Blood pressure analysis on time scales from seconds to days
Westerhof, B.E.

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Chapter 4

Quantification of wave reflection in the human aorta from pressure alone

Berend E. Westerhof\textsuperscript{1}, Ilja Guelen\textsuperscript{1}, Nico Westerhof\textsuperscript{2}, John M. Karemaker\textsuperscript{3}, Alberto Avolio\textsuperscript{4}

Wave reflections affect the pressure and flow wave in the proximal aorta (1) and their contribution depends on their magnitude and time of return. When the reflected wave arrives in systole it augments pressure. This augmentation is greater when the heart is hypertrophied. In heart failure wave reflections affect the flow wave negatively, thereby reducing stroke volume and cardiac output (2–4).

One way to estimate the amount of reflection is by waveform analysis in which aortic pressure is separated into its forward and backward components (1,5,6). The magnitudes of the backward (reflected) wave and the forward wave allow for the estimation of the amount of reflection. This waveform analysis requires measurement of both pressure and flow waves and derivation of characteristic impedance. A method that requires the measurement of pressure only is computation of the Augmentation Index, AI (7,8). AI gives reproducible results (9,10) and is in use in clinical settings (11–14). However, AI is determined by both the magnitude and timing of the reflected wave. This is evident from Figure 1, panel A. In this figure the original pressure wave is separated into its forward and backward components and then reassembled for different delays of the same backward wave. AI is clearly influenced by the time of return of the reflected wave.

\textsuperscript{1} BMEYE, Amsterdam, The Netherlands
\textsuperscript{2} Physiology, ICaR-VU, VU University medical center, Amsterdam, The Netherlands
\textsuperscript{3} Physiology, Academic Medical Center, University of Amsterdam, The Netherlands
\textsuperscript{4} Graduate School of Biomedical Engineering, University of New South Wales, Sydney Australia
Panel B gives two examples in which AI suggests no wave reflection (left) or a reflected wave that is larger than the forward wave (right). Thus the magnitude of wave reflection cannot be quantified from AI. This may explain why the AI may not be a good measure of central pulsatile load in patients with congestive heart failure (15).

Figure 1

The Augmentation Index depends not only on the magnitude but also on the time of return of the reflected wave. In panel A, on the left, the measured pressure, flow, and the derived forward and backward pressure waves are shown. On the right the pressure waves obtained by summation of the forward and backward waves are shown when the backward wave is shifted in time. Thus, with the same magnitude of the reflected wave, but different times of return, the wave shape, the Pulse Pressure, PP, and, consequently, the Augmentation Index (AI), \( \frac{\Delta P}{PP} \), are different. AIs from top to bottom were 0.20, 0.21, 0.13 and undefined, respectively, while Reflection Index (RI, see text) was 0.35. Panel B gives two examples in which AI gives erring results. On the left, the backward wave returns when the forward wave is already falling. AI was found to be 0.03 while the RI was 0.33. On the right, the forward wave is still rising when the backward wave returns, resulting in an AI of 0.59, suggesting that the backward wave is larger than the forward wave. RI in this case was 0.44.

In this study we investigate a new method to calculate pressure wave reflection in the human proximal aorta based on measured pressure alone and derive an index to quantify reflection independent of the time of return of the reflected wave. We assume a triangular shape of the flow wave based on the timing features of the aortic pressure. This is a reasonable assumption in view of the ascending aortic flow patterns obtained by a variety of flow measurement techniques (6). Subsequently, separation of the pressure wave into its forward and backward components is carried out using the measured
pressure and the triangular flow wave. The results will be compared to the actual results obtained using the measured flow wave in the aorta. The Augmentation Index will also be assessed.

**Methods**

* (Abbreviations are listed after the References)

Simultaneous measurements of pressure and flow velocity, $P_m$ and $F_m$, in the human ascending aorta recorded for previous studies were used. Twelve healthy subjects were catheterized for various clinical indications. Five healthy subjects of these twelve were kindly provided through personal communications with Dr Rubal. Data of six subjects were taken from the publications of Murgo et al. (5,15–18), including baseline conditions, exercise and Valsalva maneuvers. One subject performing a Mueller maneuver was analyzed (18). In 5 patients pressure and flow velocity were measured directly following a selective coronary angiographic procedure to evaluate ischemic heart disease and were kindly provided by Dr. Blum (20). In this group of 17 humans the total number of analyzed beats including the maneuvers was 26. All participants gave informed consent and the respective institutional review committees approved the studies.

