Clinical Utility of Aortic Pulses and Pressures Calculated From Applanated Radial-Artery Pulses

Harold Smulyan, Danish S. Siddiqui, Raymond J. Carlson, Gerard M. London, Michel E. Safar

Abstract—Brachial artery cuff blood pressures are but approximations of central aortic pressures. The actual pressures against which the left ventricle must pump would be useful clinical information if obtained noninvasively. Our aim was to determine the clinical utility of aortic pulses and pressures calculated from noninvasively obtained radial-artery pulses. Radial-arterial pulses were recorded by applanation and calibrated with arm/cuff oscillometric pressures. Aortic pulses and pressures were calculated from the radial pulses by Fourier analysis and transfer functions. These calculated aortic pulses were compared with directly recorded aortic pulses by a transducer-tip catheter in a series of 50 patients undergoing cardiac catheterization. The correlation coefficient (r) of the measured versus the calculated aortic systolic blood pressure was +0.89, but the scatter was large (standard deviation of the differences = ±11.3 mm Hg). The pulse pressure correlations were less good (r = +0.79) and also had a large scatter (±13.6 mm Hg). The average calculated pulse pressure was 11.5 mm Hg lower than the measured value because the cuff diastolic blood pressures, used to calibrate the radial pulses, were systematically higher than those in the aorta (8.9 mm Hg). Multivariable analysis incorporating height, age, heart rate, and ejection fraction as additional, independent variables eliminated mean differences between the new “predicted” and measured pressures, significantly improved correlation coefficients, and reduced the scatter. However, the improvements were small. The inaccuracy of the oscillometric cuff method for measuring arm blood pressure appears to be the limiting factor in the prediction of clinically useful, noninvasive aortic pressures. (Hypertension. 2003;42:150-155.)

Key Words: aorta ■ arterial pressure ■ Fourier analysis ■ blood pressure determination

The cuff technique for the measurement of brachial-artery (BA) pressure has been of inestimable benefit in the diagnosis and treatment of multiple diseases. It is well known, however, that BA pressure is not the same as and is often an inaccurate estimate of central aortic pressure. The difference between the 2 pressures is difficult to predict because it is influenced by many factors, such as body height, age, heart rate, stroke volume, ejection time, and the distensibility of the conduit arterial tree. An accurate, noninvasive method to measure aortic pressures would be an important clinical advance. It would permit better estimates of cardiac work, better diagnoses of hypertension, and the response to antihypertensive treatment; improve the correction of hemodynamic abnormalities in hypotensive states; and offer better assessments of thepressor responses to exercise stress, during which arm pressures are known to be falsely elevated.1

Aortic pressures can now only be measured accurately by invasive catheterization, a method unsuitable for widespread clinical use. O’Rourke and colleagues2–5 have proposed a solution involving transformation of the applanated and calibrated radial-artery pulse trace to the aortic pulse trace by Fourier analysis and transfer functions. These and subsequent studies have validated the technique by calibrating radial pulses with directly recorded, intra-arterial radial or brachial pressures.6–8 The aim of the present study then was to evaluate the accuracy of aortic pressures, calculated from applanated radial-arterial pulses, by comparing them to directly recorded aortic pressures. These noninvasive radial pulses were calibrated by using routine, oscillometric measurements of BA pressures.

Methods

Fifty patients undergoing routine coronary angiography were studied. There were 25 men and 25 women, with a mean ±SD age of 54 ± 13 years and an age range of 33 to 82 years. Their average height and weight were 169 ± 11.5 cm and 88.7 ± 18.5 kg, respectively. The indications for angiography were to confirm the suspicion of coronary heart disease or to reassess its severity. Candidates for the study were excluded if they had any arrhythmias that would disturb the regular rhythm required during pulse recordings, such as frequent atrial or ventricular premature beats or atrial fibrillation. Also excluded were patients with significant valvular heart disease (greater than 2+ regurgitation or more than minimal aortic stenosis) or any constitutional illnesses, as detected by routine history, physical examination, or laboratory study. The results of the catheterizations showed that 21 patients had normal coronary arteries or insignificant coronary artery disease; 2 patients had dilated cardiomyopathy with normal coronary arteries, and the remaining patients had coronary artery disease of varying severity. The study and its purpose were described to each patient, each of whom signed a witnessed consent form. The study protocol was approved by the...
institutional review board for the protection of human subjects of this institution.

