A New Index for Quantitative Ballistocardiography: The Velocity of Body Displacement

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Calculation of the velocity of body displacement and of the momentum of the body from 100 normal ballistic tracings shows that the values of the velocity of body displacement present a small scatter (mean value 68.3 ± 13.9 mm. per second) and are independent of body weight and surface area. For uniformity of values and simplicity of calculation, which can be effected also on many abnormal tracings, it is suggested that the velocity of body displacement be used as an index of quantitative ballistocardiography.

At present the examination of ballistic tracings includes a qualitative and a quantitative analysis. The qualitative examination is concerned with the shape of the tracings, independent of the amplitude of the various deflections, and does not require that the tracings be recorded with special calibration. Quantitative analysis, on the other hand, can be applied only to tracings recorded with ballistocardiographs that employ a swinging bed and that may be precisely calibrated.

Up to now the indexes used for the quantitative analysis of the ballistocardiogram have been: (a) the calculation of the stroke volume (SV), and (b) the calculation of the maximal cardiac force (MCF), according to Starr.

Several formulas have been applied to the calculation of stroke volume, among which the one most used and most practical is the formula of Tanner:

\[ SV = 100 \sqrt{2I + J \sqrt{C}} \]

where I and J are the areas under the I and J waves of the ballistocardiogram; C is the duration of the cardiac cycle in seconds. The values of the stroke volume obtained with this formula differ somewhat from the real values obtained with the gas analysis method which makes use of the principle of Fick. Moreover, it must be admitted that the calculation of the stroke volume from the ballistocardiogram is open to criticism from both a theoretic and practical point of view. (a) It has not been convincingly demonstrated that the areas under I and J are related to the amount of blood ejected from the ventricle. (b) The formula for the calculation of stroke volume should include the value of the cross-sectional area of the aorta, which is difficult to assess and can be estimated only approximately from the tables of Bazett; for this reason the formula of Tanner does not include this value but only a fixed coefficient. (c) Accurate location of the base line, and, therefore, the calculation of the areas under the I and J waves, is often difficult, especially in tracings with very large diastolic waves or marked tachycardia. (d) Finally, the calculation of the stroke volume is possible only on ballistocardiograms of normal configuration.

Recently Starr has devised a new index of quantitative ballistocardiography, namely, maximal cardiac force (MCF). Experimental observation shows that the ballistocardiographic tracing represents the third derivative of the curve of the acceleration of the blood in the large vessels; therefore the amplitude of the systolic waves of the ballistocardiogram is proportional, not to the amount of blood, but to the acceleration imparted to the blood during ventricular systole. The maximal cardiac force may be calculated in per cent of a hypothetic normal value; since, however, the values of the maximal cardiac force are extremely variable, this normal value is established by a critical coefficient which, according to Starr’s statistical calculations, in normal individuals ranges from 0 to 2.

There is no doubt that the calculation of the
maximal cardiac force introduces an element of considerable interest in quantitative ballistocardiography, because it represents an index of the heart dynamics which cannot be evaluated by other methods. Furthermore, the value can be calculated on both normal and abnormal tracings, independent of the location of the base line.

In our experience, however, we have noticed that the values of the maximal cardiac force in normal subjects may differ widely and also that the critical coefficient is not a reliable index, because in our cases it was found to be more than 2 in 20 per cent of normal individuals.

For these reasons we have tried to devise a new index of quantitative ballistocardiography which should fulfill the following requirements: (a) it must be easy to calculate; (b) it must be applicable also to abnormal tracings; (c) it must be a simple and direct expression of the complex hemodynamic forces which develop and act during the systolic phase of the ballistocardiogram.

Theoretic Considerations

Although the genesis of the ballistic waves has not yet been completely clarified, there is no doubt that the movements of the body, those at least which occur during systole, are due directly or indirectly (through the movement of the blood in the vessels) to the action of a force generated from a central source of energy, namely the heart.

