Studies of Quantitative Ballistocardiography

The Velocity of Body Displacement in Patients with Heart Disease

By Vincenzo Masini, M.D., and Paolo Rossi, M.D.

The speed of body displacement was calculated on 70 per cent of the ballistocardiograms recorded in 128 patients suffering from heart disease. Results show that the values are generally lower in cardiac patients than in normal subjects, with the exception of cases with high stroke volume. The diminution of the speed of body displacement is proportional to the severity of ballistic abnormalities and to the functional state of the heart. A tentative explanation of the findings is presented.

In a preceding paper we suggested that the velocity of body displacement (Vb) be used as an index of quantitative ballistocardiography, inasmuch as the calculations of cardiac output and maximal cardiac force, according to Starr, are methods open to criticism on both theoretic and practical grounds.

According to our experience, the velocity of body displacement is a useful and practical index for the following reasons: (1) It is a direct expression of the ballistic forces which develop during the ejection phase of the ventricular systole, and thus it gives an indirect estimate of the work and strength of the heart. (2) The values obtained are uniform and independent of body weight and surface area. (3) The calculation is simple. (4) The value may be calculated not only on normal tracings but also on tracings which are abnormal in form.

The value of the velocity of body displacement is obtained by dividing the vertical distance between the tips of the I and J waves, expressed in millimeters, by the time in seconds between the same points (fig. 1). In our study of 100 normal subjects, we found that the mean value was 68 with a standard deviation about the mean of 14 mm. per second. This value is higher in the male (76 with a standard deviation about the mean of 17.5 mm. per second) than in the female (59 with a standard deviation about the mean of 11 mm. per second).

We have now estimated the speed of body displacement in patients suffering from heart disease, in order to study its relations with the type of heart disease, the functional state of the heart and the various ballistic patterns.

Clinical Material and Results

Our cases included 148 cardiac patients (105 men and 43 women), ranging in age from 10 to 80 years (average age 40 years). Of these, 29 had mitral and 18 aortic or combined mitral and aortic valvular disease; 23 had arteriosclerotic heart disease without hypertension; 34 had hypertensive heart disease; 17 had arteriosclerotic heart disease complicated by angina pectoris or myocardial infarction; 21 had congenital heart disease and 6 adhesive chronic pericarditis.

The congenital malformations included nine cases of tetralogy of Fallot, four of pentalogy of Fallot, one of trilogy of Fallot, one of isolated pulmonary stenosis, two of patent ductus arteriosus, and three of stenosis of the isthmus of the aorta. In three cases the type of congenital malformation was not established.

Simultaneous recording of the ballistocardiogram and the electrocardiogram was made in every case. We used a personally devised high-frequency swinging bed ballistocardiograph, which was calibrated in the usual manner, a weight of 280 Gm. causing a deflection of 1 cm. The record was made with a larger amplification than usual, in order to make a more detailed study of the form and duration of the ballistic waves. The tracings

From the Istituto di Patologia Medica of the University of Rome, Italy.

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TABLE 1.—Frequency, in Total and Per Cent Figures, of the Different Ballistic Patterns in the Different Types of Heart Disease

<table>
<thead>
<tr>
<th>Type of Heart Disease</th>
<th>No. of cases</th>
<th>Normal No.</th>
<th>Normal %</th>
<th>Borderline No.</th>
<th>Borderline %</th>
<th>Early M No.</th>
<th>Early M %</th>
<th>Totally Abnormal No.</th>
<th>Totally Abnormal %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mitral valvular disease</td>
<td>29</td>
<td>14</td>
<td>48.3</td>
<td>6</td>
<td>20.7</td>
<td>3</td>
<td>10.4</td>
<td>6</td>
<td>20.7</td>
</tr>
<tr>
<td>Aortic valvular disease</td>
<td>18</td>
<td>8</td>
<td>44.4</td>
<td>6</td>
<td>33.4</td>
<td>1</td>
<td>5.5</td>
<td>3</td>
<td>16.7</td>
</tr>
<tr>
<td>Arteriosclerotic heart disease</td>
<td>23</td>
<td>7</td>
<td>30.4</td>
<td>8</td>
<td>10.6</td>
<td>5</td>
<td>21.6</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>Hypertensive heart disease</td>
<td>34</td>
<td>9</td>
<td>26.5</td>
<td>13</td>
<td>38.3</td>
<td>9</td>
<td>26.4</td>
<td>3</td>
<td>8.8</td>
</tr>
<tr>
<td>Coronary heart disease</td>
<td>17</td>
<td>8</td>
<td>47.1</td>
<td>2</td>
<td>11.7</td>
<td>3</td>
<td>17.7</td>
<td>4</td>
<td>23.5</td>
</tr>
<tr>
<td>Congenital heart disease</td>
<td>21</td>
<td>20</td>
<td>95.3</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1</td>
<td>4.7</td>
</tr>
<tr>
<td>Pericarditis</td>
<td>6</td>
<td>4</td>
<td>66.6</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1</td>
<td>16.7</td>
<td>16.7</td>
</tr>
<tr>
<td>Total No. of cases</td>
<td>148</td>
<td>70</td>
<td>47.3</td>
<td>35</td>
<td>23.7</td>
<td>22</td>
<td>14.8</td>
<td>21</td>
<td>14.2</td>
</tr>
</tbody>
</table>

