Effect of aortic valvular regurgitation upon the impedance cardiogram

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SUMMARY The first derivative thoracic impedance cardiogram, phonocardiogram, and electrocardiogram were recorded in three groups of 22 subjects each. In Group 1 (control), simultaneous impedance cardiogram, phonocardiogram, and aortic valve echocardiograms showed that the X point of the impedance cardiogram occurred synchronously with the aortic second heart sound and with echocardiographic aortic valve closure. In group 2 (clinical diagnosis of aortic regurgitation) the scalar magnitude of the impedance cardiogram O wave and the ratios of the impedance cardiogram wave form X/dz/dtmax and O/dz/dtmax were different from control. In addition, the early diastolic (X) and systolic portions (S) of the impedance cardiogram wave form of group 3 patients were planimetered and expressed as the ratio X/S, called the impedance cardiographic aortic regurgitant fraction (aortic RF1). The aortic RF1 was increased by handgrip, a manoeuvre which acutely increases the magnitude of aortic regurgitation. The difference between Fick cardiac output and left ventricular angiographic output was used to calculate aortic valvular regurgitant fraction, which related closely to the impedance cardiogram. These data suggest that it is useful in the noninvasive assessment of aortic regurgitation.

The impedance cardiogram was developed by Kubicek et al. (1966) as a noninvasive system to monitor cardiac output. This instrument applies a constant current across the chest and the impedance to the current is recorded. Typical records of the impedance cardiogram are shown in Fig. 1 and 2.

A previous study from our laboratory, which recorded the impedance cardiogram and the phonocardiogram simultaneously, showed that the impedance cardiogram X point occurs synchronously with the aortic component of the second heart sound (Lababidi et al., 1970). We have observed the X point to be deeper in subjects with aortic regurgitation than in normal subjects. A study previously reported from our laboratory indicated that though the impedance cardiogram could estimate cardiac output in children, in patients with aortic regurgitation, the impedance cardiogram overestimated the Fick cardiac output (Lababidi et al., 1971). These observations suggested that the impedance cardiogram was affected both in contour and magnitude by aortic regurgitation and might reflect the total left ventricular systolic output, including the regurgitant fraction.

The impedance cardiogram ratio X/dz/dtmax appears to correlate with the severity of aortic regurgitation (Schieken et al., 1975). To confirm these observations, we induced experimental aortic regurgitation in dogs using a specially designed catheter. The aortic regurgitant fraction was calculated using an electromagnetic flowmeter integrated forward and reverse aortic flows. These animal data suggested that the ratio of the area under the X wave divided by the area under the dz/dtmax herein called the impedance cardiogram aortic regurgitant fraction (aortic RF1) correlated well with the regurgitant fraction (r = 0.87) computed from the flowmeter measurements in these animals (Patel et al., 1976).

With these observations in mind, we planned this clinical study to investigate further the temporal relation of the X point to echocardiographic aortic closure and to determine the correlation of the impedance cardiogram aortic RF1 to the aortic

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Fig. 1 Simultaneous recording of the electrocardiogram (ECG), phonocardiogram (phono), echocardiographic aortic valve tracing (echo), and the impedance cardiogram (ICG) in a 10-year-old boy (group 1) with a clinical diagnosis of innocent pulmonary flow murmur. The echocardiographic aortic valve closure occurs shortly before the aortic component of the second heart sound \( (A_2) \), but synchronously with the nadir of the ICG X point \( (x) \).

regurgitant fraction calculated in patients undergoing cardiac catheterisation.

Subjects and methods

The impedance cardiograms of 22 control subjects (group 1) with a normal cardiac examination, 22 patients with a clinical diagnosis of mild to moderate aortic regurgitation (group 2), and 22 patients with a cardiac catheterisation diagnosis of aortic regurgitation (group 3) were recorded on a Minnesota impedance cardiogram Model 202 simultaneously with a phonocardiogram and electrocardiogram. The mean age of group 1 was 22.8 years (range 5 to 52), that of group 2 was 23.8 years (range 5 to 71), and that of group 3 was 31.4 years (range 18 to 56). In group 2 patients, the diagnosis of aortic regurgitation was established clinically by the typical auscultatory findings of an early diastolic decrescendo murmur, loudest at the left sternal border. Of 22 group 2 patients, 8 had both abnormal electrocardiograms with left ventricular hypertrophy, T wave changes, and chest x-ray films showing increased heart size. The impedance cardiogram was recorded in the following manner. Four coated aluminium Mylar strips with an adhesive tape backing were placed around each subject; two strips were placed around the neck and two around the lower thorax (Lababidi et al., 1971). The upper electrodes on the thorax were placed at the level of the xiphoid process. The electrodes on the neck and trunk were placed at least 3 cm apart. The outer two electrodes were attached to a constant current oscillator supplying alternating current at 100 KHz. The first derivative of the electrical impedance between the inner two electrodes was continuously recorded. Echocardiograms of the aortic valve were recorded using a Smith Kline Ekoline 20 ultrasonoscope with a 2·2 or 3·5 mHz transducer with a 1 \( \mu \)s transmission time and a repetition rate of 1000/s. Simultaneous phonocardiograms, with a frequency filter set from 50 to 100 Hz, were recorded from the second right intercostal space.

