculated, using the inbuilt validated TF, with calibration of the radial waveforms with invasively measured MBP and DBP, brachial SBP and DBP, and brachial MBP and DBP, all provided by Mobil-O-Graph NG. To ensure synchronicity, the internal clocks of the 3 recording devices have been synchronized, and each data triple has been aligned to the timestamps.

Noninvasive Study

Applanation tonometry of the radial artery and oscillometric pulse wave recordings at the brachial artery were performed in the supine position and took place at convenient room temperature and under avoidance of external influence. Medications were not withheld for the measurements. Brachial blood pressure was measured, using the Mobil-O-Graph NG, and cSBP was estimated, using brachial waveforms and the ARCSolver algorithm. Radial waveforms were recorded immediately afterward by radial applanation tonometry (SphygmoCor), and the inbuilt general TF was used to derive cSBP. Calibration of brachial (ARCSolver) or radial (TF) waveforms was performed with either SBP and DBP or MBP and DBP, as measured by the Mobil-O-Graph NG, at the brachial artery. Only high-quality recordings of the radial waveforms by visual inspection and by a device-specific quality index $>80\%$ were used. Two iterations were performed and the particular estimates for cSBP were averaged.

Statistics

All of the measurements are presented as mean $\pm 1$ SD. Linear regression was applied to determine the coefficient of determination ($R^2$). Furthermore, data were analyzed using the method presented by Bland and Altman. Those are mainly helpful to represent the data graphically and to investigate the agreement of measurements.
Results

Patient Characteristics
In the invasive study, mean age was 59±11 years (range: 33–77 years). One third of the patients had coronary artery disease, and systolic function was preserved in 87%. Central (aortic) blood pressure ranges, as measured invasively, were wide: 101 to 188 mm Hg for cSBP, 85 to 119 mm Hg for MBP, and 55 to 86 mm Hg for cDBP (additional information is provided in Tables S1 and S2 in the online Data Supplement; please see http://hyper.ahajournals.org).

In the noninvasive study, mean age was 59±11 years (range: 24–81 years); 83% were men and 65% had hypertension. Brachial blood pressure ranges were wide: 88 to 195 mm Hg for brachial SBP, 71 to 153 mm Hg for MBP, and 57 to 118 mm Hg for brachial DBP (additional information is provided in Tables S1 and S2 in the online Data Supplement).

<table>
<thead>
<tr>
<th>Blood Pressure Variable</th>
<th>Absolute Value</th>
<th>Mean Difference From Invasive Central Blood Pressure</th>
<th>SD of Difference From Invasive Central Blood Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>cSBP invasive mm Hg*</td>
<td>137.9±18.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MBP invasive mm Hg</td>
<td>101.7±9.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cDBP invasive mm Hg</td>
<td>74.4±6.6</td>
<td></td>
<td></td>
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<tr>
<td>bSBP oscillometric mm Hg†</td>
<td>129.1±15.5</td>
<td>8.8</td>
<td>10.4</td>
</tr>
<tr>
<td>MBP oscillometric mm Hg</td>
<td>103.1±10.5</td>
<td>−1.4</td>
<td>5.5</td>
</tr>
<tr>
<td>bDBP oscillometric mm Hg</td>
<td>81.1±8.5</td>
<td>−6.7</td>
<td>7.3</td>
</tr>
<tr>
<td>cSBP (osc/ARCSolver, inv cal), mm Hg‡</td>
<td>140.9±18.7</td>
<td>−3.0</td>
<td>6.0</td>
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<tr>
<td>cDBP (osc/ARCSolver, inv cal), mm Hg§</td>
<td>75.5±6.6</td>
<td>−1.1</td>
<td>0.8</td>
</tr>
<tr>
<td>cSBP (tonometry/TF, inv cal), mm Hg¶</td>
<td>136.8±18.2</td>
<td>1.1</td>
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</tr>
<tr>
<td>cDBP (tonometry/TF, inv cal), mm Hg</td>
<td>75.4±6.9</td>
<td>−1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>cSBP (osc/ARCSolver, osc cal†), mm Hg</td>
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<td></td>
<td>134.9±17.3</td>
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<td>cDBP (osc/ARCSolver, osc cal†), mm Hg</td>
<td></td>
<td></td>
<td>82.0±8.2</td>
</tr>
<tr>
<td>cSBP (tonometry/TF, osc cal†), mm Hg¶</td>
<td>131.6±17.2</td>
<td>6.2</td>
<td>8.9</td>
</tr>
<tr>
<td>cDBP (tonometry/TF, osc cal†), mm Hg</td>
<td>82.2±8.6</td>
<td>−7.8</td>
<td>7.3</td>
</tr>
<tr>
<td>cSBP (osc/ARCSolver, osc cal†), mm Hg</td>
<td></td>
<td></td>
<td>123.4±16.4</td>
</tr>
<tr>
<td>cDBP (osc/ARCSolver, osc cal†), mm Hg</td>
<td></td>
<td></td>
<td>82.6±8.4</td>
</tr>
<tr>
<td>cSBP (tonometry/TF, osc cal†), mm Hg**</td>
<td>119.7±16.3</td>
<td>18.1</td>
<td>8.9</td>
</tr>
<tr>
<td>cDBP (tonometry/TF, osc cal†), mm Hg</td>
<td></td>
<td></td>
<td>81.9±8.7</td>
</tr>
</tbody>
</table>