A 6F micromanometer-tipped catheter (model SPC 350, Millar Instruments) was adjusted to baseline, calibrated under saline at the catheterization table top, and then inserted through a femoral sheath into the descending aorta under fluoroscopic control. When possible, the catheter was advanced (25 patients) into the ascending aorta, where pressures were recorded, and the catheter was then withdrawn into the proximal descending aorta. Here, systolic (SBP), diastolic (DBP), and mean (MBP) blood pressures were recorded and averaged over several respiratory cycles. MBP was obtained by electronic damping. The frequency-amplitude performance of the catheterization laboratory amplifiers was tested by using both electrical and pressure sine-wave generators. At 7.5 and 10.0 Hz, there was 12% and 20% loss of amplitude, respectively, with a 30% amplitude loss (–3 dB) at 14 Hz. The pressure amplifiers were therefore unsuitable for accurate measurement of augmentation index and ejection times. The mean ± SD heart rate for the group was 68 ± 12.2 beats per minute. Ejection fraction (EF) data were available for 38 of the 50 patients by contrast ventriculography at the time of catheterization, by echocardiography, or by radionuclide blood-pool scanning shortly before or after catheterization.

During the direct recording of descending aortic pressure, the left radial-arterial pulse traces were obtained by applanation with a probe (model SPT 301, Millar Instruments). All radial pulses were recorded by the same investigator (H.S.). The mean ± SD height of the applanated pulses was 159.5 ± 56.3 mV. The average variability of the radial pulses in systole (average of the differences between each systolic height and the mean systolic height relative to the mean systolic height) was 5.14 ± 2.6%, and in diastole (average of the differences between each diastolic height and the mean diastolic height relative to the mean diastolic height), it was 5.36 ± 3.1%. Thus, in approximately one half of the studies, the variability in systole and diastole was >5%.

The output of the applanation probe was inspected on screen, and when satisfactory stable pulses were observed, 10 seconds of data were fed into the Sphygmocor system (PWV Medical). The radial pulses were calibrated by using the SBPs and DBPs of an oscillometric BA cuff system (Colin Medical Instruments Corp) measured immediately after the radial pulses in the same arm were recorded. MBP was calculated from the radial-artery pulses by integration. The oscillometric blood pressure system was itself calibrated by using a calibration unit (Cuff Link, DNI Nevada Inc).

Correlation coefficients between the various measured and calculated parameters were obtained by univariate regression. Multivariable regression was used to detect the influence of nonpressure pulse factors that might improve the prediction of direct aortic values from the calculated ones.

In a small substudy, the oscillometric cuff pressure technique was compared with the more traditional auscultatory method by using a mercury-calibrated aneroid manometer and phases I and V of the Korotkoff sounds. This comparison was carried out with single sequential oscillometric and auscultatory blood pressure measurements in the left arm of 50 similarly selected patients.

### Results

#### Univariate Analyses

The raw data for SBP, DBP, and pulse pressure (PP) for the measured and calculated values as well as those from the cuff are shown in Table 1. “Measured” values were those obtained from the directly recorded aortic pulses, and “calculated” values were those obtained from the output of the Sphygmocor device. Also displayed are the average differences between the cuff, measured, and calculated values and their SDs.

