The First Derivative Thoracic Impedance Cardiogram

By ZuHdi Lababidi, M.D., D. A. Ehmke, M.D., Ph.D., Robert E. Durnin, M.D., Paul E. Leaverton, Ph.D., and Ronald M. Lauer, M.D.

SUMMARY

When an alternating current of high frequency is applied to the thorax, the first derivative of the impedance to this current is affected by the cardiac cycle resulting in a characteristic waveform.

Phonocardiograms, electrocardiograms, and first derivative thoracic impedance cardiograms were recorded simultaneously in 91 subjects. The first derivative thoracic impedance cardiograms were found to have sharply demarcated points which occur synchronously with the first heart sound, aortic second sound, pulmonic second sound, mitral opening snap, third heart sound, and fourth heart sound. The first derivative thoracic impedance cardiogram may thus be used not only as a reference tracing to help identify heart sounds on the phonocardiogram, but also for directly timing the intervals within the cardiac cycle.

Additional Indexing Words:
Phonocardiogram Temporal relationships of phonocardiogram

If two electrodes in a high frequency circuit are placed on the thorax, changes in impedance may be recorded which are synchronous with events in the cardiac cycle. Investigators, including Nyober,1 Rushmer,2 Bonjer,3 Kubicek,4, 5 and their associates, have suggested that the impedance changes are related to cardiac volumetric changes. Hill and co-workers6 have questioned whether the impedance change was related to outward mechanical pressures resulting from cardiac action causing impedance variations at the electrode-tissue interface.

A four electrode impedance cardiograph was developed by Kubicek et al.4 for the recording of thoracic impedance changes during the cardiac cycle. This unit among other outputs allows the direct recording of impedance changes and their first derivatives. Utilizing such an instrument, we observed that the first derivative of the impedance has a waveform which is synchronous with the cardiac cycle. The purpose of this report is to describe the waveform of the first derivative impedance cardiogram and its relationship to heart sounds and events in the cardiac cycle.

Methods

A Minnesota impedance cardiograph,* Model 202, was used to record an impedance signal in 91 subjects. Four aluminized Mylar strips† with an adhesive tape backing were placed around each subject as shown in figure 1. The outer two electrodes were attached to a constant current oscillator supplying alternating current at 100 kHz, and the electrical impedance between the inner two electrodes was continuously recorded.

*Manufactured by the Department of Physical Medicine & Rehabilitation, University of Minnesota.
†Minnesota Mining & Manufacturing Co., St. Paul, Minnesota.

From the University of Iowa, Section of Pediatric Cardiology, Department of Pediatrics, and the Department of Preventive Medicine and Environmental Health, University Hospitals, Iowa City, Iowa.

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Address for reprints: Department of Pediatrics, Section of Pediatric Cardiology, University Hospitals, Iowa City, Iowa 52240.

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The impedance was markedly affected both by respiration and by the cardiac cycle. The impedance signal was passed through a differentiator circuit, and the first derivative of the impedance was found to be less affected by the respiratory movements.

The wave form of the first derivative thoracic impedance cardiogram was recorded simultaneously with a surface phonocardiogram and lead II of the electrocardiogram on an Electronics for Medicine recorder (Model DR-12) at a paper speed of 150 mm/sec. The uniformity and accuracy of the paper speed were measured from 0.04-sec time lines generated within the recorder. The phonocardiograms were recorded at the second and the fourth left intercostal space, and the apex of the heart with frequency filters set from 100 to 500 Hz. Phonocardiograms at the apex were also recorded at a frequency range of 50 to 100 Hz.

The morphology of the first derivative thoracic impedance cardiogram is shown in figure 2. Decreasing rates of impedance change are recorded as upward deflections in the tracing. The points A, B, X, Y, O, and Z are deflections in the first derivative of the impedance signal which relate in time to events in the phonocardiogram:

A, with the beginning of the fourth heart sound; B, with the maximal vibration of the first heart sound at the apex; X, with aortic closure; Y, with pulmonic closure; O, with the mitral opening snap, and Z, with the maximal vibration in the third heart sound.

