Prospective Evaluation of a Method for Estimating Ascending Aortic Pressure From the Radial Artery Pressure Waveform

Alfredo L. Pauca, Michael F. O’Rourke, Neal D. Kon

Abstract—Pressure wave reflection in the upper limb causes amplification of the arterial pulse so that radial systolic and pulse pressures are greater than in the ascending aorta. Wave transmission properties in the upper limbs (in contrast to the descending aorta and lower limbs) change little with age, disease, and drug therapy in adult humans. Such consistency has led to use of a generalized transfer function to synthesize the ascending aortic pressure pulse from the radial pulse. Validity of this approach was tested for estimation of aortic systolic, diastolic, pulse, and mean pressures from the radial pressure waveform. Ascending aortic and radial pressure waveforms were recorded simultaneously at cardiac surgery, before initiation of cardiopulmonary bypass, with matched, fluid-filled manometer systems in 62 patients under control conditions and during nitroglycerin infusion. Aortic pressure pulse waves, generated from the radial pulse, showed agreement with the measured aortic pulse waves with respect to systolic, diastolic, pulse, and mean pressures, with mean differences <1 mm Hg. Control differences in Bland-Altman plots for mean±SD in mm Hg were systolic, 0.0±4.4; diastolic, 0.6±1.7; pulse, −0.7±4.2; and mean pressure, −0.5±2.0. For nitroglycerin infusion, differences respectively were systolic, −0.2±4.3; diastolic, 0.6±1.7; pulse, −0.8±4.1; and mean pressure, −0.4±1.8. Differences were within specified limits of the Association for the Advancement of Medical Instrumentation SP10 criteria. In contrast, differences between recorded radial and aortic systolic and pulse pressures were well outside the criteria (respectively, 15.7±8.4 and 16.3±8.5 for control and 14.5±7.3 and 15.1±7.3 mm Hg for nitroglycerin). Use of a generalized transfer function to synthesize radial artery pressure waveforms can provide substantially equivalent values of aortic systolic, pulse, mean, and diastolic pressures. (Hypertension. 2001;38:932-937.)

Key Words: aorta ■ blood pressure monitoring ■ hemodynamics ■ nitroglycerin

Recent clinical and epidemiological studies, while endorsing the importance of arterial pressure in cardiovascular disease, have directed attention to pulsatile phenomena and arterial stiffness by demonstrating the greater importance of systolic and pulse pressures over diastolic and mean pressures in older human adults.1–4 The field currently is confused.5,6 One source of confusion is the difference in pulse pressure and systolic pressure between central and peripheral arteries, even when mean and diastolic pressures appear identical.7 Such differences can lead to errors in assessment of myocardial oxygen requirements8 and of left ventricular load and hypertrophy, as well as to differences in the actions of different vasodilator agents.9,10

Different methods have been introduced to generate indices of left ventricular load from the peripheral pressure pulse. One of those involves synthesis of the ascending aortic pressure pulse (and so left ventricular pressure during systole) through convolution of the radial artery pressure pulse in the frequency domain, with a generalized transfer function used to describe the hydraulic properties of blood vessels in the upper limb.11–15

The present study was undertaken to evaluate such a system as contained in a commercially available device (SphygmoCor, PWV Medical). The study was undertaken prospectively on a consecutive series of anesthetized adult patients undergoing cardiac surgery, with the use of fluid-filled manometer systems with adequate frequency response that had been carefully matched before each study. Simultaneously recorded aortic and radial pressure waveforms were digitized at collection, with ensemble-averaged data compared over at least 1 respiratory cycle before and after intensive vasodilation and with wave-by-wave analysis used for those patients with cardiac irregularity.

Method

Collection and Presentation of Clinical Data

Patients
The study was conducted on 62 consecutive patients between November 4, 1998, and April 14, 1999. The study was approved by

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the institution’s clinical research practices committee. Individual patients scheduled for surgery were approached, and informed consent was given. Hemodynamically significant brachial, subclavian, or innominate stenosis was excluded by ensuring that blood pressures were the same on both sides and that the radial pulse was identical by palpation in the left and right arms. The study was initiated in 62 consecutive patients and was completed in all. Data on all patients are summarized in Table 1.