**Figure 2**

Principle of method. The flow is approximated by a triangle. End-diastole and the incisura (second vertical line) of the measured pressure wave determine the start and end of the triangle. The peak is set at the inflection point (first vertical line) or at 30% of ejection time (arrow). The inflection point is determined by standard method. Calibration of flow is not required (see text).
A catheter equipped with a micromanometer and an electromagnetic flow velocity sensor was used for the measurements (Millar Instruments, Houston, Texas). All signals were sampled at a rate of 100 Hz.

The method to construct a flow wave makes use of the notion that the flow wave can be approximated by a triangular shape during ejection. The duration and the time of peak flow of this triangle can be derived from the pressure wave shape as follows (Figure 2). The time of end-diastolic aortic pressure is the time of valve opening and the start of ejection. The incisura gives the time of valve closure and the end of ejection. These times determine the ejection time and thus the base of the triangle. In a first analysis the time of the peak of the triangle is set at the time of the inflection point of the measured pressure wave in systole. The inflection point is derived using higher order derivatives of pressure as previously described (7,8). In a second analysis on the same subjects the maximum of the triangular flow was set at 30% of the ejection time, the average found from the flow measurements (see results). This was done in order to test the condition when an inflection point in the pressure wave cannot be explicitly identified.

The triangular flow with the peak time set at the inflection point of the measured pressure wave was called $F_{\text{tip}}$, and the flow with the peak time fixed at 30% of the ejection time was called $F_{\text{30}}$.

In the calculations of forward, $P_f$, and backward pressure, $P_b$, the following equations are used (5):

$$P_f(t) = (P(t) + Z_c \cdot F(t))/2$$

and

$$P_b(t) = (P(t) - Z_c \cdot F(t))/2$$

The $P(t)$ in this case is the measured pressure wave and $F(t)$ is either the measured flow wave or the constructed flow wave with a triangular shape. $Z_c$ is the characteristic impedance of the proximal aorta. The total input impedance $P/F$ was calculated in the frequency domain and the characteristic impedance was derived from the averaged value of the 4th to 7th harmonic of the input impedance modulus (6). $Z_c$ was determined for all three flow wave shapes.
From the above equations it can be seen that the product \( Z_c \cdot F \) appears in the calculation of the forward and backward waves. \( Z_c \) is a ratio of pressure and flow, \( P/F \) (explicitly, \( Z_c = P_f/F_f = -P_b/F_b \)). Thus by multiplication of \( Z_c \) and \( F \) the amplitude of flow is eliminated and \( Z_c \cdot F \) is independent of the flow calibration. When flow is twice as large, \( Z_c \) is twice as small but the product remains the same. A similar reasoning holds whether flow velocity or volume flow is used in the calculations. Thus calibration of the flow wave is not required, the shape is of importance only, and so stroke volume does not have to be determined. In the remaining text flow velocity will simply be called flow.

Using the above equations we calculated forward and backward pressure waves on the basis of the measured pressure, \( P_m \), in combination with the measured flow, \( F_m \), and each of the two triangular flows, \( F^{tIP} \) and \( F^{t30} \). The amplitudes of the forward waves obtained by the triangular flows, \( |P_f^{tIP}| \) and \( |P_f^{t30}| \), were compared with the amplitude of the forward pressure wave derived from the measured flow \( |P_f^{mf}| \). Similarly the backward waves \( |P_b^{tIP}| \) and \( |P_b^{t30}| \) were compared to \( |P_b^{mf}| \).

The accuracy of the shapes of the forward and backward pressure waves were determined by calculating the Root Mean Square Error (RMSE) between the waves derived from triangular and measured flow waves.

The Reflection Index, \( RI \), was defined as:

\[
RI = \frac{|P_b|}{(|P_f|+|P_b|)}. 
\]

The RIs derived from the measured flow, and from the two triangular flows, are called \( RI^{mf} \), \( RI^{tIP} \) and \( RI^{t30} \), respectively. Because the reflection index is a ratio of two pressures calibration of pressure is not required.

The RI was calculated instead of the Reflection Magnitude defined as \( RM = \frac{|P_b|}{|P_f|} \), to facilitate comparison with the augmentation index. We calculated the Augmentation Index, \( AI \), as the augmentation of the pressure, \( \Delta P \), divided by pulse pressure, \( PP \). See Figure 1.