The wave form of the impedance cardiogram was recorded simultaneously with the echocardiogram, phonocardiogram, and standard lead II of the electrocardiogram on an Electronics for Medicine DR12 modified for echocardiographic recording in 10 subjects from group 1. The intervals from the Q wave of the electrocardiogram to the X point of the impedance cardiogram and the Q wave to the echocardiographic closure of the aortic valve were measured. The uniformity and accuracy of the paper speed (100 mm/s) were measured from 0·04 s time lines generated within the recorder. All impedance cardiographic tracings were recorded in held midexpiration to minimise respiratory variation. The maximal deflection of \( dz/dt_{\text{max}} \), O point, and depth of the X point were measured in ohm/s (Fig. 2). Two ratios \( dz/dt_{\text{max}} \) and \( O/dz/dt_{\text{max}} \) were calculated.

Group 3 patients with aortic valvular regurgitation underwent cardiac catheterisation. Oxygen consumption was measured using a Wright respirometer and a Beckman \( E_\text{a} \) oxygen analyser. The expired air volumes were measured for 3 minutes. Cardiac output was measured by the Fick method. Left ventricular cineangiograms were performed in the right anterior oblique position. All data were analysed randomly without previous knowledge of patient identification. Ventricular volumes were computed using the formula:

\[
\pi \cdot V_0 = -M^2L(CF)^3, \quad \text{where} \quad M = \frac{6}{\text{minor axis in centimetres}}, \quad \text{perpendicular to a major}
\]
axis at mid point, L = major axis in centimetres, taken from the left atrioventricular intersection to apex, and CF = correction factor (Greene et al., 1967). This volume was further corrected using the formula (Kennedy et al., 1970): volume = \( V_0 \times 0.81 + 1.9 \).

The Fick angiographic aortic regurgitant fractions were expressed as the difference between the cineangiographic left ventricular volumes and Fick cardiac output divided by the cineangiographic left ventricular volumes (Kubicke et al., 1966). Impedance cardiograms were performed at cardiac catheterisation during the measurement of oxygen consumption. The planimetered areas \( X \) and \( S \) were measured using a Keuffel-Esser hand planimeter (Fig. 2). The baseline was established by drawing a line between the \( B^o \) of two successive beats. The \( B^o \) which marks the beginning of isovolumetric contraction was identified by the first high frequency component of the first heart sound (Lababidi et al., 1970). The \( X \) wave of the impedance cardiogram was identified and boundaries of that wave which crossed the drawn baseline were \( B' \) and \( X' \) (Fig. 2). The planimetered areas \( B' \) to \( X' \) (\( \bar{X} \)) and \( B^o \) to \( B' \) (\( \bar{S} \)) were used to compute the ratio \( \bar{X} / \bar{S} \). This ratio was called the impedance cardiographic aortic regurgitant fraction (aortic RF1).

For each subject in group 3, a correlation was sought between the impedance cardiogram \( X \) and the Fick angiographic regurgitant volume. In addition, a correlation was sought between the impedance cardiogram \( S \) and the cineangiographic left ventricular stroke volume.

Because our data showed a high correlation between \( X \) and regurgitant volume and a similar high correlation between \( S \) and left ventricular stroke volume, by substituting \( X \) and \( S \) into the standard formula for cardiac catheterisation deter-
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derived aortic RFf:

\[ AR_f = \frac{\text{Cineangiographic LVSV - Fick stroke volume}}{\text{Cineangiographic LVSV}} \times 100\% \]

Then substituting the impedance cardiogram equivalents of regurgitant volume (X) and cineangiographic left ventricular stroke volume (S) the formula becomes

\[ AR_f = \frac{X}{S}. \]

To test whether indeed the X/S is a measure of regurgitant fraction it was compared with the catheterisation-measured regurgitant fraction.

After cardiac catheterisation 8 patients of group 3 were asked to perform maximal sustained handgrip, and were then allowed to rest. The impedance cardiogram was measured at rest and during 25 per cent of maximal handgrip during held mid-expiration.

All data are expressed as the mean ±1 standard deviation. The significance of difference between the means was calculated by employing either group or paired t tests.