The phonocardiograms and first derivative thoracic impedance cardiograms of 91 subjects were studied. Their ages and whether they had underlying heart disease are shown in table 1. Independent measurements of the intervals between the electrocardiographic R wave and events in the phonocardiogram and between the electrocardiographic R wave and points on the first derivative thoracic impedance cardiogram were carried out. The intervals were measured with a millimeter ruler thus allowing measurements to be made to 0.006 sec at a paper speed of 150 mm/sec. Beats for measurement were selected on the basis of having readily recognized phonocardiographic and first derivative thoracic impedance cardiographic events. The intervals were measured in an average of four beats per subject, and the averages of the phonocardiographic and the impedance intervals were compared.

### Table 1

<table>
<thead>
<tr>
<th>Events</th>
<th>Number of subjects</th>
<th>Age (yr)</th>
<th>Sex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phono Impedance</td>
<td>Total</td>
<td>Cardiacs</td>
<td>Normals</td>
</tr>
<tr>
<td>Si, S1</td>
<td>27</td>
<td>14</td>
<td>13</td>
</tr>
<tr>
<td>A1, P2</td>
<td>37</td>
<td>16</td>
<td>21</td>
</tr>
<tr>
<td>OS</td>
<td>10</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>S1</td>
<td>17</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>

*Circulation, Volume XLI, April 1970*
Phonocardiograms. (A) Obtained at the cardiac apex of a patient with Ebstein's malformation. The A point of the first derivative thoracic impedance cardiogram occurs synchronously with the fourth heart sound. (B) Obtained at the cardiac apex of a normal subject. The B and Z points of the first derivative thoracic impedance cardiogram occur synchronously with the first and third heart sounds respectively. (C) Obtained at the pulmonic area of a normal subject. The X and Y points of the first derivative thoracic impedance cardiogram occur synchronously with the maximal deflection of the aortic and pulmonic closure sounds, respectively.

Key to abbreviations used on all illustrations: ACG = apexcardiogram with the O point (O) and rapid filling wave (RFW); EKG = electrocardiogram; impedance = first derivative thoracic impedance cardiogram with the points A, B, X, Y, O, and Z; phono = phonocardiogram with the first heart sound (S1), second heart sound (S2), aortic second sound (A2), pulmonic second sound (P2), opening snap (O.S.), third heart sound (S3), and fourth heart sound (S4). All time lines denote interval of 0.04 sec.

Results

Consistency of the Wave Form

To determine the consistency of the first derivative thoracic impedance cardiogram wave form, 469 beats of the 91 subjects were reviewed. The number of beats without recognizable impedance points are summarized in table 2.

Impedance Cardiogram

A Point

The records of 27 subjects who had well-recorded first heart sounds on the phonocardiogram, A points on the first derivative thoracic impedance cardiogram, and P waves on the electrocardiogram were selected. Ninety-seven beats with an average of 4 beats/subject were examined. In all of these, the A point occurred on the impedance cardiogram during the interval between the end of the P wave and the beginning of the QRS complex on the electrocardiogram. A fourth heart sound could be recorded in nine of these 27 subjects. In these nine patients, the A point occurred simultaneously with the beginning of the fourth heart sound (table 3).

In two other subjects with complete heart block, the A point of the impedance cardiogram was observed to follow the P wave of the electrocardiogram as it occurred in variable relationship to the ventricular depolarization (fig. 3).