DBP, diastolic blood pressure; cDBP, central diastolic blood pressure; SBP, systolic blood pressure; cSBP, systolic blood pressure; TF, transfer function; MBP, mean blood pressure; bDBP, brachial diastolic blood pressure; bSBP, brachial systolic blood pressure; osc cal, oscillometric calibration; inv cal, invasive calibration.

*†‡§¶**cSBP/MBP/cDBP indicates SBP/MBP/DBP measured invasively (Millar catheters) in the ascending aorta.
**cSBP/cDBP (tonometry/TF, inv cal) indicates cSBP/cDBP calculated from radial waveforms (tonometry) using invasive calibration (MBP and DBP).
**cSBP/cDBP (osc/ARCSolver, inv cal) indicates cSBP/cDBP calculated from brachial waveforms (oscillometric cuff) using invasive calibration (MBP and DBP).
**cSBP/cDBP (tonometry/TF, inv cal) indicates cSBP/cDBP calculated from radial waveforms (tonometry) using invasive calibration (MBP and DBP).
**cSBP/cDBP (osc/ARCSolver, osc cal†) indicates cSBP/cDBP calculated from brachial waveforms (oscillometric cuff) using noninvasive calibration (MBP and DBP).
**cSBP/cDBP (osc/ARCSolver, osc cal†) indicates cSBP/cDBP calculated from brachial waveforms (oscillometric cuff) using noninvasive calibration (MBP and DBP).
**cSBP/cDBP (osc/ARCSolver, osc cal†) indicates cSBP/cDBP calculated from radial waveforms (tonometry) using noninvasive calibration (SBP and DBP from oscillometric cuff).
**cSBP/cDBP (osc/ARCSolver, osc cal†) indicates cSBP/cDBP calculated from radial waveforms (tonometry) using noninvasive calibration (SBP and DBP from oscillometric cuff).

Invasive Study
Within this cohort, the invasively measured cSBP was 137.9±18.9 mm Hg (Table 1). Using invasively measured DBP and MBP for calibration of brachial waveforms (acquired with the oscillometric cuff), cSBP (osc/ARCSolver) was 140.9±18.7 mm Hg. The correlation between cSBP (invasive) and cSBP (osc/ARCSolver) was close, with $R^2=0.899$ ($P<0.0001$). Bland-Altman plots are shown in Figure 1, revealing good agreement (mean difference: −3.0±6.0 mm Hg) without any systematic bias. When radial waveforms (SphygmoCor system) were calibrated with invasive MBP and DBP to yield cSBP (tonometry/TF), results were comparable: correlation with invasive cSBP was close ($R^2=0.956$; $P<0.0001$). Bland-Altman analysis revealed good agreement (mean difference: 1.1±4.0 mm Hg) without
any systematic bias. Z statistic revealed that correlations between cSBP (invasive) and cSBP (osc/ARCSolver) or cSBP (tonometry/TF) were not statistically different ($P=0.87$).

