Validation of Oscillometric Pulse Wave Analysis Measurements in Children

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BACKGROUND
Pulse wave analysis (PWA) has emerged as a noninvasive, valid, reliable, and widely used technique to investigate central blood pressures and systemic arterial wave reflection (augmentation index). The gold-standard technique is tonometry, but this technique can be challenging, especially when used on children. The purpose of this study was to validate oscillometric PWA for use in children.

METHODS
Fifty-seven healthy children were recruited for participation. Central blood pressures and peripheral augmentation index (pAIx) were measured objectively using oscillometric (Pulsecor R7) and tonometric (Sphygmacor) devices. All measurements were made during the same visit under standardized conditions between the hours of 8 AM and 10 AM in the fasted state.

RESULTS
Tonometric measurements were unsuccessful on 1 child. Comparisons were made on 56 children (mean age = 9.8 ± 1.0 y; 57% male). A very strong relationship was found between devices for central systolic (r = 0.94; P < 0.001), diastolic (r = 0.99; P < 0.001) and mean (r = 0.96; P < 0.001) blood pressures. However, Bland–Altman analysis indicated a bias toward greater systolic blood pressures with the oscillometric monitor (mean difference = 4.5 mm Hg; 95% confidence interval (CI) = –5.16 to –3.89). A good relationship was found for pAIx (r = 0.71; P < 0.001); the mean difference between devices was –1.70% (95% CI = –4.47% to 1.08%), which is not significantly different from zero.

CONCLUSIONS
Findings from this study suggest that oscillometric PWA provides valid measures of central blood pressure and arterial wave reflection in children aged 8–10 years.

Keywords: arterial stiffness; blood pressure; cardiovascular disease; central blood pressures; hypertension; pediatric; pulse wave analysis; validation.

doi:10.1093/ajh/hpt243

The pathological complications of atherosclerosis, namely myocardial infarction and strokes, remain the leading cause of mortality in the Western world.1 Although the clinical manifestations of cardiovascular disease (CVD) typically appear during middle-age, the atherosclerotic process has a long, asymptomatic phase of development that often initiates early in childhood, and this process is occurring at an increasingly younger age.2,3 This equates to a larger fraction of the population being burdened by chronic diseases for a greater number of years, placing a large financial burden on the individual and society as a whole.4 Although genetic factors may influence the susceptibility of developing CVD, there is a consensus that modifiable lifestyle changes, including physical inactivity, poor nutrition, poor sleep behavior, and obesity, have driven the current epidemic.5–7 Because these risk factors are modifiable, the current trend can be reversed, and public health-care policy can and should place a stronger focus on pediatric “preventive” medicine.3 Meeting this challenge requires the identification of valid, cost-effective, time-efficient, and simple-to-use techniques for profiling and monitoring CVD risk in clinical practice.

Pulse wave analysis (PWA) has emerged as a noninvasive, valid,8 and reliable9 technique to investigate mechanical properties of the arterial tree, including central blood pressures and systemic arterial wave reflection (augmentation index (AIX)). PWA has been widely used in epidemiological and interventional studies,10 and increased AIX has been shown to independently predict CVD risk and mortality.11,12 The gold-standard PWA technique is tonometry, but this technique can be time-consuming and challenging, especially when used on young children. Oscillometric devices are user-friendly, practical for use in the clinical setting, and suitable for use on a range of populations. The purpose of this study is to determine the validity of oscillometric PWA measurements in children by comparing oscillometric central blood pressures and peripheral AIX against the gold-standard tonometric device.

METHODS
Participants
Fifty-seven healthy children aged 8–10 years were recruited from 2 primary schools located in Wellington, New Zealand.

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Children were deemed eligible if they were asymptomatic of injury or illness, as determined by a standardized health screening questionnaire completed by a parent or guardian. Children were excluded if they were prescribed any cardiovascular medications. Parent or guardian consent and child assent were obtained before participation in accordance with the requirements of the Massey University Human Ethics Committee.