With regard to SBP, the average difference between the Millar SBP and the cuff SBP was, as expected, wide (137.2 vs 148.1 mm Hg), and the SD of the differences was large (12.7 mm Hg). By contrast, the average measured and calculated values for SBP were quite close (137.2 vs 135.7 mm Hg), but the SD of the differences was approximately the same. The “predicted” values in Table 1 are those obtained from multiple regression (vide infra). Figure 1A is a

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Figure 1. A, Scatterplot of measured versus calculated SBP and the estimating equation. B, Bland-Altman plot of the same data. Mean difference = +1.5 mm Hg (– – –); SD = ± 11.13 mm Hg (– – –).
plot of the measured versus calculated SBP and shows a slope that is close to 1.0, an intercept close to zero, and a correlation coefficient ($r$) of 0.89. Figure 1B is a Bland-Altman plot of the same data showing the measured—calculated differences versus the directly measured values. The average difference between measured and calculated DBPs shown in Table 1 was large (74.4 vs 84.8 mm Hg) because of overestimation of DBP by the cuff (83.3 mm Hg). The scatter of both calculated and cuff DBP differences was also large. The plot of the measured versus calculated DBP values is shown in Figure 2A. Here, the slope and intercept are distant from 1.0 and zero, respectively, and the $r$ value was only +0.59. Figure 2B displays the measured—calculated DBP differences versus the measured DBP values in a Bland-Altman plot. The overestimation of aortic DBP by the Sphygmocor device accounts for the underestimation of its PP by approximately the same amount (11.5 mm Hg). Figure 3A illustrates the measured versus calculated PP data with some improvement in the slope and intercept when compared with the DBP plot, but the SD of the PP differences remained high (13.6 mm Hg). Figure 3B is the corresponding Bland-Altman plot. The upward slope of this plot is due to progressive overestimation by the cuff DBP at higher values (Fig 2A). As shown in Table 1, the average cuff SBP was higher than the measured SBP, but the slope of the relation was near 1.0 (data not shown).

As expected, comparisons of ascending and descending aortic SBP, DBP, and PP values were quite close, with $r$ values of +0.97, +0.92, and +0.98, respectively. All of the univariate analyses were repeated for men and women separately, and no differences in the results were observed. Differences between measurements were also analyzed for age, but no effect of age on the results was found.

### Multivariable Analyses

The aortic SBP and PP must also be determined by factors unaccounted for by the Sphygmocor device alone. Separate univariate analyses identified age, height, heart rate, and EF as variables that could contribute to the accuracy of the Sphygmocor-calculated pressures. Measured EF, however, was only available for 38 cases. The mean EF for the available 38 cases was used in place of the missing 12 values to avoid loss of the other independent variables in those cases without a measured EF. With regard to each dependent variable, SBP was significantly influenced by age and height, DBP by age and heart rate, and PP by age and EF ($P=0.08$ for 38 cases). The values for the nonstandardized regression coefficients for each of the independent variables (including the Sphygmocor values), the intercept for the estimating equations, and the partial probability values are shown in Table 2. From the estimating equations provided by multiple regression, each of the pressures was recalculated (“predicted” values) and compared with the data obtained from direct aortic measurements. The mean predicted values and their differences from the Millar catheter–generated values are

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**Figure 2.** A, Scatterplot of measured versus calculated DBP and the estimating equation. B, Bland-Altman plot of the same data. Measured—calculated differences vs measured values. Mean difference = −10.4 mm Hg (---); SD = ±12.7 mm Hg (—).

**Figure 3.** A, Scatter plot of measured versus calculated PP and the estimating equation. B, Bland-Altman plot of the same data. Measured—calculated differences vs measured values. Mean difference = 11.5 mm Hg (---); SD = ±13.6 mm Hg (—).