**Procedure and Manometric System**

Similar equipment and methodology were used as in the previous study, including the fluid-filled manometer systems. Radial artery cannulation was established as a routine, before induction of anesthesia, through a 5.1-cm, 20-gauge Teflon catheter attached to a manometer that was set at midchest level. Observations recorded for cannulation was established as a routine, before induction of anesthesia, through a 5.1-cm, 20-gauge Teflon catheter attached to a manometer that was set at midchest level. Observations recorded for the study were taken 60 to 90 minutes after anesthesia had been induced. Isoflurane (0.5% to 2%, inspired) was the primary anesthetic. Fentanyl (6 to 12 μg/kg) and midazolam (100 to 120 μg/kg) were adjuvants. Pancuronium was used for muscle relaxation. After the chest had been opened, the ascending aorta had been prepared for insertion of the cardiopulmonary bypass cannula, and heparin (300 U/kg) had been given, a 20-gauge catheter similar to that used to record pressure from the radial artery was placed in the ascending aorta at the site of intended cannulation for cardiopulmonary bypass. Recordings were obtained simultaneously during a period of 2 to 5 minutes while the surgical procedure was diverted away from the monitoring lines.

The aortic and radial cannulas both faced upstream. Both aortic and radial catheters were 91.4 cm long, with internal diameter of 1.8 mm and wall thickness of 0.9 mm. Catheters were attached to matched Transpac manometers (Abbott Critical Care Systems, Abbott Laboratories). Transducers were calibrated statically with a mercury manometer and maintained at the same vertical level. Coronary artery disease; ASA, atrial septal defect; LVEF, left ventricular ejection fraction; AF, atrial fibrillation; and VEBs, ventricular ectopic beats.

**Table 1. Clinical Features of the 62 Patients in the Study**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>61±11</td>
</tr>
<tr>
<td>Male/female, n</td>
<td>45/17</td>
</tr>
<tr>
<td>Previous hypertension (&gt;140/90 mm Hg)</td>
<td>58</td>
</tr>
<tr>
<td>CAD/aortic stenosis/ASA, n</td>
<td>60/1/1</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>83±15</td>
</tr>
<tr>
<td>Height, cm</td>
<td>172±8</td>
</tr>
<tr>
<td>LVEF, %</td>
<td>47±10</td>
</tr>
<tr>
<td>Cardiac irregularity, n</td>
<td>3 (AF=2, VEBs=1)</td>
</tr>
</tbody>
</table>

**Table 2. Comparisons of Pressure From Actual and Estimated Waveforms**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Control Mean</th>
<th>Control SD</th>
<th>Change Mean</th>
<th>Change SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synthesized aortic—measured aortic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP</td>
<td>0.0</td>
<td>4.4</td>
<td>0.0</td>
<td>4.3</td>
</tr>
<tr>
<td>DP</td>
<td>0.6</td>
<td>1.7</td>
<td>0.6</td>
<td>1.7</td>
</tr>
<tr>
<td>MP</td>
<td>-0.5</td>
<td>2.0</td>
<td>-0.5</td>
<td>1.8</td>
</tr>
<tr>
<td>PP</td>
<td>-0.7</td>
<td>4.2</td>
<td>-0.7</td>
<td>4.1</td>
</tr>
<tr>
<td>Radial—measured aortic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP</td>
<td>15.7</td>
<td>8.4</td>
<td>14.5</td>
<td>7.3</td>
</tr>
<tr>
<td>DP</td>
<td>-0.5</td>
<td>2.0</td>
<td>-0.7</td>
<td>1.7</td>
</tr>
<tr>
<td>MP</td>
<td>-0.5</td>
<td>2.0</td>
<td>-0.4</td>
<td>1.8</td>
</tr>
<tr>
<td>PP</td>
<td>16.3</td>
<td>8.5</td>
<td>15.1</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Compare the parameters derived from each of the aortic waveforms, the following data analysis procedure was adopted. Both the invasively recorded radial artery and the invasively recorded aortic 200-Hz pressure data were converted offline to 128-Hz data (as required for digital data input to SphygmoCor) by linear interpolation.

The radial artery pressure waveform data were then processed by the SphygmoCor radial/aortic transform software module to produce the estimated aortic pressure waveform. The process involved convolution of the radial waveform by a generalized transfer function, which was taken to characterize pressure wave transformation in the upper limb. The series of estimated aortic waveforms, together with the series of radial waveforms from which these were derived, were each ensemble-averaged over an 8-second period into a single calibrated waveform.

The corresponding set of simultaneously recorded aortic pressure waves were handled in a similar process that applied no modulus or phase correction but produced a single calibrated, ensemble-averaged aortic pressure waveform whose features could be compared directly with the corresponding ensemble-averaged radial and estimated aortic waveforms by the feature extraction processes.

Three patients had irregular rhythms throughout the recording period (2 atrial fibrillation and 1 with multiple supraventricular ectopic beats). The same process was applied in these patients, with a single ensemble-averaged pressure wave generated to represent radial, estimated aortic, and measured aortic waveforms. Comparisons were made with the single averaged waveforms. In addition, in these 3 patients with irregular heart rhythm, and for each intervention, directly recorded radial, directly recorded aortic, and estimated aortic waves were compared on a wave-by-wave basis for a minimum of 10 seconds. Individual waveforms were compared with respect to systolic pressure, diastolic pressure, and pulse pressure.