**Experimental design**

Participants were tested using previously reported standardized testing conditions. Briefly, all measurements were made by the same researcher during the same visit, between the hours of 8 am and 10 am. The participants reported for testing in the fasted state, having refrained from exercise for 24 hours. For each device, 2 measurements (with a 5-minute interval) were taken. If AIx varied by >4% or blood pressures varied by >5 mm Hg, a third recording was made and the 2 closest recordings were averaged.

**Anthropometric measurements**

Weight was assessed to the nearest 0.05 kg using an electronic scale (A&D Instruments, Adelaide, Australia), and height was measured to the nearest 0.1 cm with a stadiometer (Surgical and Medical Products, Seven Hills, Australia). Body mass index (kg/m²) was calculated using the assessed height and weight, and body fat percentage was measured using bioelectrical impedance analysis (InBody Biospace 230, Los Angeles, CA).

**Oscillometric PWA**

Oscillometric pressure waveforms were recorded using the R7 CardioScope (Pulsecor, Auckland, New Zealand), which measures brachial artery pressure waves on the upper arm. The Pulsecor R7 incorporates an oscillometric blood pressure module, which complies with the Association for the Advancement of Medical Instrumentation (AAMI SP10) requirements and receives an A/A rating from the British Hypertension Society evaluation protocol. Each measurement cycle (approximately 40 seconds) records brachial blood pressures and then one set of suprasystolic recordings for 10 seconds. The suprasystolic (approximately 30 mm Hg > systolic) pulse waveform is then used to determine central blood pressures and AIx. Briefly, suprasystolic pressure signals were recorded by a high-fidelity pressure transducer, and the central pressure waveform was derived in the time-domain from the relationship between the total oscillatory pressure in the aorta and the total oscillatory pressure under the occlusion cuff. This estimation was scaling independent (i.e., the estimated aortic wave shape did not depend on brachial blood pressure). AIx was calculated from the suprasystolic waveform using the formula: $\text{AIx} = \frac{P_3 - P_0}{P_1 - P_0}$, where $P_0$, $P_1$, and $P_3$ denote pressure values at time points $T_0$, $T_1$, and $T_3$ (Figure 1). This index describes the relative height of the reflected pressure wave when compared with the incident waveform. Only recordings with a high signal quality were accepted. Signal quality was assessed using the signal to noise (S/N) ratio (in decibels), where S/N values >3 dB were considered acceptable.

![Figure 1](http://ajh.oxfordjournals.org/)

Figure 1. Example peripheral and central waveforms from the Pulsecor R7. $T_0$ is time at the onset of the pulse; $T_1$ is peak of the incident wave; $T_2$ is trough between incident and reflected wave; $T_3$ is peak of the reflected wave; $T_4$ is time at the end of ejection; $T_F$ is time at the end of the pulse. $P_0$ is pressure at the onset of the pulse (diastolic); $P_1$ is peak pressure of the incident wave (systolic); $P_3$ is peak pressure of the reflective wave. For this example, AIx is 76.9%.
**Tonometric PWA**

Tonometric pressure waveforms were recorded on the radial artery with the SphygmoCor device (AtCor Medical, Sydney, Australia), as previously described. Pressure waveforms were recorded with a high-fidelity micromanometer (SPC-301; Millar Instruments, Houston, TX) from the wrist of the nondominant arm by applanation tonometry. Data were collected directly into a personal computer, and recordings were assessed visually to ensure that the best possible recording was obtained with minimization of movement-related artifacts. A corresponding aortic pressure waveform was generated using a validated transfer function from which central blood pressures (central diastolic blood pressure (cDBP), central systolic blood pressure (cSBP), central mean arterial pressure (cMBP), and AIx) were calculated using the integral software (SCOR Px 7.1; AtCor Medical, Sydney, Australia). Only high-quality readings, defined as a quality index >80%, were included in the analysis.

**Calibration of devices**

Central pressure waveforms from both devices were calibrated with the same brachial mean arterial pressure and diastolic blood pressure recorded by the oscillometric (Pulsecor R7) device. This method ensured a direct comparison of transfer functions to derive central blood pressures.

