Relationship of the Natural Body Damping and Body Frequency to the Ballistocardiogram

By Oscar Tannenbaum, M.D., Harry Vesell, M.D., and Jerome A. Schack, M.D.

By means of a direct body ballistocardiograph the relationship of body frequency and damping to the ballistocardiogram in normal subjects was investigated. The influence of age and body measurements were studied and the findings subjected to statistical analysis. The degree of body damping was related to age but not to anthropometric measurements. Overweight and underweight influenced body frequency but not body damping. Respiratory changes had no influence on either body frequency or damping. It was suggested that to record a true ballistocardiogram of the cardiovascular forces more consideration must be given to body damping.

Ballistocardiography is of current interest as a means of studying the forces generated by the heart and great vessels. This discipline is concerned with the resultant of these forces as impressed upon the body, an elastic system forced into vibration and subject to viscous damping.

Many investigators have shown that the vast majority of healthy individuals under the age of 40 have a "normal" ballistocardiogram. However, healthy older individuals, with apparently normal cardiovascular systems have a substantial number of "abnormal" ballistocardiograms. It is true that arteriosclerotic heart disease is more prevalent in the older individual and though "subclinical," may play a part in the deterioration of the ballistocardiogram. However, is this high incidence of "abnormal" ballistocardiograms in the older age group entirely due to latent or incipient coronary artery disease as proposed by some authors?

Changes in the elasticity of the total body mass itself may play an important role in the production of these "abnormal" ballistocardiographic contours. Recent studies have shown that abnormal curves may be made normal by simply changing the damping of the recording system. Thus, Tucker and Ostrom have changed abnormal curves to normal by having the subject lie in a bed of sand or putty or by the use of sandbags applied to the feet and shoulders. Nickerson, by means of a low frequency critically damped system, has obtained tracings which were quite different from those obtained by the use of the high frequency bed of Starr. Attempts have been made to inscribe the ballistocardiogram with elimination of the inherent vibration of the body, by Burger, Von Witten, and Talbot and associates. These investigators have all sought to achieve an essentially aperiodic system.

Much of the investigative work in ballistocardiography has concerned itself with the forces developed by the circulatory apparatus as impressed upon the body mass. Little attention has been directed to the vibratory characteristics of the body itself. Inasmuch as the characteristics of the body as a mechanical oscillator are of considerable importance in the resultant ballistocardiogram, a systematic investigation of the vibromechanical properties of the total body mass was undertaken.

Material and Methods

One hundred normal subjects were selected, ranging in age from 15 to 76 years; 63 males and 37 females. Normality of the cardiovascular system was based on the usual clinical examination, 12-lead electrocardiogram, teleoventgnotrogram, urinalysis and hemogram. In the older age group, there were a few individuals with evidence of slight tortuosity of the thoracic aorta on fluoroscopic examination. No attempt was made to secure a basal state. All tracings were recorded with the patient in the re-
cumbent position on a flat hard wooden surface and during normal quiet respiration.

The ballistocardiograph was a modified direct-body electromagnetic pick-up type as previously described. The frequency response of the filter-oscillograph system was determined by introducing a square wave signal in series with the pick-up coil and was found to give an essentially straight line response from 1 to 12 cycles per second to the voltage input. The ballistocardiogram recorded with this transducer and filter system was neither velocity nor displacement, but intermediate and lagged a pure velocity ballistocardiogram by 45 degrees. Standardization from subject to subject was kept constant by fixing the gap from coil to magnet at 10 mm. and maintaining the sensitivity of the galvanometer response at 10 mm. for 1 mv. This type of ballistocardiograph may be expected to yield completely reproducible tracings when used under the conditions of standardization described. Lead I of the electrocardiogram served as a timing reference for the ballistocardiogram.

The amount of damping in a system may be measured by the principle of determining the rate of decay of oscillation in the system and expressing this as the logarithmic decrement. This was determined by recording the movements of the body subsequent to displacing the subject from the resting position by pushing the right shoulder and suddenly releasing the body. The sensitivity of the recorder had been attenuated until no deflections were inscribed by the cardiovascular forces. The damping factor was determined by measuring the ratio of the amplitudes of two successive waves after the tap. Body frequencies were also measured.

The age, height, weight and body surface area of each subject were noted. The ideal weight according to age and height was determined from the normal standard tables and the deviation from the standard of each subject was calculated. In addition, the decay curve of body oscillation of 35 unselected subjects of this group was determined by the method described above, in various phases of respiration. Thus the body damping and frequency response were studied and compared during normal quiet respiration, held deep inspiration and held deep expiration.