Can the ballistocardiogram give a quantitative definition of this force? The unit of measure of a force is the dyne which corresponds to the force of 1.0 Gm. acting for 1.0 second. Obviously the ballistocardiogram cannot define in this manner the force of the heart.

An indirect means for the evaluation of a force is represented by the estimate of the work it performs. It is known that the work of the heart is expressed by the formula

\[ W = P \cdot SV + \frac{SV \cdot V^2}{2} \]

where \( P \) is the mean arterial pressure; \( SV \) is the stroke volume; \( V \) is the velocity of the blood at the level of the aortic orifice.

In fact the work of the heart is represented by a static component \( P \cdot SV \) which expresses the energy expended in developing a pressure equal to the arterial pressure upon the blood ejected at each systole, and a dynamic component \( \frac{SV \cdot V^2}{2} \) which expresses the energy expended in imposing a given velocity \( V \) on the blood mass. From the ballistocardiogram we can estimate the value of the static component but not that of the dynamic component, because we have no means of calculating the velocity of the blood. Cardiac work expressed by the value of the static component is open to criticism on the basis of the same considerations we have made regarding the calculation of the stroke volume from the ballistocardiogram, and also because the dynamic work is a negligible element under basal condition and in normal hearts, whereas it increases considerably after effort and in many forms of heart disease.

Another quantitative criterion for the evaluation of a force may be represented by the acceleration that this force imparts to the mass upon which it acts: by the second law of dynamics we know that “a force is proportional to the acceleration which it impresses on the body upon which it acts, and has the same direction as this acceleration.” The force of the heart, during systole, produces an acceleration of the blood mass and of the body, the complex movements of which are precisely those recorded by the ballistocardiogram. Therefore the value of the acceleration impressed on the body by the force of the ventricular systole may be calculated from the ballistocardiogram by computing the second derivative of the ballistic curve, that is, the derivative of velocity in relation to time. This calculation is too complex to be of practical use.

An indirect method for the estimate of the magnitude of a force may also consist of the calculation of its impulse. Impulse of a force is defined as the product of the force and the time of its action, and is expressed by the formula

\[ I = Ft \]

By the second law of dynamics

\[ F = ma \]
where $m$ is the mass of the body upon which the force acts, and $a$ is the acceleration impressed on the body by this force. Multiplying both the members of the preceding equation by $t$ we have

$$Ft = mat$$

Since $at = V$ (velocity), we can write

$$Ft = mV$$

$mV$ is defined as momentum ($M$). It may be readily seen that momentum equals impulse, expressed by the same formula.

The impulse of the cardiac force may therefore be estimated by calculating the momentum impressed on the blood (and therefore on the body) during systole. The momentum is easily calculated on the ballistocardiogram, because mass equals body weight and velocity may be derived from the ballistocardiogram by measuring the distance traveled by the body and the time employed to cover it.

In reality the ballistocardiogram shows that the movement of the body during systole is not unidirectional, inasmuch as it is recorded as a polyphasic curve. Such polyphasism is probably due to the summation of the cardiac ejection force and the forces generated by the movement of the blood within the large vessels. These forces develop in different directions, mainly on account of the curvature of the aortic arch. At the present time we do not know which is the deflection caused directly and exclusively by the cardiac ejection force. We have, therefore, thought of calculating the momentum of the body during the movement inscribed from the peak of the I wave to the peak of the J wave. This movement was chosen for the following reasons: (a) since this is the greatest movement recorded by the ballistocardiogram during systole, it can be assumed that it corresponds to the maximal impulse of the cardiac force; (b) it was chosen for practical reasons, since this is the movement which can be determined with the greatest accuracy even if the ballistocardiogram is abnormal in form. We have indicated by $Mb$ the momentum of the body thus calculated.

Not even $Mb$, however, represents a measure of the work of the heart because of the following considerations:

(a) The ballistic curve is polyphasic and in reality we are unable to establish the momentum of all the movements of the body.