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**Table 2.**
shown in Table 1, where they also may be compared with those from the Sphymocor. It is apparent that use of multiple regression brings the mean differences to near zero and slightly reduces the scatter. No predicted cuff DBP values are shown because the cuff DBP was assumed by the Sphygmo-
cor device to be the same as aortic DBP. Addition of other independent variables to the Sphygmocor data alone can also be appreciated by inspection of Table 1. Although mean differences are brought to near zero, the SDs are only slightly improved. Multiple regression necessarily brings each of the univariate regression-line slopes to near identity and improves the coefficient of determination ($R^2$) and $r$ values (Table 3). Statistical comparison of the $R^2$ values for the univariate relations between measured and calculated pressures with those obtained from multiple regression (F test) revealed that the multivariable analysis significantly improved all $R^2$ s ($P / 0.01$). Table 3 also compares the $R^2$ and $r$ values for the calculated versus cuff blood pressure values in both univariate and multivariate analyses. Except for the univariate $R^2$ and $r$ for PP, there is little improvement of the Sphygmocor data over that of the cuff. Interactive effects of the independent variables used in multiple regression were sought, and none were found.

Figures 4A and 4B show the direct and Bland-Altman plots comparing the auscultatory with the oscillometric method of measuring SBP, and Figures 5A and 5B show similar plots for DBP. Had the study been done with the auscultatory method, the cuff SBP would, on average, have been 7.1 mm Hg lower, but there would have been no difference in average DBP.

**Discussion**

It is now well established that the measurement of BA blood pressure is often an inaccurate representation of central aortic pressure—especially SBP and PP. These differences are greatest in youth, during exercise, and in low-flow hypotensive states but are difficult to predict because of the multiple factors that influence how central pressures are transmitted peripherally. Although brachial PP has recently been found to be an important predictor of cardiovascular risk in a variety of clinical states, it seems plausible that aortic PP might be even better. Therefore, a noninvasive technique for determining accurate aortic pressure...
The cuff DBPs were unexpectedly high when compared with the standards for the substitution of 1 technique for the other.\textsuperscript{12,13} Associated with large scatter, too large to meet the British or US by the Sphygmocor device. Unfortunately, the correction is by the cuff method (reduced by aging) and its average correction unit. Our data show the expected overestimation of aortic SBP calibrated the radial pulses by using a standard oscillometric cuff.\textsuperscript{6} We approached this problem by using the Sphygmocor device to radial-artery recordings as calibrations. The present study approached this problem by using the Sphygmocor device to trace and transforming it into an aortic pulse trace by Fourier analysis and transfer functions. The original descriptions validated the method in 14 patients with near-simultaneous calculated and directly measured radial and aortic pulses. Several other reports have also validated the transfer-function technique, but each has calibrated the radial pulses with direct recordings of arterial or aortic pulses.\textsuperscript{5–8} If such a system is to be acceptable for widespread clinical use, it must be validated without the need for direct brachial or directly recorded aortic DBPs. Inaccuracy of the cuff pressures is not surprising, because previous comparisons of pressures obtained with the time-honored, standard mercury device with intra-arterial values have shown mean differences for SBP ranging from 0.9 to 12.3, with SDs from 1.3 to 13.0 mm Hg. Mean differences for DBP ranged from 8.3 to 18, with SDs from 1.1 to 9.3 mm Hg.\textsuperscript{13} Some comparisons of the auscultatory versus oscillometric methods have been good,\textsuperscript{14} some poor (especially DBP\textsuperscript{15–19}), some with oscillometric pressures too high,\textsuperscript{20} and some too low\textsuperscript{21} in a variety of clinical populations. Only a single, early study measured oscillometric arm pressures along with directly recorded aortic pressures and found them comparable.\textsuperscript{22} We chose the oscillometric method because of its increasing acceptance in clinical work, avoidance of interpretive errors (digit preferences), and ease of use in the catheterization laboratory. The substudy of auscultatory versus oscillometric BA pressures showed that the substitution of auscultatory for oscillometric BA pressures would have reduced the good relation between measured and calculated SBP, but the discrepancy between oscillometric and aortic DBPs would, on average, have been unchanged.