**Results**

Ballistocardiograms were graded normal, borderline, or abnormal. In the 15 to 30 year age group, 6.8 per cent of the subjects had abnormal tracings, with a similar number judged borderline. In the 31 to 45 year age group, 12.5 per cent had abnormal tracings, with a similar number judged borderline. In the 46 to 76 year age group, 25.0 per cent of the

<table>
<thead>
<tr>
<th>Age</th>
<th>No. of Subjects</th>
<th>Borderline</th>
<th>Abnormal</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-30</td>
<td>(29)</td>
<td>2</td>
<td>6.8</td>
</tr>
<tr>
<td>31-45</td>
<td>(32)</td>
<td>4</td>
<td>12.5</td>
</tr>
<tr>
<td>46-76</td>
<td>(39)</td>
<td>8</td>
<td>20.5</td>
</tr>
</tbody>
</table>

**Table 2.—Age and Body Measurements of Subjects**

<table>
<thead>
<tr>
<th>Height</th>
<th>Weight</th>
<th>Age</th>
<th>Body Surface Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>S.D.</td>
<td>Mean</td>
<td>S.D.</td>
</tr>
<tr>
<td>Male (63)</td>
<td>65.7</td>
<td>3.2</td>
<td>151.6</td>
</tr>
<tr>
<td>Female (37)</td>
<td>62.8</td>
<td>5.0</td>
<td>120.5</td>
</tr>
<tr>
<td>Combined Male &amp; Female (100)</td>
<td>65.3</td>
<td>3.8</td>
<td>139.7</td>
</tr>
</tbody>
</table>

**Table 3.—Means, Standard Deviation and Standard Error of Mean of Body Frequency and Damping**

<table>
<thead>
<tr>
<th>Body Frequency</th>
<th>Body Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>S.D.</td>
</tr>
<tr>
<td>Male (63)</td>
<td>3.67±0.92</td>
</tr>
<tr>
<td>Female (37)</td>
<td>3.80±0.76</td>
</tr>
<tr>
<td>Combined Male &amp; Female (100)</td>
<td>3.72±0.86</td>
</tr>
</tbody>
</table>

* Cycles per second.
† Lobe ratio.
‡ Standard error of the mean.

Subjects had abnormal tracings, with 20.5 per cent judged borderline (table 1).

Mean ages and body measurements of the subjects are presented in table 2. Males averaged 7 years older, 3 inches taller and 31 pounds heavier than females, with corresponding differences in body surface areas. Mean body frequencies of both male and female subjects varied little, with only small differences between the two sexes. On the other hand, body damping was greater in the male than in the female with mean body damping coefficients of 3.25 and 2.49, respectively (table 3).

Relationship between age and body measurements to body frequency and damping: Correlation coefficients between age and body measurements with body frequency and body damping are listed in table 4. There was
significant correlation between age and body damping. Correlation coefficients between body damping and body frequency with body measurements were below the level of significance. Body frequency showed no significant correlation with body damping in the group of males and only borderline correlation at the 1 per cent level of significance in the group of females.

In order to better evaluate the effects of age on body frequency and body damping the series was divided into two groups, namely: those between 15 and 45 years of age and those between 46 and 76 years of age. The means and standard deviations of body frequency and body damping for these two age groups are listed in table 5. Mean body damping of the older age group was significantly higher than that of the younger age group. However, the mean body frequency of each of the two groups did not differ significantly. Application of the "t test" for the significance of these differences is noted in table 6.

The effects of deviation from "ideal weight" on body frequency and body damping: The subjects were considered in four groups: Group 1, "ideal weight" ± 9 per cent; group 2, "overweight" 10 to 25 per cent; group 3, "underweight" 10 to 19 per cent; and group 4, "underweight" 20 to 29 per cent. Table 7 summarizes the means and standard deviations of the four groups in regard to age, body damping and body frequency. There was no significant difference in the mean ages of the four groups. Likewise, there was no significant difference in the mean body damping of the four groups. Body frequency was definitely higher in those subjects who were 20 to 29 per cent below "ideal weight." Body frequency was lower in those subjects who were 10 to 25 per cent above "ideal weight." Application of the "t test" for the significance of these differences is noted in table 8.
Table 7.—Effects of Overweight and Underweight on Body Frequency and Damping

<table>
<thead>
<tr>
<th>No. of Subjects</th>
<th>Age</th>
<th>Body Damping</th>
<th>Body Frequency*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>S.D.</td>
<td>S.E.M.</td>
<td>Mean</td>
</tr>
<tr>
<td><strong>±9% Ideal</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight..........</td>
<td>(48)</td>
<td>39.6</td>
<td>14.44</td>
</tr>
<tr>
<td>10-20% Overweight...</td>
<td>(18)</td>
<td>43.8</td>
<td>16.53</td>
</tr>
<tr>
<td>10-19% Underweight...</td>
<td>(17)</td>
<td>42.6</td>
<td>16.61</td>
</tr>
<tr>
<td>20-29% Underweight...</td>
<td>(17)</td>
<td>45.00</td>
<td>15.09</td>
</tr>
</tbody>
</table>

* Cycles per second
† Lobe ratio

Table 8.—Significance of Difference Between Body Damping and Frequency in Groups of Subjects that are of Ideal Weight, Underweight and Overweight

<table>
<thead>
<tr>
<th>t Value Found for Ideal Weight Vs. 10–20% Overweight</th>
<th>p Significance</th>
<th>t Value Found for Ideal Weight Vs. 10–19% Underweight</th>
<th>p Significance</th>
<th>t Value Found for Ideal Weight Vs. 20–29% Underweight</th>
<th>p Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Damping†</td>
<td>0.05</td>
<td>0.09</td>
<td>0.27</td>
<td>0.8</td>
<td>0.83</td>
</tr>
<tr>
<td>Body Frequency*</td>
<td>3.38</td>
<td>0.001</td>
<td>0.60</td>
<td>0.5</td>
<td>1.53</td>
</tr>
</tbody>
</table>

* Cycles per second.
† Lobe ratio.