To provide an estimate of clinical usefulness of the whole system, we compared the values for cSBP, as measured invasively, and cSBP, as estimated by ARCSolver method from brachial waveforms, calibrated with either SBP/DBP or MBP/DBP, as measured at the brachial level by the oscillometric method. Using brachial MBP and DBP for calibration, cSBP was 134.9±17.3 mm Hg. Again, correlation with invasive cSBP was close ($R^2=0.748$; $P=0.0001$). Bland-Altman analysis revealed an increase in scatter (mean difference: 3.0±9.5 mm Hg) compared with the invasive calibration (Figure 2). Using brachial SBP and DBP for calibration, cSBP was 123.4±16.4 mm Hg. The according differences were systematically larger (mean difference: 14.4±9.7 mm Hg).

Using brachial MBP and DBP for calibration of radial waveforms (SphygmoCor system), cSBP was 131.6±17.2 mm Hg. The according differences to cSBP (invasive) are shown in Figure 2 (mean difference: 6.2±8.9 mm Hg). Using brachial SBP and DBP for calibration of radial waveforms (SphygmoCor system), cSBP was 119.7±16.3 mm Hg. The correlation between cSBP (osc/ARCSolver) and cSBP (tonometry/TF) was 131.7±19.1 mm Hg and cSBP (tonometry/TF) was 131.4±19.9 mm Hg. The correlation between cSBP (osc/ARCSolver) and cSBP (tonometry/TF) was 131.4±19.9 mm Hg. The correlation between cSBP (osc/ARCSolver) and cSBP (tonometry/TF) was 0.929 ($P<0.0001$) for SBP/DBP calibration and 0.955 ($P<0.0001$) for MBP/DBP calibration, respectively. Bland-Altman plots are shown in Figure 3, revealing good agreement (mean difference: 0.5±4.7 and 0.3±4.2 mm Hg for both calibration methods) without any systematic bias.

**Noninvasive Study**

Blood pressures, as measured in the 111 patients included in the noninvasive study, are shown in Table 2. Brachial SBP was 128.0±17.2 mm Hg. Using brachial SBP and DBP for calibration, cSBP (osc/ARCSolver) was 118.5±15.2 mm Hg and cSBP (tonometry/TF) was 119.0±16.9 mm Hg. Using MBP and brachial DBP for calibration, cSBP (osc/ARCSolver) was 131.7±19.1 mm Hg and cSBP (tonometry/TF) was 131.4±19.9 mm Hg. The correlation between cSBP (osc/ARCSolver) and cSBP (tonometry/TF) was 0.929 ($P<0.0001$) for SBP/DBP calibration and 0.955 ($P<0.0001$) for MBP/DBP calibration, respectively. Bland-Altman plots are shown in Figure 3, revealing good agreement (mean difference: 0.5±4.7 and 0.3±4.2 mm Hg for both calibration methods) without any systematic bias.

**Figure 1.** A, Scatterplot of invasively measured vs tonometry/transfer function–derived central systolic blood pressure (cSBP) with invasive calibration of radial waveforms. B, Bland-Altman plot of the same data. C, Scatterplot of invasively measured vs oscillometric/ARCSolver-derived cSBP with invasive calibration of brachial waveforms. D, Bland-Altman plot of the same data.
Discussion

The aim of this study was to investigate the ability of a novel TF-like formula, the ARCSolver algorithm, that can be used in connection with pressure waveforms recorded with regular oscillometric brachial blood pressure cuffs, to estimate central systolic blood pressure. Our results indicate the following: (1) the ARCSolver algorithm, applied on brachial waveforms, when calibrated with invasive pressures, provides accurate values for cSBP; (2) the ARCSolver algorithm, applied on brachial waveforms, when calibrated with brachial pressures obtained with a commercially available, validated, oscillometric brachial cuff, still yields reliable estimates for cSBP; (3) cSBP, as obtained with the ARCSolver and brachial cuff-based waveforms, shows good agreement with the validated, radial tonometry/general TF-based, noninvasive reference method (SphygmoCor); and (4) for calibration of radial or brachial waveforms, peripheral MBP and DBP, rather than peripheral SBP and DBP, should be used.

