Normal Standards for Amplitude of Ballistocardiograms Calibrated by Force

By Isaac Starr, M.D.

Normal standards for ballistocardiogram amplitude have been estimated by statistical methods from a series of 194 healthy men and women. The application of new knowledge of the genesis of ballistocardiograms has resulted in normal standards with a smaller scatter than those previously formulated, and so the ability to detect cardiac abnormality has been correspondingly increased.

Ballistocardiograms may indicate abnormality because they are too large or too small in amplitude; or because the contour of the record is abnormal. Determination of abnormality from the contour, a purely qualitative approach, has been the more popular method. The quantitative approach is more difficult, and to determine abnormality in amplitude, one must possess both normal standards and a ballistocardiograph which can be calibrated. But, obviously, a quantitative approach, if feasible, would permit finer distinctions and so would be more rewarding.

From the very first, it seemed likely that the amplitude of the record had quantitative meaning, for whenever circumstances caused the subject’s heart to beat more strongly, as after exercise, the record increased markedly in amplitude. More recently, the results of experiments have demonstrated that the quantitative relationship between ballistocardiographic amplitude and certain aspects of cardiac force is closer than we had expected. This has encouraged us to seek once more to improve the normal standards in the light of the newer knowledge of the genesis of ballistocardiograms. These standards have been in need of improvement.

Our first normal standards for the amplitude of ballistocardiograms were published in 1941, and they were related to attempts to measure cardiac output from these records. However, we soon became aware of theoretical objections to the formulae employed to estimate stroke volume in this early work, and when these were corrected by the omission of the factor for aortic size, the scatter of results secured in healthy persons increased considerably.

Later, Tanner, using a method based on multiple regression equations containing items for body surface area and age, as well as measurements secured from the ballistocardiogram, provided normal standards for estimates of stroke volume from the ballistocardiogram having a smaller scatter, the deviations for men and women respectively being 13.4 per cent and 11.0 per cent of the mean values.

Somewhat later, normal standards for ballistocardiogram wave areas, pulse rate and body weight were made up without attempting to estimate stroke volume, these studies yielded standard deviations which were about 16 per cent of the mean in persons under 40 years of age. Still later, after the results of the initial cadaver experiments had been analyzed, a variety of normal standards for “cardiac” force were set up, using the sum of the vertical I and J distances of the largest and the smallest waves of the respiratory cycle. In these, the scatter was considerably larger, the standard deviation of the equation we most frequently used being 24 per cent of the mean value.

Direct measurement of the I and J wave amplitudes has also shown a large scatter in data secured in healthy persons. In our data,
an adjustment was made for difference in body size, men and women were studied together, and the subjects were grouped by decades. Thus handled, the averages of the standard deviations of the I and J wave altitudes of subjects from 20 to 49 years of age, expressed in per cent of the means of each decade, were similar, both being 28 per cent. In the results secured in the large series of healthy persons, reported by Scarborough and his co-workers, the data were treated somewhat differently; men and women were studied separately, and there was no adjustment for differences in body size; the standard deviation of the I wave of both sexes averaged 26 per cent, of the J wave 23 per cent, in persons from 20 to 50 years of age. In both these formulations, the I and J waves were measured separately; therefore, the scatter was increased by the error involved in placing the base line, which can be avoided by measuring directly from the I to the J wave tips, as has been done in the statistics to be reported in this paper.

Thus, for a considerable time the experience was discouraging, for it seemed that the scatter of results secured in healthy persons was proving to be so large that our ability to identify abnormality of the cardiac contraction from measurements of the waves was far less than we had hoped. Indeed, our early attempts to improve the normal standards in the light of increasing knowledge of the genesis of the ballisticardiogram, not only failed to accomplish this, but actually made matters worse by yielding normal standards with larger scatters. However, since these results were published, quantitative knowledge of the physiological genesis of ballisticardiograms has increased much further. The technique of simulating systole at necropsy, improved in many ways, and gave much better quantitative information about the relation of the ballistic amplitude to the forces generating it, information sure to be helpful in designing better normal standards. This and other evidence5, 6, 7, 8 suggested that, to secure the best normal standards, there were three requirements: first, data from men and women should be considered separately; second, the square root of the measurements made on the ballisticardiogram should be used, rather than the measurements themselves; and third, factors related to the size of the subject should be omitted, even though we were seeking a measure of cardiac strength per unit of body size.