were recorded in inspiratory apnea, expiratory apnea, and during normal respiration, but the calculations were all made on the tracings recorded in expiratory apnea, because in this position a complete absence of artifacts is more easily obtained.

We customarily classify the ballistic patterns into six groups: (1) Normal. Tracings with normal amplitude, duration and contour of the various deflections and normal relations between the various waves are included in this group. (2) Tracings which are borderline by reason of slight abnormalities in form of one or a few deflections (notching of the I-J segment, splitting of the apex of H or J, notching of K, H waves as high or higher than I waves, L waves as high or higher than J waves, etc.). (3) Tracings which are border-

line because of diminished depth of the I wave which reaches the baseline but does not cross below it as normally. (4) Abnormal tracings of the “early M” type. Because of the diminished I, the ballistic complex loses its common W-shaped appearance and resembles an M. This group can be further subdivided into two groups, on the basis of the large or small size of the H wave. (5) Tracings with prominent diastolic waves. The marked decrease in the amplitude of H, I and J causes K and the other diastolic waves to stand out as the dominant deflections. (6) Totally abnormal tracings. The pattern is completely irregular and indefinite and the complexes vary in form from beat to beat.

For this study we have used a simplified classification, dividing the tracings into four main groups:

1. Normal. This corresponds to groups 1 and 2 of the preceding classification.
2. Borderline. Tracings showing reduced amplitude of the I wave are so classified.
3. Early M pattern.
4. Completely abnormal. This corresponds to groups 5 and 6 of the preceding classification.

Table 1 shows the frequency, in total figures and percentages, of the different abnormalities in the total number of cases and the different forms of heart disease.

On the ballistic tracings of 128 patients (that is, on all the tracings except those with a completely abnormal pattern) we have
calculated the velocity of body displacement according to the technic described in an earlier paper, dividing the distance, expressed in millimeters, from I to J by the time in seconds between the same points. Results are shown in figures 2 and 3.

The functional state of the heart was known in 121 cases. In this respect the patients were divided into two groups: group 1 includes patients classified as 1 and 2a (subjects with normal functional capacity or slight exertional dyspnea); group 2 includes the subjects classified as 2b and 3 (dyspnea even at rest or signs of congestive heart failure). The values of the velocity of body displacement according to the type of heart disease and the functional capacity of the heart are shown in figure 2. Table 2 shows the mean values for the speed of body displacement in the total number of cases, the various types of heart disease

![Fig. 2](image1.png)

**Fig. 2.** Values of the speed of body displacement (Vb) according to cardiac functional capacity and the type of heart disease. a, aortic valvular disease; b, mitral valvular disease; c, arteriosclerotic heart disease; d, hypertensive heart disease; e, arteriosclerotic heart disease with angina pectoris or infarction; f, congenital heart disease; g, adhesive pericarditis. Broken line indicates upper limit of mean values in normal subjects.