To test the reliability of the aortic RFf, we measured an additional 3 beats the next day in 10 patients from group 3. These 3 beats were compared one with another and their average with the previous average aortic RFf. The reliability between beats within the same individual and between the averages of two different sets of beats was determined for the impedance cardiogram. This was calculated using a 2 factor (randomised block) analysis of variant design.

Results

The X point of the impedance cardiogram is an event that occurs nearly synchronously with aortic valve closure. In 10 of 22 control subjects who had echocardiograms of the aortic valve, the Q to aortic closure time (0·36 ± 0·08 s) was not significantly different from the Q to X point on the impedance cardiogram (0·34 ± 0·06) (Fig. 1). An analysis of variance indicated no significant difference between these intervals (r = 0·87).

The impedance wave for scalar measurements in both group 2 and group 3 were compared with group 1 (Table 1). There was no significant difference between the measurement of the height of dz/dtmax or the depth of the X point between the groups. None the less, the X point appeared to be increased in subjects with aortic regurgitation. The O point was diminished (P < 0·01) in subjects with aortic regurgitation. The ratio X/dz/dtmax was increased (P < 0·001) and the ratio O/dz/dtmax was diminished (P < 0·01) in subjects with aortic regurgitation.

The catheterisation measurements in group 3 patients of left ventricular stroke volume, aortic regurgitant stroke volume, regurgitant fraction, and the impedance measurements, S, X, and ratio X/S are given in Table 2. In group 3 patients (Table 2), there was a range of angiographic stroke volumes of 32 to 156 ml. The impedance area S correlated (r = 0·96) with left ventricular stroke volume; while X correlated (r = 0·89) with aortic regurgitant volume. The ratio X/S, the aortic RFf, correlated highly with the angiographic aortic regurgitant fraction (r = 0·90). This relation is shown in Fig. 3.

Sustained handgrip of 25 per cent maximum grip increased the aortic RFf in all 8 patients. The aortic RFf rose from a resting level of 0·48 ± 0·09 to 0·71 ± 0·1 (P < 0·01).

Statistical analysis of the reproducibility of the impedance cardiogram measurements (X, S) showed that the intraclass correlation coefficient was 0·94 between beats within the same individual and 0·85 between the averages of two different sets of beats in the same individual recorded on the next day.

Discussion

The data presented confirm the temporal relation of the impedance cardiogram X point to aortic closure. This temporal relation allows the impedance cardiogram X point to be a useful marker

Table 1  First derivative impedance cardiogram measurements in control subjects and patients with aortic regurgitation

<table>
<thead>
<tr>
<th>Subjects</th>
<th>No.</th>
<th>( \frac{dz}{dt_{\text{max}}} ) (( \text{\Omega} )s)*</th>
<th>X point (( \text{\Omega} )s)*</th>
<th>O point (( \text{\Omega} )s)*</th>
<th>X</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>[\text{\Omega} \text{S}]</td>
<td>[\text{\Omega} \text{S}]</td>
<td>[\text{\Omega} \text{S}]</td>
<td>[\text{\Omega} \text{S}]</td>
<td>[\text{\Omega} \text{S}]</td>
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<tr>
<td>Group 1</td>
<td>22</td>
<td>2·64 ± 0·95</td>
<td>0·93 ± 0·36</td>
<td>0·42 ± 0·24</td>
<td>0·35 ± 0·02</td>
<td>0·16 ± 0·08</td>
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<tr>
<td>Group 2</td>
<td>22</td>
<td>2·50 ± 1·08</td>
<td>1·20 ± 0·51</td>
<td>0·17 ± 0·09†</td>
<td>0·51 ± 0·19†</td>
<td>0·08 ± 0·07†</td>
</tr>
<tr>
<td>Group 3</td>
<td>22</td>
<td>2·73 ± 0·96</td>
<td>1·57 ± 0·49</td>
<td>0·15 ± 0·08‡</td>
<td>0·46 ± 0·12‡</td>
<td>0·08 ± 0·08‡</td>
</tr>
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</table>

*These values are the means and standard deviations of the maximal heights or depths of these points.
†Indicates a significance level of P < 0·01, comparing group 1 measurements (control) with group 2 or group 3 by group t tests.
Table 2  Cardiac catheterisation and impedance cardiogram data in group 3 subjects (n = 22)