All derivations were carried out in a set of 26 simultaneous aortic pressure and flow pairs recorded in the group of 17 subjects. Data are presented as mean ± standard deviation. Repeated Measures Analysis of Variance was used to investigate differences between derivations based on measured flow, both triangular flows and augmentation.
index. Cases in which no inflection point was found and thus F_{\text{IP}} and AI could not be determined were excluded from testing. Distributions were normal and a parametric test was used. Differences were assumed to be significant if $P < 0.05$. Regressions of RI_{\text{IP}} and RI_{30} and AI on RI_{\text{mf}} were calculated and plotted for all available data points. Regression of RI_{30} on RI_{\text{mf}} was also calculated using all heartbeats excluding those that had no inflection point.

To investigate the influence of convexity and concavity of the flow wave on the reflection index we approximated the most extreme cases of convexity and concavity in our study population by using a trapezoidal flow and compared it to the results from triangular flow.

**Results**

Median age of the subjects was 50 years, ranging from 29 to 57 years. Excluding exercise and Valsalva maneuvers, systolic and diastolic pressures were $126 \pm 17$, $75 \pm 10$ mmHg (mean ± SD) and heart rate was $69 \pm 6$ bpm. Ejection time and the time of the inflection point in pressure were $0.31 \pm 0.03$ and $0.10 \pm 0.03$ seconds, respectively. Thus the ratio of time of inflection point to ejection period was $32 \pm 9\%$. The ratio of time of peak flow to ejection period was $30 \pm 5\%$.

**Figure 3**

Example of a measured pressure and forward and backward waves when calculated from measured flow (bold lines) and calculated from triangular flow, F_{\text{IP}} (thin lines).
Figure 3 shows an example of the measured pressure wave and the calculated forward and backward pressure waves using measured flow, bold lines, and triangular flow based on the inflection point in the pressure wave, thin lines.

Table 1 shows the averaged amplitudes of the forward and backward waves based on all three methods.

Table 1

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
<th>ANOVA</th>
<th>Range of differences</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>min</td>
</tr>
<tr>
<td>$</td>
<td>P_f</td>
<td>_{mf}$</td>
<td>33.2 ± 7.3</td>
</tr>
<tr>
<td>$</td>
<td>P_f</td>
<td>_{tIP}$</td>
<td>35.0 ± 6.4</td>
</tr>
<tr>
<td>$</td>
<td>P_f</td>
<td>_{t30}$</td>
<td>33.4 ± 7.0</td>
</tr>
<tr>
<td>$</td>
<td>P_b</td>
<td>_{mf}$</td>
<td>23.4 ± 7.2</td>
</tr>
<tr>
<td>$</td>
<td>P_b</td>
<td>_{tIP}$</td>
<td>22.5 ± 6.4</td>
</tr>
<tr>
<td>$</td>
<td>P_b</td>
<td>_{t30}$</td>
<td>21.7 ± 6.9</td>
</tr>
<tr>
<td>RI$_{mf}$</td>
<td>0.41 ± 0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RI$_{tIP}$</td>
<td>0.39 ± 0.05</td>
<td>NS</td>
<td>-0.06</td>
</tr>
<tr>
<td>RI$_{t30}$</td>
<td>0.39 ± 0.04</td>
<td>NS</td>
<td>-0.07</td>
</tr>
<tr>
<td>AI</td>
<td>0.34 ± 0.16</td>
<td>$P &lt; 0.01$</td>
<td>(range: 0.02 to 0.59)</td>
</tr>
</tbody>
</table>

The $|P|$ are the amplitudes of the pressure waves in mmHg. RI is Reflection Index, and AI Augmentation Index. The subscripts $f$ and $b$ indicate forward and backward waves. The superscripts $mf$, $tIP$, $t30$ give results that are based on the wave analysis using measured pressure, together with measured flow, triangular flow with peak time at inflection point of pressure and triangular flow where peak time is set at 30% of ejection time, respectively. Parametric ANOVA testing was used. The range of differences gives smallest and largest deviation from reference, but in the case of AI it gives the range of all AI determinations.

The average amplitudes of the forward waves $P_f^{dp}$ and $P_f^{t30}$ are not different from the reference. The average amplitudes of the backward waves $P_b^{dp}$ and $P_b^{t30}$ are different from the reference. This difference, however, is quite small, namely 0.9 mmHg for $P_b^{dp}$ and 1.8 mmHg for $P_b^{t30}$. The average Reflection Index and Augmentation Index are also
presented in Table 1. Only AI differs from RI\textsuperscript{mf}. AI also has a larger variance, while RI\textsuperscript{tIP} and RI\textsuperscript{t30} do not (F-test).