![Fig. 3](image2.png)

**Fig. 3.** Values of the speed of body displacement (Vb) in the different ballistic patterns.

**Table 2.**—Mean Values of the Velocity of Body Displacement in the Total Number of Cases, the Various Types of Heart Disease and in the Different Grades of Cardiac Functional Capacity

<table>
<thead>
<tr>
<th>Type of Heart Disease</th>
<th>No. of Cases</th>
<th>Functional Capacity</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Grades 1 &amp; 2a</td>
<td>Grades 2b &amp; 3</td>
</tr>
<tr>
<td>Aortic valvular disease</td>
<td>16</td>
<td>87</td>
<td>75.6</td>
</tr>
<tr>
<td>Mitral valvular disease</td>
<td>20</td>
<td>50.8</td>
<td>31.4</td>
</tr>
<tr>
<td>Arteriosclerotic heart disease</td>
<td>17</td>
<td>29</td>
<td>19</td>
</tr>
<tr>
<td>Hypertensive heart disease</td>
<td>30</td>
<td>37.7</td>
<td>27.3</td>
</tr>
<tr>
<td>Coronary heart disease</td>
<td>12</td>
<td>32.3</td>
<td>30</td>
</tr>
<tr>
<td>Congenital heart disease</td>
<td>21</td>
<td>39.2</td>
<td>20.2</td>
</tr>
<tr>
<td>Pericarditis</td>
<td>5</td>
<td>35</td>
<td>15</td>
</tr>
<tr>
<td>Total no. of cases</td>
<td>121</td>
<td>42</td>
<td>33.3</td>
</tr>
</tbody>
</table>
TABLE 3.—Mean Values of the Velocity of Body Displacement in the Different Ballistic Patterns

<table>
<thead>
<tr>
<th>Ballisticardiogram</th>
<th>No. of Cases</th>
<th>Mean Value of Vb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>70</td>
<td>41.7</td>
</tr>
<tr>
<td>Borderline</td>
<td>35</td>
<td>35.2</td>
</tr>
<tr>
<td>Early M</td>
<td>22</td>
<td>26.3</td>
</tr>
<tr>
<td>Total</td>
<td>127</td>
<td>36.7</td>
</tr>
</tbody>
</table>

A. Aortic insufficiency
Vb: 133.2 mm/sec.
Borderline pattern

B. Mitral valvular disease
Vb: 89 mm/sec.
Normal Pattern

C. Mitral valvular disease
Vb: 33 mm/sec.
Normal Pattern

D. Arteriosclerotic heart disease
Vb: 25 mm/sec.
Early M pattern

E. Same case as in D with increased amplification

F. Arteriosclerotic heart disease
Vb: 30 mm/sec.
Early M pattern

G. Same case as in F with increased amplification

FIG. 4. Some examples of the speed of body displacement (Vb).

and in the different grades of cardiac functional capacity.

The relation between the values of the speed of body displacement and the form of the ballisticardiogram is shown in figure 3 (single values) and table 3 (mean values).

COMMENT

The following conclusions may be drawn from our study:

1. The speed of body displacement can be calculated in a large percentage of heart patients; that is, on all the ballisticardiograms in which the I-J interval can be identified with certainty. This proves the practical value of this index which, in this respect, is of greater value than the calculation of stroke volume, inasmuch as the latter can only be computed on tracings normal in form.

2. The figures for the velocity of body displacement are usually lower in cardiac patients than in normal individuals; consequently the mean value obtained in our patients was lower than the mean value of normal subjects. Exceptions to this rule are found in patients with aortic insufficiency or patent ductus arteriosus; the values obtained in these patients were notably higher than normal.

3. The velocity of body displacement varies according to the functional capacity of the heart, being lower in patients with heart failure. This conclusion is confirmed by the higher mean values found in patients with
good functional capacity, regardless of the particular type of heart disease, as compared with the mean values obtained in patients with impaired functional capacity.

4. A comparison between the velocity of body displacement and the form of the ballistocardiogram has shown that the speed of body displacement diminishes as I becomes smaller, so that the mean value of normal tracings is higher than that of borderline tracings, and the last in turn is higher than the value of tracings of the early M type. It should be noted, however, that this is only a general rule, inasmuch as very low values of the velocity of body displacement may be observed not infrequently even in the presence of tracings normal in form.

It is difficult to give an exact interpretation of the results, because we do not yet know all the elements which determine the amplitude of the ballistocardiogram.

It was thought at first that there was a direct relationship between the amplitude of the ballistocardiogram and the value of the stroke volume, because the size of the ballistocardiogram increases with exercise and in many physiologic and pathologic conditions that cause an increase in the stroke volume. Recent studies on the action of nitrites have shown that an increase in the amplitude of the ballistocardiogram can occur without a concurrent increase in the stroke volume.6

Starr2, 4 also has demonstrated experimentally that, the stroke volume being equal, the amplitude of the ballistic tracing is related both to the amplitude of the force of the heart and to the way this force is applied during the ventricular ejection.

