Oscillometric estimation of aortic pulse wave velocity: comparison with intra-aortic catheter measurements

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Objectives **Recently, a novel method to estimate aortic pulse wave velocity (aPWV) noninvasively from an oscillometric single brachial cuff waveform reading has been introduced. We investigated whether this new approach provides acceptable estimates of aPWV compared with intra-aortic catheter measurements.**

Methods **Estimated values of aPWV obtained from brachial cuff readings were compared with those obtained using an intra-aortic catheter in 120 patients (mean age 61.8±10.8 years) suspected for coronary artery disease undergoing cardiac catheterization. Differences between aPWV values obtained from the test device and those obtained from catheter measurements were estimated using Bland–Altman analysis.**

Results **The mean difference±SD between brachial cuff-derived values and intra-aortic values was 0.43±1.24 m/s. Comparison of aPWV measured by the two methods showed a significant linear correlation (Pearson's $R=0.81$, $P<0.0001$). The mean difference for repeated oscillometric measurements of aPWV was 0.05 m/s, with 95% confidence interval limits from −0.47 to 0.57 m/s.**

Conclusion **aPWV can be obtained using an oscillometric device with brachial cuffs with acceptable accuracy compared with intra-aortic readings. *Blood Press Monit* 00:000–000 © 2013 Wolters Kluwer Health | Lippincott Williams & Wilkins.**

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Background

In the last decade, there has been increasing evidence that surrogates related to arterial function such as aortic systolic blood pressure or aortic pulse wave velocity (aPWV) may be better predictors of adverse cardiovascular events than brachial blood pressure alone [1,2]. However, in daily clinical practice, these surrogates are not in common use. One reason may be that current measurement devices have serious limitations in terms of time consumption and operator requirements. To overcome these shortcomings, we recently developed the ARCSolver method, which provides brachial cuff-based measurement features for arterial stiffness surrogates [3–5]. Several groups have validated the central pressure and wave reflection features of the ARCSolver algorithm invasively and noninvasively with respect to accuracy [6–8], reproducibility, and feasibility [8–11]. With a focus on aPWV, Luzardo *et al.* [8] recently reported a successful comparison between carotid-femoral PWV measured using tonometry and aPWV estimated using our novel oscillometric method. A comparison with invasive aPWV measurements has not been reported as yet. Therefore, the aim of this work is to compare aPWV measured invasively using an intra-aortic catheter with aPWV estimated noninvasively using the novel oscillometric method.

Materials and methods

We carried out our study on 120 patients undergoing elective cardiac catheterization for suspected coronary artery disease; 22 patients were 50 years of age or younger and 29 patients were 70 years of age or older. Exclusion criteria were unstable clinical conditions, arrhythmias that would disturb the regular rhythm required during pulse recordings, and significant ($\geq 2+$) valvular heart disease. All participants were recruited at the Paracelsus Medical University Teaching Hospital of Wels-Grieskirchen in Wels and provided written informed consent. The study was part of an ongoing project, investigating determinants of aPWV, which has been approved by the regional ethics committee.

aPWV was measured invasively after diagnostic cardiac catheterization using fluid-filled standard (6 Fr) pigtail catheters according to the procedure reported previously by Weber *et al.* [12]. The position of the catheter was verified by fluoroscopy; the catheter was positioned in the ascending aorta and at the level of aortic bifurcation. The catheter was marked at those two sites, and after the removal of the catheter, the travel distance could be measured. Along with the high-speed pressure wave registration, the electrocardiogram was also recorded digitally (1 kHz) and as a high-speed (200 mm/s) readout.

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The time difference between the footpoints of the pressure waves at the two recording sites was measured by ECG gating. The footpoint of the pressure wave was identified manually using the method of intersecting tangents. The interobserver variability in the manual measurements in our laboratory is adequate, as reported previously [13]. In addition, the manual measurements in our laboratory compare favorably with computerized techniques [12].

The noninvasive assessment of estimated aPWV was performed in a quiet, temperature-controlled examination room at the Cardiology Unit, usually the day before or after cardiac catheterization. Two measurements were taken with a 2-min break between them. The procedure was performed with the patient in a supine position and using an adequately sized cuff. To account for the possible influence of different cardiovascular conditions between the sessions, special emphasis was placed on determinates of PWV such as mean arterial pressure or heart rate. The Mobil-O-Graph 24 h PWA ABPM device (IEM, Stolberg, Germany) [14–16] with inbuilt ARCSolver (Austrian Institute of Technology, Vienna, Austria) algorithms was used to obtain conventional blood pressure readings such as brachial systolic and diastolic pressures. In the second step, the brachial cuff is inflated to the diastolic blood pressure level and held for about 10 s to record the pulse waves. Subsequently, central pressure curves obtained through a transfer function from the peripheral reading are plotted. To estimate aPWV, the ARCSolver method utilizes several parameters from pulse wave analysis and wave separation analysis combined in a proprietary mathematical model, whereby the major determinants are age [17], central pressure, and aortic characteristic impedance [18,19], but not timings of brachial supra systolic wave reflections [20].