Table 2 gives the RMSErrors of the forward and backward waves when using a triangular flow compared with the actual forward and backward waves.

**Table 2**

RMS Errors of the forward and backward waves over 21 determinations in 17 humans.

<table>
<thead>
<tr>
<th>RMSError</th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>min</td>
</tr>
<tr>
<td>P\textsuperscript{f} tIP</td>
<td>1.83 ± 0.68</td>
<td>0.90</td>
</tr>
<tr>
<td>P\textsuperscript{f} t30</td>
<td>1.79 ± 0.99</td>
<td>0.63</td>
</tr>
<tr>
<td>P\textsuperscript{b} tIP</td>
<td>1.83 ± 0.68</td>
<td>0.90</td>
</tr>
<tr>
<td>P\textsuperscript{b} t30</td>
<td>1.79 ± 0.99</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Errors in mmHg. For identification of the parameters see table 1.

Figure 4 shows the relations between the RI derived from the measured pressure and flow and the RI calculated from the measured pressure and triangular flows (A and B). The relation for the triangular flow based on the inflection point in pressure can be described by: RI\textsuperscript{tIP} = 0.86 RI\textsuperscript{mf} + 0.03 (R\textsuperscript{2} = 0.73, n = 21). For the relation between the triangular flow with its maximum set at 30% of ejection time, we found RI\textsuperscript{t30} = 0.84 RI\textsuperscript{mf} + 0.04 (R\textsuperscript{2} = 0.88, n = 26). In Figure 4C the relation between the Augmentation Index and the Reflection Index based on measured pressure and flow is shown, described by AI = 2.62 RI\textsuperscript{mf} – 0.74 (R\textsuperscript{2} = 0.57, n = 21). Both intercept and slope contribute to the model, whereas in the regressions of RI\textsuperscript{tIP} and RI\textsuperscript{t30} on RI\textsuperscript{mf} the intercepts do not contribute. The range of the AI is much larger than that of the RI. In 5 cases no inflection point was found in the pressure and thus panels A and C of Figure 4 show 21 data points while panel B shows all 26 points. When the 5 points in which no inflection point could be determined are excluded, the relation between RI\textsuperscript{t30} and RI\textsuperscript{mf} becomes RI\textsuperscript{t30} = 0.77 RI\textsuperscript{mf} + 0.06 (R\textsuperscript{2} = 0.67, n=21). The data is also presented as a Bland-Altman plot in Figure 5. Note that the AI is too low for small RI and too high for large RI.
Relation between Reflection Index calculated from measured pressure and measured flow on the horizontal axes, $RI_{mf}$ and, on the vertical axes, calculated from pressure and triangular flows, $RI_{tIP}$ (A, $n = 21$) and $RI_{t30}$ (B, $n = 26$), and also the Augmentation Index (C, $n = 21$).
Bland-Altman plot of Reflection Indices (A, n = 21 and B, n = 26) and Augmentation Index (C, n = 21). Dashed lines are averages; dotted lines are 95% confidence intervals.
While $RI^{dp}$ and $RI^{10}$ are comparable with the measured reflection index, $RI^{mf}$, AI is not proportional to the $RI^{mf}$.

**Figure 6**

The two most extreme cases of convexity (left) and concavity (right) of the flow wave shape. A trapezoidal flow approximates the measured flow and gives better estimates of RI. See text for calculated RIs. The triangular flow can be based on measured pressure, but a trapezoidal flow wave cannot.

Figure 6 shows the extreme cases of convex and concave flow in our study population. On the left, the measured pressure and convex flow give a reflection index of 0.33, with a triangle this is 0.28 and with the trapezoid 0.33 is found. In the case of concavity, on
the right in Figure 6, measured pressure and flow give 0.49, with a triangle this is 0.44, with the trapezoid 0.48 is found.

Discussion

We found that from aortic pressure measurement alone and an assumed triangular flow wave derived from the timing features of the pressure wave, an accurate estimate of the Reflection Index can be obtained. The amplitudes of the forward waves calculated from the triangular flows are not significantly different from those calculated from measured pressure and flow, but the amplitudes of the backward waves derived from triangular flows are different. The comparison of $|P_b^{\text{tIP}}|$ and $|P_b^{\text{t30}}|$ with $|P_b^{\text{mf}}|$, however, shows that the differences are small, particularly the difference between $|P_b^{\text{tIP}}|$ and $|P_b^{\text{mf}}|$.