<table>
<thead>
<tr>
<th>S (Ohms)</th>
<th>Angiographic left ventricular stroke volume (ml/beat)</th>
<th>X (Ohms)</th>
<th>Fick angiographic regurgitant volume (ml)</th>
<th>Fick angiographic regurgitant fraction (%)</th>
<th>Aortic RFi X/S (%)</th>
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<tr>
<td>3.86</td>
<td>192</td>
<td>1.0</td>
<td>42.24</td>
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<td>26</td>
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<tr>
<td>3.19</td>
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<td>0.56</td>
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<tr>
<td>4.02</td>
<td>200</td>
<td>2.13</td>
<td>92.0</td>
<td>46</td>
<td>52</td>
</tr>
<tr>
<td>2.3</td>
<td>120</td>
<td>0.60</td>
<td>36.0</td>
<td>30</td>
<td>26</td>
</tr>
<tr>
<td>5.5</td>
<td>231</td>
<td>2.02</td>
<td>103.95</td>
<td>45</td>
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<tr>
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<tr>
<td>6.6</td>
<td>260</td>
<td>3.4</td>
<td>114.4</td>
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<td>51</td>
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<tr>
<td>8.4</td>
<td>265</td>
<td>4.8</td>
<td>129.85</td>
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<tr>
<td>4.8</td>
<td>230</td>
<td>2.6</td>
<td>138</td>
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<td>5.7</td>
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<td>4.1</td>
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<td>119.7</td>
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<td>44.2</td>
<td>68</td>
<td>69</td>
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<tr>
<td>2.95</td>
<td>150</td>
<td>1.35</td>
<td>54</td>
<td>36</td>
<td>45</td>
</tr>
<tr>
<td>5.3</td>
<td>220</td>
<td>1.9</td>
<td>77</td>
<td>35</td>
<td>36</td>
</tr>
<tr>
<td>2.9</td>
<td>145</td>
<td>1.6</td>
<td>63.8</td>
<td>44</td>
<td>55</td>
</tr>
<tr>
<td>3.9</td>
<td>195</td>
<td>2.3</td>
<td>109.2</td>
<td>56</td>
<td>58</td>
</tr>
<tr>
<td>1.9</td>
<td>90</td>
<td>1.1</td>
<td>54</td>
<td>60</td>
<td>57</td>
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<tr>
<td>3.1</td>
<td>174</td>
<td>1.78</td>
<td>87</td>
<td>50</td>
<td>57</td>
</tr>
<tr>
<td>5.4</td>
<td>210</td>
<td>1.8</td>
<td>94.5</td>
<td>45</td>
<td>33</td>
</tr>
<tr>
<td>2.8</td>
<td>140</td>
<td>1.5</td>
<td>64.4</td>
<td>46</td>
<td>53</td>
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</table>

Fig. 3  Relation of the impedance cardiogram aortic regurgitant fraction (aortic RFi) to the angiographically determined regurgitant fraction. The dotted lines represent the 95 per cent confidence limits.

for the aortic component of the second heart sound.

The physical principles that govern changes in the impedance cardiogram are not completely understood. Kubicek and others using simultaneous recordings of impedance and aortic flow in dogs showed the relation of peak dz/dt max to the peak aortic ejection rate (Kubicek et al., 1974).

We have shown that the systolic portion of the impedance cardiogram (S) has a strong correlation with the left ventricular stroke volume as determined by cineangiography. In patients with aortic regurgitation, the cineangiographic left ventricular stroke volume exceeds the Fick calculated cardiac output. The regurgitant volume within the left ventricle is responsible for this discrepancy.

The early diastolic portion of the impedance cardiogram (X) correlates highly with the per beat volume regurgitated across the aortic valve. This explains the deepened X point observed in subjects with aortic regurgitation. Moreover, the impedance cardiogram ratio X/S, the aortic RFi, correlates with the resting aortic regurgitant fraction found at cardiac catheterisation.

To test the response of the impedance cardiogram ratio X/S to acute changes in the regurgitant volume, we employed isometric handgrip exercise, which has been shown to increase the amount of aortic regurgitation (Lind et al., 1964; Kivowitz et al., 1971). Because the aortic RFi did increase with handgrip, the impedance cardiogram appears to respond concordantly to an acute change in regurgitant volume.

The noninvasive assessment of the severity of aortic regurgitation is difficult. Bounding peripheral pulses are unreliable markers for severe aortic regurgitation (Demany and Zimmerman, 1966). Early mitral valve closure is found by echocardiography with severe aortic regurgitation (Botvinick et al., 1975). Left ventricular dysfunction associated with severe aortic regurgitation correlates with
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change in fraction of shortening of the echocardiographic minor axis (McDonald, 1976). Moreover, Boughner has found transcutaneous Doppler assessment to relate closely to the regurgitant fraction (Boughner, 1975). Despite these techniques, the clinical assessment of aortic regurgitation remains difficult.

Our findings, both clinical and experimental, suggest that the impedance cardiogram may prove to be a sensitive noninvasive measure of the severity of aortic regurgitation.

References


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