Thus guided, we have calculated new standards for amplitude of ballisticardiograms of healthy persons as a measure of cardiac force, and find that they are the greatest improvement over the previous formulations, for in some the scatter has been reduced until the standard deviation of the data in healthy young persons is only about 10 per cent of the mean value. So, by using these new standards, our ability to detect abnormality of the strength of the cardiac contractions should be greatly increased. In this presentation we introduce these new standards and give instructions for their use.

MATERIAL, METHODS AND RESULTS

From the original normal series of ballisticardiograms5 taken on healthy persons in 1937, 1938 and 1939, we have eliminated all records from persons who subsequently developed any serious disease, and there remained 56 young men and 48 young women from 20 to 39 years of age. This is a remarkably fine series because the normality of the cases at the time of the test has been established by the fact that they remained in good health for many years. This group will be called our selected series of healthy young adults, and there is a strong argument for basing our normal standards on these data alone. But as we proposed to analyze the data secured from men and women separately and to investigate the effect of age, the series seemed too small and too restricted in age range to be ideal for this purpose. So we added more data from the original series by including 42 healthy persons from 40 to 49 years of age, and also data from results secured from other healthy persons from 20 to 49 years of age, who had been tested after the original series had been completed. All these latter were tested over five years ago and none are known to have developed any serious disease up to the present time. The inclusion of these gives a total of 106 healthy men and 88 healthy women, which we will
speak of as the enlarged series. The failure to record measurements of wave duration and blood pressure in a few of the early tests has slightly diminished the number available for statistical analysis in some aspects of this study.

In order to aid in keeping track of these subjects in the succeeding years, the great majority had been secured from the more stable parts of the population of the hospital and medical school. So they consisted chiefly of doctors, medical students and their wives, of medical secretaries and technicians, and of the family and friends of the author. In a few instances, in the enlarged series, the same person has been used twice, when he or she had a second test 10 years or more after the first, and the data fell into a different age group.

The use of this group as a basis for normal standards for the whole population has certain disadvantages. Only the white race is represented, and it should be pointed out that the series does not include persons regularly engaged in hard physical labor.

Despite my large experience, it seemed wiser not to include data secured from medical students taking part in class experiments in which drugs were to be given them, as I feared that apprehension would warp the results.

All subjects were tested after lying at rest on the ballistocardiograph for a period of at least 15 minutes. Our original instrument was used;3 it was of the resisted table type. No tests were made on any subject within two hours of completing a meal. Care was always taken that the subjects' heels were firmly pressed against the foot plate when the record was taken. So the standards to be described are those of resting persons, and no attempt was made to have the subjects in the strictly basal state.

Statistical analysis of the measurements made on the records secured on these subjects form the basis of the normal standards to be presented. These were performed by standard statistical methods with the aid of a Marchand calculator.

The type of normal standard finally adopted stemmed from the relations discovered in the data secured in the more recent cadaver experiments.7 The regression giving the highest correlation discovered in a previous study,7 in which the maximum velocity of the cardiac ejection was used as our measure of cardiac force is as follows:

Cardiac stroke force

\[
\text{Cardiac stroke force} = (\text{body surface area})[5I \sqrt{I + J + 5}] \tag{1}
\]

where body surface area is in square meters and \(I + J\) is the vertical distance between the tips of 1 and J waves of the ballistocardiogram, when a force of 280 Gm. displaces the light spot 1 cm., as is standard for our instruments. The solution of this equation does not give cardiac force in absolute units but simply a figure which one has good reason to believe is related to it; a conception based on evidence previously discussed.7