**Statistics**

Agreement between the 2 methods was assessed by measuring the Pearson product-moment correlation coefficient. In general, r values >0.75 are considered to indicate excellent agreement, and values of 0.40–0.74 are considered to indicate fair to good agreement. Bland–Altman analysis was used to provide an indication of systematic bias and random error. In a Bland–Altman plot, the differences between 2 measurements per patient are plotted against the means of 2 measurements per patient. If differences are associated with mean values, a correction has to be applied. The 95% confidence interval (CI) of the mean difference should include zero to exclude systematic differences. A Bland–Altman 95% limits of agreement analysis quantified the agreement (bias ± random error (1.96 × SD)) between devices for each parameter. In accordance with recommendations for conducting limits of agreement analysis, the data were checked for heteroscedastic error by conducting correlation analysis on the measurement error and the mean of the scores derived from both devices. Only changes greater than the limits of agreement can be interpreted as real change, not change due to measurement error. All data were analyzed using the Statistical Package for Social Sciences version 20.0 for Windows (SPSS, Chicago, IL). The critical α level was set at 0.05 for all analyses.

**RESULTS**

Data are reported for 56 of the 57 children because tonometric PWA assessments were unsuccessful on 1 child.

Table 1 summarizes the physical characteristics of the participants.

**Central systolic blood pressure**

Excellent agreement (r = 0.94; P < 0.001) was found for cSBP (Table 2 and Figure 2a). The mean difference between devices was −4.5 ± 2.4 mm Hg (95% CI = −5.16 to −3.89), which is significantly different from zero and indicates consistently higher values for the oscillometric device. Inspection of the Bland–Altman plot (Figure 2b) indicated systematic random error; correcting for the mean difference, the mean average for the oscillometric device changed from 90.9 ± 7.2 mm Hg to 86.4 ± 7.2 mm Hg, and the 95% CI for the mean difference became −0.63 to 0.63 mm Hg, which was not significantly different from zero. The Bland–Altman plot also indicated 1 unexplained outlier; removal of the outlier improved the strength of the correlation to r = 0.96.

**Central diastolic blood pressure**

Excellent agreement (r = 0.99; P < 0.001) was found for cDBP (Table 2). The mean difference between devices was 0.20 ± 1.0 mm Hg (95% CI = −0.05 to 0.45), which is not significantly different from zero. Inspection of the Bland–Altman plot (not shown) indicated no systematic error.

**Central mean arterial pressure**

Excellent agreement (r = 0.96; P < 0.001) was found for central mean arterial pressure (Table 2). The mean difference between devices was −2.5 ± 1.8 mm Hg (95% CI = −2.99 to −2.06), which is significantly different from zero and indicates consistently higher values for the oscillometric device. Inspection of the Bland–Altman plot (not shown) indicated systematic random error.

<table>
<thead>
<tr>
<th>Characteristic</th>
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<th>SD</th>
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<tr>
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</tr>
<tr>
<td>MBP, mm Hg</td>
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<tr>
<td>HR, beats/min</td>
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<td>8</td>
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</table>

Abbreviations: BMI, body mass index; DBP, diastolic blood pressure; HR, heart rate; MBP, mean blood pressure; SBP, systolic blood pressure.
Table 2. Comparison of tonometric and oscillometric outcomes

<table>
<thead>
<tr>
<th>Statistic</th>
<th>cDBP Tono Oscillo</th>
<th>cSBP Tono Oscillo</th>
<th>cMBP Tono Oscillo</th>
<th>pAIx Tono Oscillo</th>
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<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Abbreviations: cDBP, central diastolic blood pressure; cSBP, central systolic blood pressure; Oscillo, oscillometric device; pAIx, peripheral augmentation index; Tono, tonometric device.

Augmentation index

Good agreement ($r = 0.71; P < 0.001$) was found between devices for AIx (Table 2 and Figure 3a). The mean difference between devices was $-1.7\% \pm 10.7\%$ (95% CI = $-4.47$ to $1.08$), which is not significantly different from zero. Inspection of the Bland–Altman plot (Figure 3b) indicated no systematic random error.

DISCUSSION

There remains a pressing need to identify practical tools for monitoring CVD risk in children; a relatively operator-independent PWA method would be a useful advancement. The gold-standard PWA technique is radial artery tonometry, but this technique can be time consuming and challenging, especially when used on young children. Our study found excellent agreement for central blood pressures derived from tonometric and oscillometric devices and good agreement for AIx.