In the present study, oscillometric cuff DBPs were higher than the aortic DBPs. This technical difference accounted for the calculated underestimation of PP and the overestimation of MBP. On the other hand, the cuff method also overestimated SBP and DBP by almost the same amount, resulting in a much closer prediction of aortic PP (difference of 2.5 mm Hg).

There are many possible explanations for the disparities and scatter in the results. \textbf{Radial pulses were unstable and poorly recorded.} All recordings were made by a single individual (H.S.), and pulse heights were those recommended in the Sphygmocor manual. Approximately one half of the recordings had systolic and diastolic variability $>5\%$, levels higher than recommended in the instrument manual. When the SBP data for the 24 patients whose systolic and diastolic variability was 5\% or less were analyzed separately, there was no difference from the entire group in the $r$ value (+0.87) or in the SD of the differences (±13.2 mm Hg). This makes technical variability in radial-pulse recording an unlikely explanation. Another possible source of variability is the spontaneous oscillations in diameter and distensibility known to occur in the human radial artery.\textsuperscript{23}

\textbf{Catheterization patients were unstable.} Many of the patients had been sedated and some were undoubtedly anxious, resulting in respiratory variations in aortic pressures. These variations should have been smoothed out by averaging the pressures across respiratory cycles but could have affected the stability of the radial-artery pulses. \textbf{The cuff pressures and radial and aortic pulses were not exactly simultaneous.} Because we wished to have the radial pulses and cuff pressures in the same arm, simultaneity was not possible. The radial pulses were recorded simultaneously with those of aortic pressures, but there was no beat-to-beat correspondence. \textbf{It was assumed that BA pressure is the same as the radial-artery pressure.} Although they cannot be exactly the same, the differences should be small. \textbf{Errors were made in the measurement of BA pressure by the oscillometric technique.} This is probably the largest source of measurement error in the study. It is a single calibration pressure for a series of radial-artery pulses reduced to an average pulse. Although manufacturers’ algorithms vary, the most accu-
rate measurement by the oscillometric method is the MBP, which is selected as the cuff pressure when the oscillations are at their maximum. The use of averaged, multiple-cuff MBPs for calibration purposes, in settings more stable than the catheterization laboratory, would likely increase the accuracy of these values. It has been recently suggested\textsuperscript{24} that cuff pressures performed about as well (or better, for SBP) than the Sphygmocor device in the prediction of aortic pressures. In the present study, the SBP was better predicted by the Sphygmocor device, but the discrepancy between the DBPs was about the same. In our study, however, the oscillometric cuff was independently calibrated, and the aortic pressures were recorded with a transducer-tip rather than a fluid-filled catheter. These methodological differences could account for the differences in the results.

Obviously, the generalized transfer function cannot account for all of the factors that influence the way in which the aortic pulse is transmitted to the radial artery. When age, height, heart rate, and EF were incorporated into a multivariable analysis, there was a significant improvement (F test; \( P<0.01 \)) in the correlation of calculated pressures with direct aortic measurements, a reduction in the scatter, and a mathematically obligatory elimination of the mean differences. When the same independent variables were incorporated into the analyses for cuff pressures, similar improvements in the differences, correlations, and scatter occurred, PP being the most improved.

**Perspectives**

An accurate yet noninvasive means for measuring central aortic pressure would be an important clinical advance over that provided by BA pressure. The Sphygmocor device has the potential to fill this need. This study shows that the Sphygmocor method is limited by the variability and inaccuracy of the cuff blood pressure required for radial-artery calibration. Comparison of calculated and measured aortic pressures might be improved if MBP only were used for calibration and multiple cuff measurements over a short period of time had been available and averaged. Although further validation studies requiring direct aortic pressures in a variety of clinical situations will be difficult to obtain, they should be pursued, because the clinical benefits would be great if the device can realize its potential.

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**References**


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