However, it seems obvious that to make normal standards we need a measure of cardiac strength in units related to the size of the subject, for obviously one has every right to expect that large persons will have stronger hearts than small ones, so, after dividing equation (1) by body surface area and, in order to compensate for the respiratory variations, using the average amplitudes of typical large and small waves of the ballistocardiogram for the single value used in equation (1) we have

Cardiac stroke force

\[
\frac{\text{Cardiac stroke force}}{\text{Body surface area}} = 5I \sqrt{I + J + I_2 + J_2} + 5 \tag{2}
\]

where \(I\) and \(J\) and \(I_2\) and \(J_2\) are the vertical amplitudes of the waves of typical large and small complexes of the respiratory cycle of any record, expressed as in equation (1).

As cardiac stroke force is to be expressed only in relative units, we can ignore any coefficient the left side of this equation might obtain and slightly simplify the estimate by basing the standards on the sum of the amplitudes of the large and small waves rather than on their average, so we have

Cardiac stroke force

\[
\frac{\text{Cardiac stroke force}}{\text{Body surface area}} = 5I \sqrt{I + J + I_2 + J_2 + 7} \tag{3}
\]

To further simplify formula (3), since the
### Table 1: Normal Standards for Amplitude of Ballistocardiograms. Statistics from Series of Healthy Young and Middle Aged Adults

<table>
<thead>
<tr>
<th>No.</th>
<th>Aspect Studied</th>
<th>Measurements Analyzed</th>
<th>Group Studied</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>In general</td>
<td></td>
<td>No. and Sex</td>
<td>Age Range</td>
</tr>
<tr>
<td>1</td>
<td>Wave altitudes (select series)</td>
<td>$\sqrt{I + J + I_2 + J_2}$ mm.</td>
<td>56 M</td>
<td>20-39</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>48 F</td>
<td>20-39</td>
</tr>
<tr>
<td>2</td>
<td>Wave altitudes × pulse rate</td>
<td>$\sqrt{I + J + I_2 + J_2}$ mm. × rate per min.</td>
<td>56 M</td>
<td>20-39</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>48 F</td>
<td>20-39</td>
</tr>
<tr>
<td>3</td>
<td>Wave altitudes (enlarged series)</td>
<td>$\sqrt{I + J + I_2 + J_2}$ mm.</td>
<td>106 M</td>
<td>20-49</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>88 F</td>
<td>20-49</td>
</tr>
<tr>
<td>4</td>
<td>Wave areas (enlarged series)</td>
<td>$\sqrt{I + J + I_2 + J_2}$ mm. sec.</td>
<td>103 M</td>
<td>20-49</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>81 F</td>
<td>20-49</td>
</tr>
<tr>
<td>5</td>
<td>Wave areas × pulse rate</td>
<td>$\sqrt{I + J + I_2 + J_2}$ mm. sec. × rate per min.</td>
<td>101 M</td>
<td>20-49</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>81 F</td>
<td>20-49</td>
</tr>
<tr>
<td>6</td>
<td>Values related to &quot;work&quot; per beat derived from wave areas</td>
<td>$\sqrt{I + J + I_2 + J_2}$ mm. sec. × mean B.P.</td>
<td>98 M</td>
<td>20-49</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>81 F</td>
<td>20-49</td>
</tr>
<tr>
<td>7</td>
<td>Values related to &quot;work&quot; per min. derived from wave areas</td>
<td>$\sqrt{I + J + I_2 + J_2}$ mm. sec. × mean B.P. × P.R.</td>
<td>98 M</td>
<td>20-49</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>81 F</td>
<td>20-49</td>
</tr>
</tbody>
</table>
regression so nearly passes through the origin, one can omit the added constant; and since our interest is confined to relations rather than absolute values for the left side, we can omit the slope also, obtaining:

\[
\text{Cardiac stroke force} \quad \frac{\text{Body surface area}}{I + J + I_2 + J_2} \quad (4)
\]

The units of measurement of the amplitude of the waves could be most readily expressed in millimeters by those using the standard calibration we employ \(10 \text{ mm.} = 280 \text{ Gm.}\); but knowing the relationship between amplitude and force one could also express the magnitude of the deflection in units of force such as grams or dynes.