It is our opinion that the changes in the amplitude of the ballistocardiogram may be due both to variations in the stroke volume and changes in the speed of ejection. It should in fact be noted that the law of the conservation of momentum cannot be rigidly applied to the ballistic system of the body, because the impact of the blood upon the aortic arch and the pulmonary vessels generates other forces acting in the opposite direction. However, it seems obvious that the quantity of motion imparted to the body should be roughly proportional to the quantity of motion imparted to the blood, and as the latter is determined by multiplying mass by velocity, we believe that variations in the size of the ballistocardiogram may be due to either one or the other or both of these factors. Therefore we can interpret the diminished speed of body displacement in patients with heart disease as being the result of diminished stroke volume, and/or diminished ejection speed; according to Starr, the latter may be caused by changes in the amplitude of the force of the heart or in the way the force is applied.

This would also explain why the decrease in the velocity of body displacement is proportional to the degree of heart impairment.

The increased speed of body displacement which has been noted in some forms of heart disease (aortic insufficiency, patent ductus arteriosus) is probably related to increased stroke volume.

Generally the decrease in the speed of body displacement is more evident in tracings abnormal in form. Inasmuch as, according to Starr’s experiments, the morphologic changes are caused by abnormalities in the contour of the ventricular ejection curve, one must admit that in these cases, in addition to a low stroke volume and/or diminished speed of the blood, there is also an abnormal ventricular ejection.

It is difficult to understand clearly why in some forms of heart disease the velocity of body displacement is diminished, in spite of the absence of graphic abnormalities. According to our experience, this finding is confined almost exclusively to mitral stenosis with moderately good functional capacity. This leads to the hypothesis that in these cases the diminished speed of body displacement is related to the low stroke output, due to purely mechanical factors, whereas the speed and contour of the ventricular ejection curve are still normal owing to the good functional condition of the heart muscle.

Conclusions

The following conclusions may be drawn from our study:

1. The velocity of body displacement (Vb)
may be estimated on over 70 per cent of the ballistocardiograms recorded in patients suffering from heart disease.

2. The value of the speed of body displacement is usually lower in cardiac patients than in normal subjects.

3. However, in patients having heart disease with a high stroke output, and especially in aortic regurgitation, the values of the velocity of body displacement are higher than normal.

4. There is a direct relationship between the values of the velocity of body displacement and the functional state of the heart.

5. As a general rule, the values of the velocity of body displacement diminish as the graphic abnormalities become more pronounced. However, a marked decrease of the speed of body displacement may be found not infrequently when the ballistocardiogram is still normal in form. It is suggested that the diminished velocity of body displacement observed in these cases may be due to a diminished stroke output, independent of hemodynamic changes in the ventricular ejection. The results of our study confirm that the calculation of the speed of body displacement is a valuable index of quantitative ballistocardiography. In addition they provide confirmatory evidence for the theoretic assumption that the velocity of body displacement is a reliable quantitative expression of the complex hemodynamics of the ejection phase of the ventricular systole.

Summary

The velocity of body displacement (Vb) has been calculated on 128 ballistocardiograms recorded in 128 patients suffering from heart disease. The relations of the values of the speed of body displacement, to the type of heart disease, the functional state of the heart and the different ballistic patterns have been studied.

The following conclusions are presented:

1. The velocity of body displacement may be estimated over 70 per cent of the ballistic tracings recorded in cardiac patients.
2. The figures for the velocity of body displacement are usually lower in cardiac patients than in normal subjects. However, in heart disease with high stroke output and especially in aortic regurgitation, the values are higher than normal.
3. As a general rule, the values of the velocity of body displacement diminish as the ballistic abnormalities become more pronounced. However, a marked decrease of these values may be found not infrequently when the ballistocardiogram is still normal in form. A tentative explanation of this finding is presented.

Acknowledgment

The authors wish to express their appreciation and gratitude to Dr. Isaac Starr for his helpful suggestions and for the revision of the manuscript.

SUMARIO ESPAÑOL

La velocidad de desplazamiento del cuerpo fue calculada en 70% de los balistocardiogramas registrados en 128 pacientes con enfermedad cardiaca. Los resultados demostraron los valores generalmente mas bajos en pacientes cardíacos que en los sujetos normales, con la excepción de casos con volumen de emisión sistólica alto. La diminución en velocidad del desplazamiento del cuerpo es proporcional a la severidad de la anormalidad balística y al estado funcional del corazón. Una explicación tentativa de los hallazgos se presenta.

References

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