The Reflection Index derived from the triangular flow $F^{\text{t30}}$, with maximal flow at 30% of ejection, shows the strongest correlation, panel B in Figure 4. This correlation, however, is based on more data, including very low values occurring during Valsalva maneuvers and during one of the exercise recordings. In these data no inflection point was found and therefore RI$_{^{\text{tIP}}}$ and AI could not be determined. When these five points are also excluded from the analysis of RI$_{^{\text{t30}}}$, the correlation between RI$_{^{\text{t30}}}$ and RI$_{^{\text{mf}}}$ becomes weaker than the correlation between RI$_{^{\text{tIP}}}$ and RI$_{^{\text{mf}}}$. Thus the use of the inflection point in the pressure wave is preferred to determine the flow wave shape but in case an inflection point cannot be found in the pressure wave, the 30% value of ejection time for the peak time still gives useful results. In all situations in which an Augmentation Index can be determined, the Reflection Index using the flow wave based on the inflection point can be calculated as well.

We defined Reflection Index as the ratio $|P_b|/(|P_f| + |P_b|)$. Wave reflection is usually quantified as the ratio $|P_b|/|P_f|$, which we here call RM for reflection magnitude. The RI is conceptually comparable with the Augmentation Index because both give a similar ratio. For the RI the backward wave, $|P_b|$, with respect to the summed waves, $|P_b| + |P_f|$, is derived. For the AI the secondary pressure increase, related to the backward wave, with respect to total wave (pulse pressure) is calculated. The summation of the amplitudes $|P_b| + |P_f|$ is well defined because timing is excluded from the calculation. In AI the pulse pressure is the summation of the wave shapes, i.e., $P_b(t) + P_f(t)$ and this sum depends on timing as discussed above (Figure 1). The RM and RI as used in the present study can be converted into each other without loss of information:
When the Reflection Magnitude, RM, is calculated as $RM = |P_b| / |P_f|$, average values are $0.70 \pm 0.13$, $0.64 \pm 0.12$ and $0.64 \pm 0.11$ for $RM_{mf}$, $RM_{tIP}$ and $RM_{t30}$, respectively. Both $RM_{tIP}$ and $RM_{t30}$ are significantly different from $RM_{mf}$. The regressions are $RM_{tIP} = 0.79 \, RM_{mf} + 0.08 \, (R^2 = 0.72, n = 21)$ and $RM_{t30} = 0.73 \, RM_{mf} + 0.13 \, (R^2 = 0.65, n = 21)$. These regressions are comparable to those found earlier for the regressions of $RI_{tIP}$ and $RI_{t30}$ on $RI_{mf}$ with exclusion of the data without an inflection point.

We found that the AI varies over a much larger range than the Reflection Index (Figure 4C). From the Bland-Altman plot (Figure 5), we see that both $RI_{tIP}$ and $RI_{t30}$ give results comparable to the measured reflection index, $RI_{mf}$. However, AI is not proportional to the $RI_{mf}$ as can also be seen from Figure 4C in which the regression line has an intercept different from zero. This results from the contribution to wave shapes of incident and reflected waves and on the timing of the reflected wave as can be seen from Figure 1. Even when a reflected wave of similar amplitude returns, the time of reflection has a strong effect on the AI. When the reflected wave returns in diastole (right bottom curve in panel A of Figure 1) the AI does not give a good estimate of the amount of reflection.

By using the information contained in the flow wave, even in the simplified form of a triangle, wave analysis can be carried out and the forward and backward pressure waves can be obtained. From the amplitudes of these waves Reflection Index and Reflection Magnitude can be calculated, without the confounding effects of timing.

The triangular flow, using the assumption that its time of maximum is 30% of the ejection time, is based on average data. To obtain some insight into the errors, we calculated the Reflection Index as a function of peak time, while the ejection period and heart rate were kept constant. We found that the percentage error in $RI$ was about half the percentage error in peak time. Thus, a 10% error in time of peak flow results in a 5% error in $RI$.

The wave shape of pressure and flow depend on the pump function of the heart and the arterial load. In a strong heart, which approximates a flow source, the flow wave will be convex. In a weak heart, which approaches a pressure source, the flow wave will be scalloped or concave (2). We found that convexity of the flow wave shape leads to overestimation and concavity leads to underestimation of the reflection index. We have calculated the reflection index for the most extreme cases of convexity and concavity using a triangular flow and a trapezoidal flow. The trapezoidal flow can accurately
mimic convexity or concavity (Figure 6). This better approximation of the flow wave results in better estimations of the reflection index with errors of 2% and 0% respectively. Using a triangular flow these errors were 15% and 10%. However, these examples are chosen at the extreme of the range of aortic flows. In practice we do not have the information to construct a trapezoidal flow wave shape.