No further simplification is possible, so we propose to employ equation (4) for the construction of normal standards, using the right side as our measure of cardiac stroke force related to body size. Accordingly, the square root of the sum of the vertical amplitudes of typical large and small waves was determined for each normal subject and the data subjected to statistical analysis. The results using both the selected and the enlarged series are given in table 1.

Several other types of normal standards were also explored. The regression equation relating the area of the I and J waves to cardiac stroke force in relative units has been previously published,\(^7\) and it resembles equation (1) in character. Therefore for the same reasons as are given above it is proper to simplify it to:

\[
\text{Cardiac stroke force} \quad \frac{\text{Body surface area}}{I + J + I_2 + J_2 \text{ areas}} \quad (5)
\]

where the waves are measured as triangles and their areas are expressed in millimeter seconds, or as dyne seconds. A frequency diagram of these results is presented as figure 1, and other statistics are in tables 1 and 2.

It also seemed desirable to explore the normal values when pulse rate was used as a factor by employing an equation which yielded an abstract value which might be called cardiac force per minute, as follows:

\[
\text{Cardiac force per minute} \quad \frac{\text{Body surface area}}{I + J + I_2 + J_2 \times \text{ pulse rate}} \quad (6)
\]

This was estimated from wave amplitudes of the 104 healthy young persons of the selected series with the results shown in table 1, no. 2, and pulse rate was similarly employed in the

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**Fig. 1.** Frequency diagram of the square root of average wave areas found in men and women in the first three decades of adult life. The smallest rectangle shown represents a single unit.
TABLE 2.—Normal Standards for Amplitude of Ballistocardiograms. Regression Equations Allowing for the Effect of Age on Ballistocardiograms

<table>
<thead>
<tr>
<th>No.</th>
<th>Aspect Studied</th>
<th>Regression Equation</th>
<th>Group Studied</th>
<th>Standard Deviation About the Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Wave altitudes</td>
<td>$\sqrt{1 + J + I_2 + J_4 \text{ mm.}} = -0.04 \text{ Age years} + 6.68$</td>
<td>105 M 20-49</td>
<td>0.60 mm. 11.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sqrt{1 + J + I_2 + J_4 \text{ mm.}} = -0.03 \text{ Age years} + 5.45$</td>
<td>87 F 20-49</td>
<td>0.53 mm. 11.8%</td>
</tr>
<tr>
<td>9</td>
<td>Wave areas</td>
<td>$\sqrt{1 + J + I_4 + J_3 \text{ mm. sec.}} = -0.0071 \text{ Age years} + 1.4$</td>
<td>101 M 20-49</td>
<td>0.142 mm. sec. 12.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sqrt{1 + J + I_4 + J_3 \text{ mm. sec.}} = -0.0042 \text{ Age years} + 1.07$</td>
<td>81 F 20-49</td>
<td>0.085 mm. sec. 9.0%</td>
</tr>
<tr>
<td>10</td>
<td>Wave areas × pulse rate</td>
<td>$\sqrt{1 + J + I_4 + J_3 \text{ mm. sec.} \times \text{ pulse rate per min.}} = -0.608 \text{ Age years} + 102.3$</td>
<td>101 M 20-49</td>
<td>11.0 13.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sqrt{1 + J + I_4 + J_3 \text{ mm. sec.} \times \text{ pulse rate per min.}} = -0.495 \text{ Age years} + 82.4$</td>
<td>81 F 20-49</td>
<td>11.6 17.0%</td>
</tr>
</tbody>
</table>

construction of the regression equation in table 2, no. 10.

In the normal standards given in table 1, the age of the subjects was neglected, although the diminution in average size of ballistocardiograms as age advances is well known, a diminution which may take place even though good health commensurate with one's age is maintained. Therefore, regression equations defining the relation of the age of the subjects to both the amplitudes and the areas of the I and J waves were calculated, and the results are given in table 2. The use of these regressions accomplishes a small reduction in the scatter and these equations may also be used as normal standards.