(b) The calculated movement is undoubtedly is the resultant in the head-to-foot direction of many forces acting in different directions. On the other hand our present understanding of the genesis of the ballistic waves is too uncertain to establish whether, to what extent, and under what physiologic or pathologic conditions, changes in the direction of these forces may modify the resultant in the head-to-foot direction, independently of the total variance in the work of the heart.

(c) The momentum impressed on the body could be taken to represent the work of the heart provided the resistance to the ejection of the blood during the ventricular systole were always the same. Instead there are many conditions which greatly modify such resistance: among these are variations in the size of the aortic orifice and changes in the viscosity of the blood. For instance, in aortic stenosis the momentum impressed on the blood, and therefore on the body, can be greatly reduced owing to the obstacle to the passage of the blood through the narrow aortic orifice, whereas in reality the work of the heart is greater than normal.

Even with these reservations concerning the possibility of evaluating the work of the heart, it is nevertheless undeniable that the momentum impressed on the body is proportional to the momentum impressed on the blood during ventricular systole. And as the latter is the resultant of at least two main factors (ventricular ejection force and resistance), it is evident that the momentum and consequently the speed of body displacement ($Vb$) represent reliable quantitative indexes of the complex hemodynamic and ballistic condition of ventricular ejection.

We have, therefore, considered it useful to estimate the values of these measurements in normal persons and to establish whether they could represent a practical index of quantitative ballistocardiography.
TECHNIC

From the ballistocardiogram of 100 healthy subjects we have calculated the momentum of the body \((Mb)\) and the velocity of body displacement \((Vb)\). Our cases included 52 males and 48 females ranging in age from 15 to 40 years (mean age 31 years).

The ballistocardiograms (all normal in form) were recorded at basal rest with a ballistocardiograph of our construction, which consists of a high-frequency swinging bed, exactly calibrated so that release of a 280 Gm. weight displaces the base line 1 cm. The momentum \((Mb)\) was estimated according to the formula

\[
Mb = mVb
\]

where \(m\) is the body weight in kilograms. Velocity of body displacement \((Vb)\) was calculated according to the formula\(^*\)

\[
Vb = \frac{D}{t}
\]

where \(D\) represents the distance in meters from the peak of 1 to the peak of \(J\), and \(t\) is the time in seconds between the same points (fig. 1).

Thus computed, the velocity \((Vb)\) is expressed in meters per second and the momentum \((Mb)\) in kilogram-meters per second. For practical convenience the values of \(Vb\) have been reduced to millimeters per second.

RESULTS AND COMMENT

Maximal, mean and minimal values of the momentum of the body \((Mb)\) and of velocity of body displacement \((Vb)\) obtained in men, in women and in both sexes together, the values of the standard deviation \((\sigma)\) and those of the standard deviation from the mean \((\sigma_m)\) are given in tables 1 and 2.

Tables 3 and 4 show the frequency in per cent of the values of \(Mb\) and \(Vb\) in men, women and in both sexes together.

Figures 2 and 3 show the values of the speed of body displacement \((Vb)\) in relation

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\(^*\) It may be noted that this formula corresponds to the one proposed by Nickerson\(^1\) (IJ amplitude divided by I-J interval) for the calculation of stroke volume from ballistocardiograms recorded with a low frequency ballistocardiograph. However, the reliability of Nickerson’s formula has been questioned by Brandt and associates,\(^6\) especially during the action of drugs or diseases.
to body weight and body surface area estimated according to the tables of Dubois.

Table 4.—Frequency in Per Cent of the Values of the Speed of Body Displacement (Vb)

<table>
<thead>
<tr>
<th>Vb mm/sec.</th>
<th>Men %</th>
<th>Women %</th>
<th>Both sexes %</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-39</td>
<td>—</td>
<td>6.1</td>
<td>3</td>
</tr>
<tr>
<td>40-49</td>
<td>3.8</td>
<td>14.5</td>
<td>9</td>
</tr>
<tr>
<td>50-59</td>
<td>19.3</td>
<td>39.5</td>
<td>29</td>
</tr>
<tr>
<td>60-69</td>
<td>17.3</td>
<td>21.3</td>
<td>19</td>
</tr>
<tr>
<td>70-79</td>
<td>21.3</td>
<td>12.5</td>
<td>17</td>
</tr>
<tr>
<td>80-89</td>
<td>17.3</td>
<td>6.1</td>
<td>12</td>
</tr>
<tr>
<td>90-99</td>
<td>17.3</td>
<td>—</td>
<td>9</td>
</tr>
<tr>
<td>100-110</td>
<td>3.8</td>
<td>—</td>
<td>2</td>
</tr>
</tbody>
</table>