If not stated otherwise, in the statistical analysis results are expressed as mean ± SD. Data from the comparisons were analyzed using the method of Bland–Altman [21]. The correlation between variables was calculated using Pearson's correlation coefficient. To analyze determinants of differences between estimated and invasive measurements, regression analysis was used. Analyses were carried out using MedCalc 11.5 (MedCalc software, Mariakerke, Belgium).

Results

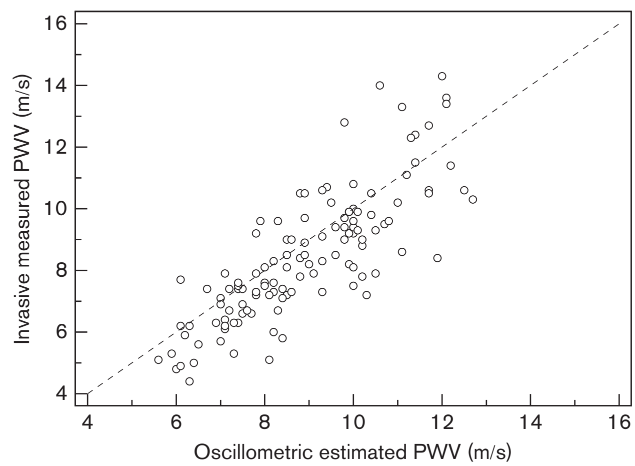
The baseline characteristics for the study group are presented in Table 1.

Table 1 Basic clinical data for the patient group

Parameters	Total or mean value	SD
Patients	120	
Men/women	109/11	
Age (years)	62	11
Height (cm)	174	9
Weight (kg)	85	14
SBP brachial (mmHg)	134	18
DBP brachial (mmHg)	82	11

DBP, diastolic blood pressure; SBP, systolic blood pressure.

Fig. 1



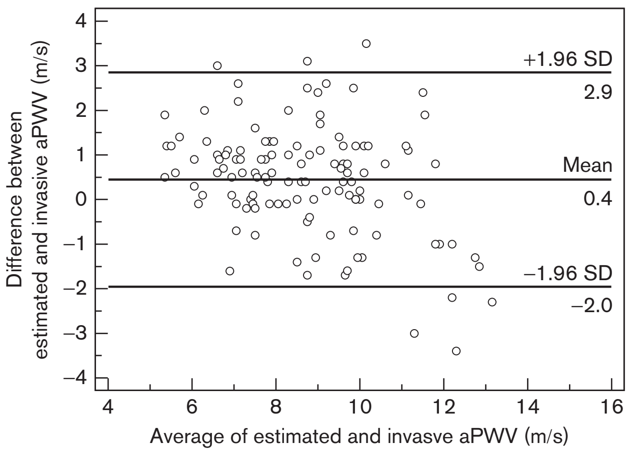
Scatter plot with line of equality comparing noninvasively estimated and invasively measured aPWV. aPWV, aortic pulse wave velocity.

The values of invasively measured aPWV and estimated aPWV (first measurement) were 8.47 ± 2.11 and 8.92 ± 1.70 m/s, respectively. We observed a close correlation ($R = 0.81$, $P < 0.0001$), with a 95% confidence interval from 0.74 to 0.86. Figure 1 shows a scatter plot including the line of equality. The mean difference from a pairwise comparison between readings of the two methods is 0.43 m/s with an SD of 1.24 m/s. Figure 2 shows the corresponding Bland–Altman plot. Linear regression analysis of method differences against age and systolic blood pressure always showed a nonsignificant relationship ($R^2 = 0.00249$, $P = 0.588$ and $R^2 = 0.00235$, $P = 0.577$, respectively). To provide an estimate on the intrarater reproducibility for aPWV by the oscillometric method, repeated measurements were performed. Using Bland–Altman analysis (Fig. 3), the mean difference in repeated measurements was 0.05 m/s, with 95% limits of agreement from −0.47 to 0.57 m/s. The coefficient of variation was 2.14%.