**Analysis of Ensemble-Averaged Data**

Two separate data sets were compared: under control conditions immediately after insertion of the aortic cannula and after intravenous infusion of NTG to reduce arterial pressure. Comparisons were made of the above parameters from the actual and estimated aortic waveforms (Table 2).

The ensemble-averaged wave comparison was applied to the data from all 62 patients, including the 3 with irregular heart rhythms. The approach recognizes the difficulties in characterizing an “average”
pulse waveform with the heart beating irregularly, as in atrial fibrillation, but acknowledges the fact that clinicians still describe averages of heart rate, blood pressure, and cardiac output in the presence of irregular heart rhythm.

**Results**

In all patients, manometric matching was checked by displaying the same radial tracing from the 2 manometers on the monitoring screen, with confirmation that these overlapped. If there was any significant disparity, the study was abandoned and the operative procedure proceeded in routine fashion. In 37 patients, time permitted entry of the data into the computer for Bland-Altman analysis. Differences were (±SD) 0.2±1.5, 0.1±0.7, 0.3±1.7, and 0.2±1.5 mm Hg for mean, pulse, systolic, and diastolic pressures, respectively (Figure 1).

Ensemble-averaged waves were generated for measured aortic, estimated aortic, and measured radial pressure in all 62 patients before and during NTG infusion. In general, there was correspondence between measured and estimated aortic waveforms before and during NTG but a lack of correspondence with the radial waveform, especially during NTG infusion.

Figure 2 shows Bland-Altman comparisons of systolic and diastolic, mean, and pulse pressures for estimated and measured aortic waves in the 62 patients before and during NTG infusion. Figure 2 also shows comparisons of the same indices in measured aortic and radial waves. Mean difference and SD of all indices are given in Table 2, with control and treatment results listed separately. Convolution of the radial pulse into the estimated aortic pressure reduced both the mean difference and SD of the systolic and pulse pressure indices compared with measured aortic pressure. In the 3 patients with irregular heart rhythm, indices determined from the ensemble-averaged waves fell within those obtained within the entire group and did not constitute any of the outlying points. When individual waveforms were compared (Figure 3), the convolutional process was found to effectively track measured aortic pressure and its fluctuations under control conditions and with NTG infusion.

**Discussion**

The earliest studies of arterial hemodynamics in humans, performed after diagnostic cardiac catheterization was introduced, confirmed observations from animal experimental studies that the ascending aortic pressure wave during systole is virtually identical to left ventricular pressure during ejection but that both are quite different from the systolic part of the pressure wave as recorded in the brachial, radial, and other peripheral arteries. Such differences were attributed to wave travel and reflection in the systemic circulation and were shown to be substantial, especially in young adults, during tachycardia and physiological maneuvers such as Valsalva and prolonged expiration. Subsequent studies confirmed these results and showed variable differences between ascending aortic and upper-limb pressure waves in older subjects and patients, especially those with tachycardia or hypotension or those undergoing vasodilator therapy.

Despite these findings, epidemiologists and clinicians have not yet embraced the notion of systematic error in measurement of peripheral systolic pressure with respect to events involving the left ventricle, aorta, and central (coronary and carotid) arteries. At least 3 recent studies published in major cardiological journals assumed that brachial systolic and pulse pressures were identical to aortic pressures. Despite having relevant findings for ACE inhibitors in humans and experimental animals, the recently reported HOPE study did not consider the possibility that beneficial effects of an ACE inhibitor (over those predicted from trials of other agents) might be due to greater reduction of ascending aortic rather than brachial systolic pressure.

Our interest in this field has evolved from long-term involvement with analysis of the arterial pulse in the frequency and time domains, together with the experience of anesthesiologists who have long known that assessment of
cardiac function from peripheral pulse tracings may be misleading.\textsuperscript{7,8} Our view that the brachial vasculature (in contrast to the aorta) might be represented in adult humans by a generalized transfer function arose from the findings that upper-limb pulse wave velocity changes little with age,\textsuperscript{33} upper-limb muscular arteries change little with age and hypertension,\textsuperscript{34} and vasoactive agents such as NTG appear to have corresponding effects on indices of wave reflection in the ascending aorta and in the brachial and radial arteries.\textsuperscript{26} These views were supported by noninvasive studies of central (carotid) and upper-limb pressure waves under different conditions\textsuperscript{35} and by modeling studies.\textsuperscript{18} Formal studies of transfer function between the ascending aorta and upper-limb arteries showed relative consistency,\textsuperscript{12–15,25,36} including studies conducted with NTG used as a vasodilator agent. For the most part, these findings have been confirmed by others\textsuperscript{13–15} who understandably had initially indicated strong skepticism.