With respect to the invasive study, our results support the concept that a generalized mathematical TF is capable of calculating cSBP based on peripheral waveforms. When calibrated with invasive blood pressures, the accuracy of the ARCSolver algorithm meets the data published by Pauca et al., who found a difference between directly recorded cSBP and TF-derived cSBP (from invasively recorded radial pressure waveforms) of 0.0 ± 4.4 mm Hg. This level of accuracy has been confirmed, when radial tonometric waveforms were calibrated invasively, but we are among the first to show that brachial waveforms, acquired with a regular blood pressure cuff, can be used as well. It should be pointed out that our results were obtained against gold-standard high-fidelity microtip catheters, thus avoiding potential problems associated with fluid-filled systems, particularly those related to zeroing and damping, and enabling us, because of the high frequency response, to record waveforms accurately.

Interestingly, our data show a better performance of the oscillometric sphygmomanometer, as compared with previous studies. In these studies, the inaccuracy of the oscillometric cuff method used for measuring brachial blood pressure limited the ability of the TF to predict cSBP, with mean differences between cSBP (invasive) and the noninvasive calibration (brachial MBP/DBP) of brachial waveforms.}

Figure 2. A, Scatterplot of invasively measured vs tonometry/transfer function–derived central systolic blood pressure (cSBP) with noninvasive calibration (brachial mean blood pressure [MBP]/diastolic blood pressure [DBP]) of radial waveforms. B, Bland-Altman plot of the same data. C, Scatterplot of invasively measured versus oscillometric/ARCSolver derived cSBP with noninvasive calibration (brachial MBP/DBP) of brachial waveforms. D, Bland-Altman plot of the same data.
number of measurements would also decrease the influence of single outlying values on the averages, and this is exactly what automated oscillometric blood pressure measuring devices are built for, for example, during ambulatory blood pressure monitoring.

When invasively measured aortic blood pressures and noninvasively measured brachial blood pressures (by the oscillometric technique) were compared, it has been almost uniformly shown that SBPs were underestimated and DBPs were overestimated with oscillometric measurements, and we could confirm the results in our present study. When these values are used for calibration of radial or brachial blood pressure curves, inaccuracies with respect to derived aortic SBP, DBP, and pulse pressure, as well as amplifications, inevitably will result. However, it has been suggested previously that MBPs can be estimated with greater accuracy with oscillometric cuffs. This may be because of the fact that MBP is directly measured with the oscillometric technique as the point of maximal oscillations of cuff pressure during gradual cuff deflation. We can confirm these results now with direct implications for calibration of radial or brachial pressure curves: calibration with brachial SBP/DBP resulted in a systematic underestimation of cSBP of \( \approx 10 \) mm Hg as compared with calibration with brachial MBP/DBP. Of note, the most widely used system for estimating cSBP (SphygmoCor) allows calibration with brachial DBP/SBP or brachial MBP/DBP up to the latest software version, which may be because of the fact that most available oscillometric sphygmomanometers do not display measured MBP.

With respect to the noninvasive study, our data prospectively confirm previously published findings regarding the accuracy of the ARCSolver TF. In that study, using a similar design (comparing cSBP by the SphygmoCor device with cSBP by ARCSolver formula using waveforms acquired with a dedicated brachial cuff), mean difference for cSBP was \( -0.1 \pm 3.1 \) mm Hg. The slightly higher SD in the recent study (4.7 mm Hg) may be caused by a different population (in the current trial, mainly patients and only few young and healthy controls were included), but still the Association for the Advancement of Medical Instrumentation limits are met. Again, calibration with MBP/DBP resulted in less scatter than calibration with SBP/DBP.