B Point

The 27 subjects were also studied for the B point relationship to the maximal deflection of the first heart sound at the apex of the heart.
Table 2

Consistency of the First Derivative Thoracic Impedance Cardiogram Wave Form: 469 Consecutive Heart Beats in 91 Subjects

<table>
<thead>
<tr>
<th>Impedance points</th>
<th>Heart beats without a definite impedance point</th>
<th>Subjects without a definite impedance point in all beats</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>45 9.6</td>
<td>2 2.2</td>
<td>4/45 beats—short PR</td>
</tr>
<tr>
<td>B</td>
<td>12 2.5</td>
<td>0 0</td>
<td>4/12 beats—Ebstein's anomaly</td>
</tr>
<tr>
<td>X</td>
<td>21 4.5</td>
<td>0 0</td>
<td>8/21 beats—60 cycle electrical interference</td>
</tr>
<tr>
<td>Y</td>
<td>98 21.0</td>
<td>0 0</td>
<td>72/98 beats—60 cycle electrical interference</td>
</tr>
<tr>
<td>O</td>
<td>68 14.5</td>
<td>0 0</td>
<td>These beats were analyzed without reference to the phase of respiration. Inspiration enhances the O, Z configuration.</td>
</tr>
<tr>
<td>Z</td>
<td>112 24.0</td>
<td>0 0</td>
<td></td>
</tr>
</tbody>
</table>

Ninety-seven beats with an average of 4 beats/subject were examined. Data relating the B point to the first heart sound are shown in table 3. In 19 subjects the B point was synchronous with the maximal deflection of the first heart sound at the apex; in the remaining eight, it occurred within 0.002 sec of the first heart sound.

**X and Y Points**

Tracings obtained from another 37 subjects were selected because both components of the second heart sound, and the X and Y points

Table 3

Difference Between Phonocardiogram and Impedance Cardiogram Intervals

<table>
<thead>
<tr>
<th>Subjects</th>
<th>(R to S1)</th>
<th>(R to S0)</th>
<th>(R to A)</th>
<th>(R to B)</th>
<th>(R to X)</th>
<th>(R to Y)</th>
<th>(R to O)</th>
<th>(R to Z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. with identical intervals</td>
<td>9</td>
<td>19</td>
<td>28</td>
<td>25</td>
<td>6</td>
<td>14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Difference between average intervals (sec)*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. without identical intervals</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>-</td>
<td>-0.002</td>
<td>-0.002</td>
<td>-0.003</td>
<td>-0.01</td>
<td>-0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>-0.002</td>
<td>-0.002</td>
<td>-0.003</td>
<td>-0.01</td>
<td>-0.01</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>-0.002</td>
<td>-0.002</td>
<td>-0.004</td>
<td>+0.01</td>
<td>-0.01</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>-0.002</td>
<td>-0.003</td>
<td>-0.004</td>
<td>+0.01</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>+0.002</td>
<td>-0.007</td>
<td>-0.005</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>+0.002</td>
<td>+0.002</td>
<td>+0.002</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>+0.002</td>
<td>+0.003</td>
<td>+0.002</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>+0.002</td>
<td>+0.003</td>
<td>+0.005</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>-</td>
<td>+0.010</td>
<td>+0.007</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+0.008</td>
<td>-</td>
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<td>-</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+0.010</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+0.010</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Total subjects</td>
<td>9</td>
<td>27</td>
<td>37</td>
<td>37</td>
<td>10</td>
<td>17</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*An average of 4 beats/subject was measured. The average differences between the phonocardiographic and impedance intervals are shown. Note that measurement accuracy is only to 0.006 sec, but average of differences may be as low as 0.002 sec.

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were well recorded. The time intervals between the electrocardiographic R wave and the maximal deflection of the aortic and pulmonic second heart sounds were independently measured and compared with the intervals between the electrocardiographic R wave and the X and Y points on the first derivative thoracic impedance cardiogram. One hundred and forty-six beats were measured with an average of 4 beats/subject. The results were as shown in table 3. Twenty-eight of the X points were synchronous with the aortic closure, and 25 of the Y points were synchronous with the pulmonic closure; the remainder varied within 0.01 sec.

The duration between the X and the Y points of the first derivative thoracic impedance cardiogram and the intervals from the maximal deflection of the aortic second sound to the maximal deflection of the pulmonic second sound were averaged for each subject.