From the foregoing findings we may conclude:

1. The mean value of \( M_b \) is 4.3, and the standard deviation about the mean is 1.4 kilogram-meters per second, with maximal value of 8.8 and minimal of 1.8. The figures are decidedly greater in men than in women, the mean value for women being 3.07 kilogram-meters per second, and 5.12 for men.

The values of \( V_b \) range from 115 to 30 mm. per second, mean value being 68.3 with a standard deviation about the mean of 13.99 mm. per second. Also, \( V_b \) is greater in men (mean 76 mm. per second) than in women (mean 59 mm. per second).

2. There is a direct relationship between the values of the momentum and those of body weight, inasmuch as the former is expressed by the formula

\[
M_b = mV_b
\]

The values of \( V_b \), instead, are irregularly distributed in the various groups of body weight and surface area (figs. 2 and 3). For this reason the figures of \( V_b \) must be considered as independent of the values of these two elements. From this it may be inferred that
the variance of \( Mb \) is dependent principally on the body weight and only in a small part on the value of \( Mb \). In reality, therefore, \( Mb \) must have a greater variance than is shown in our study, inasmuch as our cases include subjects of about the same age and with little difference in body weight.

3. It seems, therefore, that \( Vb \) should be preferred as an index of quantitative ballistocardiography because the findings show little variance and are not related to body weight. It should also be noted that \( Vb \) can be estimated not only on normal tracings but also on many abnormal tracings, provided the interval I-J is still recognizable.

**Conclusions**

From theoretic considerations we may conclude that the momentum of the body (\( Mb \)) and the velocity of body displacement (\( Vb \)) are of interest from the point of view of pathologic physiology because they represent a quantitative evaluation of the ballistic forces generated by the complex hemodynamics of the ejection phase of the ventricular systole.

The findings show that the values of \( Vb \) present a small scatter in normal subjects and that, unlike those of \( Mb \), they are independent of body weight and surface area. For the uniformity of the values and the simplicity of the calculation, which may be made also on many abnormal tracings, we suggest that \( Vb \) be used as an index of quantitative ballistocardiography.

**Summary**

From the ballistocardiographic tracings of 100 healthy subjects we have calculated with a personally devised method (a) the momentum of the body (\( Mb \)), and (b) the velocity of body displacement (\( Vb \)) during ventricular systole.

The mean value of the momentum of the body was 4.3 with a standard deviation about the mean of 1.4 kilogram-meters per second, and that of the velocity of body displacement was 68.3 and 13.9 mm. per second. The figures for men are higher than those for women.

We suggest that the velocity of body displacement (\( Vb \)) be used as an index of quantitative ballistocardiography for the following reasons: (a) the values are uniform and are independent of body weight and surface area; (b) the calculation is simple and can be made also on many abnormal tracings; (c) it is a quantitative expression of the complex hemodynamics of the ejection phase of the ventricular systole.

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**Sumario Español**

La calculación de la velocidad de desplazamiento del cuerpo y del momento del cuerpo en 100 trazados balísticos demuestra que los valores de la velocidad del desplazamiento del cuerpo presentan un pequeño esparcido (valores promedio 68.3 ± 13.9 mm. por segundo) y son independientes al peso del cuerpo o al área de superficie. Para la uniformidad de los valores y la simplicidad de cálculo que se puede efectuar también en muchos trazados anormales, se sugiere que la velocidad de desplazamiento del cuerpo se use como un índice cuantitativo de balistocardiografía.

**References**


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