Discussion

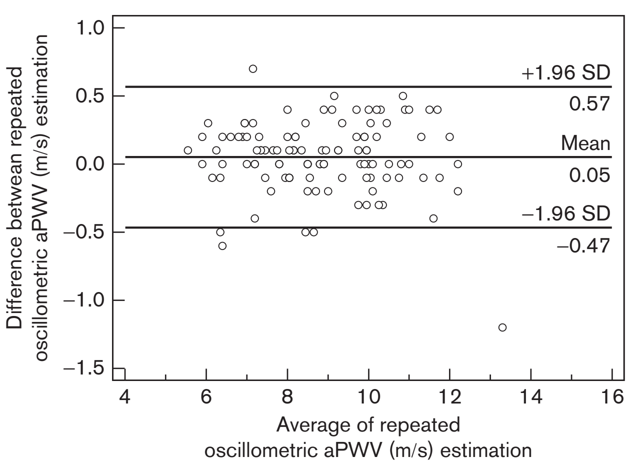
Although the measurement of aPWV is not currently part of the daily clinical routine, its assessment has been recommended by the actual ESH-ESC guidelines on the management of arterial hypertension [22]. A simplified method for estimating aPWV would therefore allow introduction of this technique into primary and secondary levels of care. Reproducibility is therefore an essential requirement. The presented data on repeated measurements may be classified as excellent according to the ARTERY guidelines [23]. Our comparison presented here

Fig. 2



Bland–Altman plot comparing noninvasively estimated and invasively measured aPWV. aPWV, aortic pulse wave velocity.

Fig. 3



Bland–Altman plot of repeated estimations of aPWV. aPWV, aortic pulse wave velocity.

shows that aPWV estimated from a brachial cuff waveform yields values similar to those obtained from intra-aortic catheter measurement with a mean difference and SD that is in line with that obtained in comparable studies [8,24]. According to previously published recommendations for the validation of noninvasive devices for PWV measurements [23], this is consistent with excellent (mean difference < 0.5 m/s) to acceptable (SD < 1.5 m/s) accuracy. Although the mean values of differences slightly differ from zero, the correlation between estimated and intra-aortic PWVs is close. Therefore, the observed shift in the mean difference may be explained by the fact that the measurements could only be taken in a consecutive order, and we observed a significantly lower average mean arterial pressure of 8 mmHg and an increased average heart rate of about 4 beats/min during angiography compared with noninvasive assessment (data not shown) [17]. Further, Bland–Altman plots indicate an overestimation of lower values of estimated aPWV and vice versa. As shown here and typically for these kinds of comparisons, scatter increases with absolute values, although no significant trend in differences is observed. This also holds true with respect to age and blood pressure, the major determinants of PWV [17]. A limitation of invasive trials is always the available study cohort with respect to the distribution of age, sex, health status, etc. This of course also applies to this comparison and should always be kept in mind.

Conclusion

The oscillometric estimation of aPWV using a cuff is acceptable compared with intra-aortic measurements in this cohort.

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Conflicts of interest

S.W. and C.M. are owners of a patent that is partly used in the ARCSolver method. For the remaining authors, there are no conflicts of interest.

References

1 Agabiti-Rosei E, Mancia G, O'Rourke MF, Roman MJ, Safar ME, Smulyan H, *et al.* Central blood pressure measurements and antihypertensive therapy: a consensus document. *Hypertension* 2007; **50**:154–160.
2 Laurent S, Cockcroft J, Bortel LV, Boutouyrie P, Giannattasio C, Hayoz D, *et al.* European Network for Non-invasive Investigation of Large Arteries. Expert consensus document on arterial stiffness: methodological issues and clinical applications. *Eur Heart J* 2006; **27**:2588–2605.
3 Wassertheurer S, Mayer C, Breitenecker F. Modeling arterial and left ventricular coupling for non-invasive measurements. *Simulat Model Pract Theor* 2008; **16**:988–997.
4 Wassertheurer S, Kropf J, Weber T, vdGiet M, Baulmann J, Ammer M, *et al.* A new oscillometric method for pulse wave analysis: comparison with a common tonometric method. *J Hum Hypertens* 2010; **24**:498–504.
5 Weber T, Wassertheurer S, Rammer M, Haiden A, Hametner B, Eber B. Wave reflections, assessed with a novel method for pulse wave separation, are associated with end-organ damage and clinical outcomes. *Hypertension* 2012; **60**:534–541.
6 Weber T, Wassertheurer S, Rammer M, Maurer E, Hametner B, Mayer CC, *et al.* Validation of a brachial cuff-based method for estimating central systolic blood pressure. *Hypertension* 2011; **58**:825–832.
7 Weiss W, Gohlisch C, Harsch-Gladisch C, Tölle M, Zidek W, van der Giet M. Oscillometric estimation of central blood pressure: validation of the Mobil-O-Graph in comparison with the SphygmoCor device. *Blood Press Monit* 2012; **17**:128–131.
8 Luzardo L, Lujambio I, Sottolano M, da Rosa A, Thijs L, Noboa O, *et al.* 24-h ambulatory recording of aortic pulse wave velocity and central systolic augmentation: a feasibility study. *Hypertens Res* 2012; **35**:980–987.
9 Protogerou AD, Argyris A, Nasothimiou E, Vrachatis D, Papaioannou TG, Tzamouranis D, *et al.* Feasibility and reproducibility of noninvasive 24-h ambulatory aortic blood pressure monitoring with a brachial cuff-based oscillometric device. *Am J Hypertens* 2012; **25**:876–882.