The characteristic impedance derived from triangular flow wave is close to that one derived from measured pressure and flow. The relations between characteristic impedance calculated from measured pressure and flow, and from the triangular flows, $F_{tIP}$ and $F_{t30}$, are given by the following correlation coefficients: $R^2 = 0.86$ for $F_{tIP}$ and $R^2 = 0.89$ for $F_{t30}$. Thus there is good relation between the characteristic impedances. We also found that a factor 2 change is $Z_c$ results in about 16% error in $RI$. This is a substantial change and any real changes in $Z_c$ would be much smaller than that.

The use of the 30% of ejection time allows the calculation of the Reflection Index even if an inflection point in the systolic pressure wave is not apparent. Thus, our method allows comparison of the Reflection Index in young and old subjects. However, by using an average value of 30% of ejection time, individual differences are not accounted for. The use of the inflection point of pressure allows for the estimation a peak time for an individual patient. The calculations to find peak flow from the timing features of the pressure waves, the separation of the waves, and the subsequent calculation of the Reflection Index are straightforward and can be automated, allowing for Reflection Index to be routinely obtained.

As shown in the methods section flow calibration is not required. Moreover, when the Reflection Index is calculated, calibration of the pressure is not required either. This implies that derivation of the Reflection Index has the same advantage as the derivation of the AI, namely that calibration is not necessary.

**Limitations**

The triangular wave shape that is assumed for the flow is an approximation that may differ from the actual flow wave shape. In the present study however, this approximation gave results close to those obtained with high fidelity measured flows even during the Valsalva maneuver and exercise. We therefore believe that the approximation of flow with a triangular shape to calculate $RI$ is a useful one and we showed that the results can give potentially more detailed information on wave reflection than AI.
Perspectives

We suggest that the calculations to quantify wave reflection can also be performed using the carotid pressure wave as a surrogate for the aortic pressure. In this study we have shown that the RI does not depend on the calibration of pressure. Therefore the pressure can be obtained non-invasively, as, for instance, by applanation tonometry. The entire derivation then may be based on the noninvasive measurement of the pressure wave shape only. For instance, the effects of pharmacological interventions on the timing of the reflected wave (21) could be studied without measurement of aortic flow. Also, accurate estimation of the amount of reflection as a function of age in large epidemiological studies is considerably more practical when flow measurement is not required (22). When the calculations are automated, the derivation of the Reflection Index would be as easy as the derivation of the Augmentation Index with improved quantitative information on the magnitude of wave reflection.

Acknowledgements

We cordially thank Dr Viktor Blum, and the Cardiology Service, Brooke Army Medical Center, Fort Sam Houston, TX 78234 (Dr Bernard J. Rubal), for allowing us to use their data.
References


List of abbreviations

AI Augmentation Index calculated as pressure augmentation divided by pulse pressure, $\Delta P/PP$

$F^m$ measured flow wave

$F^{dP}$ triangular flow wave with maximum flow at the time of the inflection point in the pressure wave

$F^{t30}$ triangular flow wave with maximum flow at the time of 30% of ejection time determined from the pressure wave

$\Delta P$ pressure augmentation, the extra rise in pressure after an inflection point

PP pulse pressure

$P^m$ measured pressure wave

$P_f(t)$ forward or incident pressure wave as a function of time

$P_b(t)$ backward or reflected pressure wave as a function of time

$P_f^{mF}, P_b^{mF}$ forward, backward pressure wave determined using measured flow

$P_f^{dP}, P_b^{dP}$ forward, backward pressure wave determined using $F^{dP}$

$P_f^{t30}, P_b^{t30}$ forward, backward pressure wave determined using $F^{t30}$

$|P_f|$ amplitude of $P_f$

$|P_b|$ amplitude of $P_b$

RI Reflection Index calculated as $|P_b|/(|P_f|+|P_b|)$

RM Reflection Magnitude calculated as $|P_b|/|P_f|$

$RI^{mF}, RM^{mF}$ RI and RM calculated from measured pressure and measured flow

$RI^{dP}, RM^{dP}$ RI and RM calculated from measured pressure and $F^{dP}$

$RI^{t30}, RM^{t30}$ RI and RM calculated from measured pressure and $F^{t30}$

$Z_c$ characteristic impedance