There was very strong agreement for central blood pressure estimates made by the 2 devices, suggesting that the transfer function used by the oscillometric device is at least as accurate as the tonometric device. The mean difference between devices for cDBP was negligible. However, Bland–Altman analysis indicated a bias toward greater cSBPs with the oscillometric monitor (mean difference = 4.5±2.4 mm Hg). This finding is consistent with previous studies reporting a positive mean bias (1.3–3.6 mm Hg) for the oscillometric device. It is also consistent with the finding that the advocated SphygmoCor procedure (i.e., using brachial artery pressures to calibrate the radial-to-aortic transfer function) results in underestimation of central pulse pressure by 3.1–5.7 mm Hg. Collectively, the mean difference reported between devices for the previous studies and this study is within the American Association for the Advancement of Medical Instruments (AAMI) standards (<5 mm Hg; SD < 8 mm HG). Furthermore, the oscillometric device would obtain an A grade rating according to the British Hypertension Society classification for blood pressure devices.

Excellent agreement ($r = 0.93–0.97$) has been found between PusleCor and aortic catheter assessments of cSBP, with a reported mean difference between 0.0 and 1.0 mm Hg ($r = 0.93–0.95$). Similarly, Pauca et al. reported excellent agreement between SphygmoCor and aortic catheter-based cSBP assessments (0.0±4.4 mm Hg). A subsequent study reported underestimation, albeit nonsignificantly, of cSBP by the tonometric device compared with catheter-derived values (144±29 vs. 148±30 mm Hg). More recently, Ding et al. similarly reported lower cSBP values derived from the tonometric device compared with a catheter (123±20 mm Hg vs. 138±22 mm Hg; $P < 0.001; r = 0.91$). Based on findings from our study, we are unable to conclusively state whether the oscillometric device overestimates or the tonometric device underestimates cSBP in children.

There was a good correlation between devices for peripheral AIx assessments, although not as strong as observed for central blood pressures. The mean difference between devices was small (−1.7% ± 10.7%), although Bland–Altman analysis revealed wide limits of agreement (−22.7% to 19.3%). This dis-sipation may be explained by the difference in measurement sites. Although blood pressure is similar in brachial and radial arteries, the radial artery is a smaller, stiffer artery with different functional and structural characteristics; it has long been known that the brachial artery exhibits greater extensibility and slower pulse wave velocity (i.e., lower intrinsic arterial stiffness). However, contrary to this argument, and consistent with recent findings by Gunjaca et al., slightly lower AIx values were derived from the radial artery with the tonometric device (48.6% vs. 50.3%). The tonometric device records the pressure waveform from the radial artery at the level of the wrist; the proximity to the peripheral reflection site in the hand and effect of reflections from the radial–ulnar branch may result in an additive effect from the reflected wave occurring immediately at the impact of the forward wave. Conversely, the suprasystolic oscillometric device records the pressure wave on the middle of the occluded brachial artery, directly above the cuff reflection site. The difference in reflection sites may explain the slightly lower AIx values derived from the tonometric device. Collectively, these arguments suggest that radial artery AIx and brachial artery AIx may confer different information. Although previous studies have demonstrated radial artery–derived AIx and brachial artery–derived AIx to be related to CVD risk factors in adults, to the best of our knowledge no previous comparative study has determined which parameter best predicts CVD risk and mortality.

Limited data exist exploring the use of AIx with children. Using the SphygmoCor device, previous studies have
demonstrated central Alx to be significantly increased in children who were born with low birth weight,31 in children on hemodialysis,32 and in children with type 1 diabetes mellitus.33 Furthermore, nonsignificant differences have been reported for obese compared with normal-weight children31,34 and for hypertensive compared with normotensive children.31 To the best of our knowledge, only 1 study35 has used the Pulsecor R7 device on children, similarly reporting no effect of obesity on peripheral Alx and a positive effect of Mediterranean diet adherence. Further investigation is warranted to determine the value of Alx in monitoring CVD risk in children, including comparisons against well-established techniques such as pulse wave velocity and flow-mediated dilation.