Our study has potential limitations. First, because of economic reasons, the number of patients investigated invasively was relatively small. Next, patients undergoing diagnostic coronary angiography are obviously selected with respect to clinical characteristics, particularly age and comorbidities. However, in general, waveforms are easier to record in younger, healthy, lean people; therefore, the selection of our patients may actually be a strength of the study. Moreover, the noninvasive study, together with the previous report, provides complimentary data in younger and healthier subsets of people. Finally, we did not provide data on waveform characteristics, although features of the aortic pressure wave may improve the relationship to cardiovascular disease and outcomes beyond the known inaccuracies of

### Table 2. Hemodynamics in the Noninvasive Study (n=111)

<table>
<thead>
<tr>
<th>Hemodynamic Variable</th>
<th>Absolute Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Oscillometric pressures</strong></td>
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<tr>
<td>bSBP, mm Hg</td>
<td>128.0 ± 17.2 (88–195)</td>
</tr>
<tr>
<td>bDBP, mm Hg</td>
<td>84.6 ± 9.7 (57–118)</td>
</tr>
<tr>
<td>MBP, mm Hg</td>
<td>104.4 ± 12.5 (75–152)</td>
</tr>
<tr>
<td>HR/min</td>
<td>66 ± 13 (45–107)</td>
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<td><strong>Calibration with bSBP and bDBP</strong></td>
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<tr>
<td>cSBP (osc/ARCSolver), mm Hg</td>
<td>118.5 ± 15.2 (81–183)</td>
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<tr>
<td>cDBP (osc/ARCSolver), mm Hg</td>
<td>86.1 ± 9.9 (59–120)</td>
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<tr>
<td>MBP (tonometry/TF), mm Hg</td>
<td>99.3 ± 12.4 (70–144)</td>
</tr>
<tr>
<td>HR (tonometry), /min</td>
<td>65 ± 12 (43–106)</td>
</tr>
<tr>
<td>cSBP (tonometry/TF), mm Hg</td>
<td>119.0 ± 16.9 (82–188)</td>
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<tr>
<td>cDBP (tonometry/TF), mm Hg</td>
<td>85.3 ± 9.9 (58–119)</td>
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<tr>
<td><strong>Calibration with MBP and bDBP</strong></td>
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<tr>
<td>cSBP (osc/ARCSolver), mm Hg</td>
<td>131.7 ± 19.1 (100–212)</td>
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<tr>
<td>cDBP (osc/ARCSolver), mm Hg</td>
<td>86 ± 10 (59–120)</td>
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<tr>
<td>cSBP (tonometry/TF), mm Hg</td>
<td>131.4 ± 19.9 (95–212)</td>
</tr>
<tr>
<td>cDBP (tonometry/TF), mm Hg</td>
<td>85 ± 10 (58–119)</td>
</tr>
</tbody>
</table>

Central blood pressures were derived from brachial pressure curves and ARCSolver formula (osc/ARCSolver) or from radial tonometry and transfer function (tonometry/TF). Values are mean ± SD (minimum-maximum). bSBP indicates brachial systolic blood pressure; cSBP, central systolic blood pressure; bDBP, brachial diastolic blood pressure; cDBP, central diastolic blood pressure; MBP, mean blood pressure; HR, heart rate; TF, transfer function.
Perspectives

We, for the first time, present invasive as well as noninvasive data that an estimation of cSBP by applying a transfer-function like algorithm to waveforms recorded by a regular cuff and calibrated with brachial MBP and DBP measured with a commercially available, validated automated oscillometric device may be possible with reasonable accuracy. If our findings can be confirmed, central blood pressures can be easily and operator-independently measured in routine daily practice. Moreover, because the sphygmomanometer used throughout the study is usually used for ambulatory automated blood pressure measurement, we are able to study 24-hour central blood pressure profiles (and their potential differences to brachial profiles) as well. Studies investigating the clinical value of 24-hour cSBP with respect to end-organ damage and clinical outcomes are now warranted.