10 Nunan D, Wassertheurer S, Lasserson D, Hametner B, Fleming S, Ward A, Heneghan C. Assessment of central haemomodynamics from a brachial cuff in a community setting. *BMC Cardiovasc Disord* 2012; **12**:48.

11 Reppel M, Franzen K, Bode F, Weil J, Kurowski V, Schneider SA, *et al*. Central hemodynamics and arterial stiffness during the finals of the world cup soccer championship 2010. *Int J Cardiol* 2011. doi: 10.1016/j.ijcard.2011.11.096 [Epub ahead of print].

12 Weber T, Ammer M, Rammer M, Adji A, O'Rourke MF, Wassertheurer S, *et al*. Noninvasive determination of carotid-femoral pulse wave velocity depends critically on assessment of travel distance: a comparison with invasive measurement. *J Hypertens* 2009; **27**:1624–1630.

13 Weber T, Maas R, Auer J, Lamm G, Lassnig E, Rammer M, *et al*. Arterial wave reflections and determinants of endothelial function a hypothesis based on peripheral mode of action. *Am J Hypertens* 2007; **20**:256–262.

14 Jones CR, Taylor K, Chowienzyk P, Poston L, Shennan A. A validation of the Mobil-O-Graph (version 12) ambulatory blood pressure monitor. *Blood Press Monit* 2000; **5**:23–28.

15 Weiss W, Tölle M, Zidek W, van der Giet M. Validation of the Mobil-O-Graph 24 h blood pressure measurement device. *Blood Press Monit* 2010; **15**:225–228.

16 Franssen PML, Imholz BPM. Evaluation of the Mobil-O-Graph new generation ABPM device using the ESH criteria. *Blood Press Monit* 2010; **15**:229–231.

17 Mattace-Raso F, Hofman A, Verwoert GC, Wittemana JC, Wilkinson I, Cockcroft J, *et al*. Determinants of pulse wave velocity in healthy people and in the presence of cardiovascular risk factors: 'establishing normal and reference values'. *Eur Heart J* 2010; **31**:2338–2350.

18 Chirinos JA, Segers P. Noninvasive evaluation of left ventricular afterload. Part 1: pressure and flow measurements and basic principles of wave conduction and reflection. *Hypertension* 2010; **56**:555–562.

19 Hametner B, Wassertheurer S, Kropf J, Mayer C, Holzinger A, Eber B, Weber T. Wave reflection quantification based on pressure waveforms alone – methods, comparison, and clinical covariates. *Computer Methods Programs Biomed* 2013; **109**:250–259.

20 Baulmann J, Schillings U, Rickert S, Uen S, Düsing R, Illyes M, *et al*. A new oscillometric method for assessment of arterial stiffness: comparison with tonometric and piezo-electronic methods. *J Hypertens* 2008; **26**:523–528.

21 Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986; **327**:307–310.

22 Mancia G, De Backer G, Dominiczak A, Cifkova R, Fagard R, Germano G, *et al*. 2007 Guidelines for the management of arterial hypertension: The Task Force for the Management of Arterial Hypertension of the European Society of Hypertension (ESH) and of the European Society of Cardiology (ESC). *Eur Heart J* 2007; **28**:1462–1536.

23 Wilkinson IB, McEniery CM, Schillaci G, Boutouyrie P, Segers P, Donald A, Chowienczyk PJ. On behalf of the ARTERY Society. ARTERY Society guidelines for validation of non-invasive haemodynamic measurement devices: Part 1, arterial pulse wave velocity. *Artery Res* 2010; **4**:34–40.

24 Hickson SS, Butlin M, Graves M, Taviani V, Avolio AP, McEniery CM, *et al*. The relationship of age with regional aortic stiffness and diameter. *JACC Cardiovasc Imaging* 2010; **3**:1247–1255.