Several studies have reported that directly measured central blood pressure indices as well as noninvasively estimated central blood pressure indices (e.g., central pulse pressure and Alx) may predict the onset of diabetes, cardiovascular

Figure 2. Correlation and Bland–Altman plots for tonometric and oscillometric central systolic blood pressures (cSBP). (a) Correlation between cSBP measured with tonometric and oscillometric devices. Line of best fit (dashed line) and perfect agreement (solid line) are shown. (b) Bland–Altman plot. The mean difference (solid line) and limits of agreement (dashed lines) are shown. Abbreviations: LCI, lower confidence interval; UCI, upper confidence interval.
events, and all-cause mortality independent of peripheral (brachial) blood pressure measures.\textsuperscript{16,16} The prognostic value of central blood pressures has been recognized by expert consensus,\textsuperscript{17} however, conventional brachial blood pressures remain the standard method used in clinical practice. The status quo can be explained by the difficulties associated with the gold-standard technique, i.e., radial artery tonometry. Although this technique is well validated,\textsuperscript{8} highly reliable,\textsuperscript{9} and widely used in the research setting,\textsuperscript{10} tonometry is potentially operator dependent as well as time-consuming and challenging, especially when used on young children. The oscillometric device used in our study is simple and quick (approximately 1 minute per recording) to use, is well tolerated, and worked on every child. On a number of children, particularly children with smaller radial arteries or overweight children, the radial artery was difficult to locate and obtain a high-quality pressure waveform. Furthermore, the recording of a quality waveform with tonometry requires

- **Figure 3.** Correlation and Bland–Altman plots for tonometric and oscillometric augmentation index (AIx). (a) Correlation between augmentation index (AIx) measured with tonometric and oscillometric devices. Line of best fit (dashed line) and perfect agreement (solid line) are shown. (b) Bland–Altman plot. The mean difference (solid line) and limits of agreement (dashed line) are shown. Abbreviations: LCI, lower confidence interval; UCI, upper confidence interval.
that the child remain completely still, which can be difficult for a young child. With some children, tonometric pressure waveforms were quick to collect, whereas with other children it was a lengthy process. Although PWA has been widely used with adult populations, a limited number of studies have used this methodology on children. Further research is warranted to generate pediatric-centric reference values and to relate central blood pressures and AIx to CVD risk and target organ damage in children.

This study used a noninvasive method (tonometry) as the reference for comparison with the oscillometric device, limiting the comparison to transfer functions used by the 2 devices. Although the transfer function used by the tonometric device appears to be well validated, this function has been criticized, including with respect to the estimation of central AIx. Furthermore, validation studies for either the tonometric or oscillometric devices have not been performed in children. Future studies should validate oscillometric and tonometric assessments against pressure waveforms directly derived from the aorta.

This study compared AIx values calculated from peripheral, not central, pressure waveforms. Although there was a very strong relationship for peripheral AIx and central AIx values derived from the tonometric device, the peripheral AIx values derived from the 2 devices may not be interchangeable. The tonometric device estimates both peripheral and central AIx, whereas the oscillometric device only estimates AIx directly from the brachial pressure waveform. The rationale for this decision by Pulsecor R7 is twofold: (i) this procedure minimizes the risk of error being introduced by the generalized transfer function, and (ii) AIx measured on the brachial artery closely correlates with invasively measured aortic AIx. Further investigation is required to determine the respective value of each parameter (radial AIx, brachial AIx, and central AIx) in predicting CVD risk in children and adults.

Findings from this study suggest that oscillometric PWA measurements may be suitable for monitoring CVD risk in pediatric populations. In particular, the oscillometric device appears to be at least as accurate as the gold-standard tonometric device for estimating central blood pressures. The cuff-based device is quick and easy to use, well tolerated by children, and suitable for use in clinical practice. Further studies are warranted that (i) compare PWA assessments in children to well-established techniques, including pulse wave velocity and flow-mediated dilation, and (ii) determine the respective value of brachial AIx vs. central AIx recordings.

DISCLOSURE

The authors declared no conflict of interest.

REFERENCES


American Journal of Hypertension