Figure 3
Patient with complete heart block. The A points on the impedance cardiogram follow the P waves on the electrocardiogram. See figure 2 for abbreviations on this and subsequent illustrations.

Figure 4
The relationship between the X-Y interval on the first derivative thoracic impedance cardiogram and the interval between the aortic and pulmonic second sounds in 29 subjects. Dashed lines indicate 0.01 sec time limits. \(X_m\) and \(Y_m\) refer to the maximal deflections of the X and Y waves.
stenosis with well-recorded opening snaps were chosen. An average of 4 beats/subject were measured. Data relating the intervals from electrocardiographic R wave to the impedance O point, and the intervals between the electrocardiographic R wave and the maximal vibration of the phonocardiographic opening snap are shown in Table 3. In six of the subjects, the O point of the first derivative thoracic impedance cardiogram was synchronous with the opening snap; in the remaining four, it occurred within 0.01 sec.

Figure 6 shows a simultaneously recorded apexcardiogram, phonocardiogram, and first derivative thoracic impedance cardiogram. The O point of the apexcardiogram is synchronous with the O point of the impedance cardiogram and the opening snap of the phonocardiogram.

Z Point

The phonocardiograms of 17 subjects were chosen with well-recorded third heart sounds and first derivative thoracic impedance cardiogram Z points during held inspiration. It has been observed that inspiration enhances the Z point configuration. Sixty-two beats with an average

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**Figure 5**

Tracings obtained on a normal child. The X-Y intervals vary with the A2-P2 intervals with respiration.

**Figure 6**

Tracings from two patients with mitral stenosis. (A) A woman, 26 years old. (B) A man, 50 years old. The O point of the apexcardiogram and opening snap of the phonocardiogram are synchronous with the O point of the first derivative thoracic impedance cardiogram.
The third heart sound of the phonocardiogram and the rapid filling wave of the apexcardiogram are synchronous with the Z point of the first derivative thoracic impedance cardiogram.

of 4 beats/subject were measured. Data relating the intervals from the electrocardiographic R waves to the Z points, and the intervals from the electrocardiographic R waves to the peak of the third heart sounds are shown in table 3. In 14 subjects, the Z point was synchronous with the third heart sound; in the remaining three, it occurred within 0.01 sec. Figure 7 shows the relationship between the Z point of the impedance cardiogram to the third heart sound and the rapid filling wave of the apexcardiogram.

Discussion

In clinical situations wherein the heart sounds are obscured by murmurs or in which they are difficult to recognize, the first derivative thoracic impedance cardiogram may be a useful tool in timing heart sounds. Figure 8A shows a phonocardiogram of a patient with pulmonic stenosis with intact ventricular septum. The pulmonic closure is difficult to discern on the phonocardiogram, but the tracing of first derivative thoracic impedance shows both X and Y points thus allowing the width of the split of the second heart sound to be estimated. Figure 8B shows the phonocardiogram of a patient with a patent ductus arteriosus. The aortic and pulmonic second sounds are obscured by the murmur. The X and Y points allow their recognition and timing. Figure 6 shows the

Figure 7

The third heart sound of the phonocardiogram and the rapid filling wave of the apexcardiogram are synchronous with the Z point of the first derivative thoracic impedance cardiogram.

Figure 8

(A) Tracing from patient with severe valvular pulmonic stenosis. (B) Tracing from patient with patent ductus arteriosus.

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phonocardiograms of two patients with mitral stenosis. The opening snap occurs after the first derivative impedance Y point and is synchronous with the O point of the first derivative impedance cardiogram. The Z point relates to the third heart sound.

The first derivative thoracic impedance cardiogram is recorded easily without the necessity of searching for pulsations. It has sharply demarcated points that relate in time to the four heart sounds and to the opening snap in mitral stenosis. These points are consistent both in normal subjects and in those with heart disease. Thus, the impedance cardiogram can be used not only as a reference tracing for simultaneously recorded phonocardiograms, but also for directly timing intervals within the cardiac cycle.

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