Acknowledgments

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Disclosures

S.W. and C.C.M. are inventors of a patent that is partly used in ARCSolver.

References


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VALIDATION OF A BRACHIAL CUFF-BASED METHOD FOR
ESTIMATING CENTRAL SYSTOLIC BLOOD PRESSURE

Short title: Estimation of central systolic blood pressure

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Table S1: Baselines characteristics in the invasive study.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>30</td>
</tr>
<tr>
<td>Men</td>
<td>26 (87)</td>
</tr>
<tr>
<td>Age years</td>
<td>59 ± 11 (33-77)</td>
</tr>
<tr>
<td>Body height cm</td>
<td>174 ± 6 (165-190)</td>
</tr>
<tr>
<td>Body weight kg</td>
<td>85 ± 15 (61-128)</td>
</tr>
<tr>
<td>Body mass index kg/m²</td>
<td>28.1 ± 4.6 (20.6-42.3)</td>
</tr>
<tr>
<td>Hypertension</td>
<td>16 (53)</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>3 (10)</td>
</tr>
<tr>
<td>Smoking</td>
<td>10 (33)</td>
</tr>
<tr>
<td>Coronary artery disease</td>
<td>11 (37)</td>
</tr>
<tr>
<td>Heart failure</td>
<td>5 (17)</td>
</tr>
<tr>
<td>Pulmonary disease</td>
<td>8 (27)</td>
</tr>
<tr>
<td>Normal systolic function</td>
<td>26 (87)</td>
</tr>
<tr>
<td>Ejection fraction (ventriculography)</td>
<td>70 ± 13 (43-89)</td>
</tr>
<tr>
<td>ACE-I or ARB</td>
<td>8 (27)</td>
</tr>
<tr>
<td>Betablocker</td>
<td>9 (30)</td>
</tr>
<tr>
<td>CCB</td>
<td>2 (7)</td>
</tr>
<tr>
<td>Diuretics</td>
<td>2 (7)</td>
</tr>
<tr>
<td>Statin</td>
<td>12 (40)</td>
</tr>
</tbody>
</table>

Values are mean ± standard deviation (Min – Max) or numbers (percentages). ACE-I … angiotensin-converting enzyme inhibitor; ARB … angiotensin receptor blocker; CCB … calcium channel blocker
Table S2: Baseline characteristics in the non-invasive study.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total</th>
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<tbody>
<tr>
<td>n</td>
<td>111</td>
</tr>
<tr>
<td>Men</td>
<td>92 (83)</td>
</tr>
<tr>
<td>Age years</td>
<td>59 ± 11 (24-81)</td>
</tr>
<tr>
<td>Body height cm</td>
<td>173 ± 8 (150-191)</td>
</tr>
<tr>
<td>Body weight kg</td>
<td>83 ± 15 (52-145)</td>
</tr>
<tr>
<td>Hypertension</td>
<td>72 (65)</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>16 (14)</td>
</tr>
<tr>
<td>Coronary artery disease</td>
<td>48 (43)</td>
</tr>
<tr>
<td>Heart failure</td>
<td>18 (16)</td>
</tr>
<tr>
<td>Normal systolic function</td>
<td>90 (81)</td>
</tr>
<tr>
<td>Any antihypertensive medication</td>
<td>72 (65)</td>
</tr>
<tr>
<td>ACE-I or ARB</td>
<td>52 (47)</td>
</tr>
<tr>
<td>Betablocker</td>
<td>54 (49)</td>
</tr>
<tr>
<td>CCB</td>
<td>13 (12)</td>
</tr>
<tr>
<td>Diuretics</td>
<td>23 (21)</td>
</tr>
</tbody>
</table>

Values are mean ± standard deviation (Min – Max) or numbers (percentages). ACE-I … angiotensin-converting enzyme inhibitor; ARB … angiotensin receptor blocker; CCB … calcium channel blocker