The transfer function for convolving radial to aortic pressure that we have developed is incorporated in a commercial system (SphygmoCor, PWV Medical Sydney). Three previous validation studies\textsuperscript{37–39} have been reported that used the original system. All gave results similar to those reported here, although in far smaller studies. All were identified as having possible deficiencies before commencement of the present study. In our initial study,\textsuperscript{37} pressure waves were digitized by hand, and data were analyzed from a retrospectively collected series. In a second study,\textsuperscript{38} changes in the estimated aortic wave mirrored those seen in the measured aortic pulse, but there were quantitative differences that could not be explained; one possible explanation was a mismatch between the catheter-tip manometer for aortic pressure recording and the fluid-filled catheter for radial recording. This was the reason for careful matching of manometric devices before data collection in the present study (Figure 1). In the third study,\textsuperscript{39} the radial waveform was measured by applation tonometry, as in validation studies of similar process-

Figure 2. Bland-Altman plots for all 62 patients before and during NTG infusion for systolic pressure (SP), diastolic pressure (DP), mean pressure (MP), and pulse pressure (PP). Comparisons between measured radial and measured aortic pressure waves (top) and between estimated and measured aortic pressure waves (bottom) are shown. M indicates mean.
and therefore absolute values could not be calculated with precision.

In the present study, correspondence for matching between manometer systems was checked before recording of data in every patient (Figure 1) and was shown to be adequate. The difference between central (aortic) and peripheral (radial) systolic pressures was similar to that in our 2 previous studies and was associated with a similar substantial difference in pulse pressure.

Association for the Advancement of Medical Instrumentation (AAMI SP10) criteria have been set for comparison of arterial pressures measured with different methods. Mean values need to correspond by 5 mm Hg or less, with SD 8 mm Hg or less, in an appropriately large number of measurements (25 or more for invasive comparisons). For the present study, AAMI SP10 criteria were met for comparisons between estimated and measured aortic pressures both under control conditions and with NTG infusion (Figure 2; Table 2). AAMI SP10 criteria were met only for mean and diastolic pressure comparisons between radial and directly recorded aortic waveforms.

The present study appears to show substantial equivalence between the estimated aortic and measured aortic waveform when the estimated aortic waveform is convolved from the simultaneously recorded radial waveform by use of a generalized transfer function.

A process similar to that used here has been used by Harms et al to determine aortic pressure and cardiac output, and accuracy has been demonstrated in recumbent patients.

Summary

Ascending aortic and radial artery pressure waves were recorded simultaneously in 62 anesthetized patients before initiation of cardiopulmonary bypass, both before and during intravenous infusion of NTG, with fluid-filled manometer systems that had been carefully matched for dynamic and static accuracy. A generalized transfer function was used in a computerized process to generate ascending aortic pressure waveforms from the radial pulse; estimated aortic pulse waveforms were compared with simultaneously recorded aortic waves. Comparisons were made for systolic, diastolic, mean, and pulse pressures of individual paired waveforms for patients with regular and irregular heart rhythms and in corresponding ensemble-averaged waveforms over a 10-second period for all.

Figure 3. Continuous pressure wave tracings in 3 patients with irregular heart rate (2 with atrial fibrillation, 1 with multiple supraventricular ectopic beats). Tracings at left are simultaneously recorded radial and aortic pressures; at right, measured and estimated aortic pressures (same wave train as at left). From top to bottom: patient 1, control; patient 1, NTG; patient 2, control; patient 2, NTG; patient 3, control; and patient 3, NTG.
As in previous studies, correspondence between aortic and radial diastolic and mean arterial pressures was good (±SD) (mean difference 1±2.2 mm Hg), but for systolic and pulse pressures, correspondence was poor (mean difference 15±7 mm Hg) and well outside AAMI guidelines. In contrast, when estimated (from radial) and measured aortic pressure waveforms were compared, there was good correspondence, within AAMI requirements, for systolic (mean 0.0±2.4 mm Hg) and pulse (0.7±4.2 mm Hg) pressures, as well as for mean (0.5±2.0 mm Hg) and diastolic (0.6±1.7 mm Hg) pressures. Pressure differences remained of the same order during infusion of NTG.

For patients with irregular heart rhythm, values of systolic, pulse, mean, and diastolic pressures in estimated aortic waveforms agreed with measured aortic waveforms, within AAMI criteria. The system tested provides a substantially equivalent estimate of the ascending aortic systolic, diastolic, mean, and pulse pressures under different conditions.

References
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