Table 9.—The Effect of Respiration on Body Frequency and Damping (35 Subjects)

<table>
<thead>
<tr>
<th>Normal Respiration</th>
<th>Deep Inspiration</th>
<th>Deep Expiration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Frequency*</td>
<td>Body Damping</td>
<td>Body Frequency*</td>
</tr>
<tr>
<td>Mean.............</td>
<td>3.35</td>
<td>3.98</td>
</tr>
<tr>
<td>S.D.........</td>
<td>0.84</td>
<td>1.89</td>
</tr>
<tr>
<td>S.E.M........</td>
<td>0.198</td>
<td>0.445</td>
</tr>
</tbody>
</table>

* Cycles per second.
† Lobe ratio.

The body frequency and damping of 35 of the subjects were determined during normal quiet respiration, deep held inspiration and deep held expiration. The results are listed in tables 9 and 10. No significant difference was noted in body frequency or body damping during any phase of respiration.

Discussion

In the production of the ballistocardiographic record the forces generated by the cardiovascular system are impressed on the body mass which has complex couplings, damping resistances and various mechanical impedances to the transmission of these forces to the surfaces of the body. This results in considerable distortion of the ballistocardiogram both as to the contour and phase of the various waves and segments. The concept of Von Wittern11 and Reissmann and Dimond18 of dividing the body into an external and internal network contributes to the understanding of the various mechanical damping factors.

Ballistocardiograms in our series in the younger age group who body damping factor was low had a definite oscillatory pattern. There were exceptions in four young individuals. These four all had abnormal ballistocardiograms, but their body damping factor was found to be high and in the range usually observed in much older individuals.

The data in this report indicate that the damping of the body shows definite variation with age. On the other hand, weight, height and body surface areas did not show any significant correlation with body damping. The correlation of high degrees of body damping with increasing age may be of importance in explaining the greater number of "abnormal"
ballistocardiograms which are encountered among "healthy" older individuals.29

Our data further indicate that body frequency is quite constant and does not vary with age, sex or normal range of body measurements. However, overweight tends to decrease the natural frequency of the body and underweight tends to increase the natural frequency of the body.

Distortion of the ballistocardiogram may be due to variation in the frequency of the impressed force, the circulatory apparatus, the natural frequency of the vibrating mechanical mass, the body, or the frequency response of the recording system, transducer-filter-oscillograph. The ratio of the frequency of the impressed force to the natural frequency of the body is a factor in tachycardias where the ratio of the two frequencies is such that there may be accentuation of the resultant ballistocardiographic waves due to resonance.

It becomes apparent that the damping and frequency response of the body mass is of considerable importance in the present methods of recording the force of the heart by the ballistocardiograph. In order to record the true ballistocardiographic waves one must control the large variable of body damping. If the damping of either the body or the associated recording system be altered so that the overall damping is made constant at some optimum level, then a more accurate registration of the cardiac forces will become possible. The use of a critically damped, low frequency table or an aperiodic system approaches such an ideal. A direct body ballistocardiograph can be used for recording a "true" or undistorted tracing by changing the surface upon which the body lies or the application of sandbags to the subject which effectively changes the body damping.7 The direct body ballistocardiograph may also be utilized in conjunction with an electronic system designed to "smooth out" these factors of frequency and damping and thus approach a "true" force curve.19

In ordinary clinical use however, from the data presented in this report, one could record the oscillatory decay curve of the body after each tracing and make suitable allowance for unusual variations in body damping or frequency, in the clinical interpretation of the ballistocardiogram.

SUMMARY AND CONCLUSIONS

1. The natural frequency of the body and body damping of 100 normal subjects were studied for their effects on the ballistocardiogram.

2. After an impressed external force the oscillatory decay curve of the body was measured.

3. A standard statistical analysis of the results showed that body frequency was not correlated to age or normal anthropometric measurements.

4. Body damping correlated significantly with age but not with normal body measurements.

5. Overweight and underweight affected body frequency but not body damping.

6. Respiratory variations did not significantly modify body frequency or body damping.

7. There was no significant correlation between natural body frequency and body damping.

8. It was suggested that truer recording of the cardiovascular forces by the ballistocardiogram could be obtained by adjustments of apparatus to make allowance for variations in body damping.

REFERENCES


TANNENBAUM, VESELL AND SCHACK


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