As it is obvious that the resistance against which the heart expels its blood must be considered in any estimate of its strength, we also explored the effect of multiplying the square root of the wave areas by the mean blood pressure defined as the sum of the systolic and diastolic pressures divided by 2. The correlation of these products with the ages of the subjects was not significant, the regression being almost horizontal, so the increase of blood pressure as age advances neutralizes in large measure the effect of the diminution of the ballistocardiogram amplitude, which also takes place as one grows older. Therefore we have not demonstrated that age is a significant factor in what is a kind of cardiac work, and the regression equation has been omitted from table 2 for this reason. The means of the values obtained in the enlarged series and the scatter around them are given in table 1, no. 6.

The products of the square root of wave areas, mean blood pressure and pulse rate, represent a type of cardiac work per minute. The means and the standard deviations about the means have also been given in table 1, no. 7.

**DISCUSSION**

The reason for the wide scatter of our previous formulations of data secured on healthy persons is now obvious. The measurements of the I and J waves scatter widely because the data is skewed, and points outlying far on the high side greatly increase the standard deviation. Using the square root of the measurements abolishes this skewness and greatly reduces the scatter. In other formulations, although the square root was employed—our original theoretical conceptions had indicated that the square root should be used—the data secured in men and women were combined and some aspect of body size such as actual or ideal weight, or body surface area, was relied upon to compensate for differences between the sexes. This has proved to be a poor plan be-
cause it appears that women's hearts are weaker than men's hearts, not because women are smaller but for some more subtle reason. On second thought, this does not seem unexpected; doubtless, an athletic contest conducted between men and women of similar weight would prove the men to be the stronger. When the sexes are treated separately the scatter of the normal standards is much improved.

The thought that body size should play no part in constructing normal standards came to us as a surprise. It does, of course, play a part in our theoretical conceptions, for \( \text{force} = \text{mass} \times \text{acceleration} \), but, when an estimate of cardiac strength in terms of body size is sought, the effect of body size cancels out. The lack of this knowledge was an important factor in the large scatter of the older standards.

One now sees the reason for the small scatter in our first formulation. The use of the factor "A", an estimate of aortic cross-section area derived in part from body size, supplied the need for a factor related to body size in the numerator of the equation; we did the right thing for the wrong reason, and when "A" was omitted from the estimate, the scatter increased markedly. Tanner's formulation conforms most closely to the present conceptions and the scatter of these results was but little larger than that of the best of our present formulations.

Comparison of the scatter of the square root of the wave areas (table 1, no. 4) with that of wave altitudes (table 1, no. 3) indicates that the former formulation is superior. In males the difference in scatter is not significant, but in females the wave areas are significantly less scattered. There are many reasons for thinking that wave areas would provide more useful normal standards for clinical work than would wave altitudes. Different pressures of the subject's heels against the foot board, or the error of forgetting to have the subject's heels in contact with the foot board, may cause a measurable difference in wave altitudes, but as wave duration increases as height decreases, such differences of technique cause less, if any, differences in I and J wave areas. Similarly, differences in the weight of tables, judging from the effect when iron bars are added to our light tables, affect wave areas less than they do wave altitudes. Also, fine vibrations super-imposed on the ballistocardiogram, such as is caused in our records by vibrations in the building, may markedly distort the height of wave tips, but they have much less influence on wave areas. Finally in cadaver experiments, in which asynchronous systoles of the two sides of the heart were simulated, the height of the resulting distorted waves was far more affected than the areas. In short there are many reasons to prefer wave areas to wave altitudes for quantitative work in the clinic although in our series the gain is not great.

Studying the regression equations for square root of wave altitudes in terms of age (table 2, no. 8) one finds that the amplitude of the ballistocardiograms of men diminishes more rapidly than that of women as age advances; this is true of the data of Scarborough and his associates also. And, as one would expect, the scatter about the regression is smaller than when age is not considered. This is especially true of the data secured on women. The data concerned with wave areas behaves similarly and the scatter about the regression of the square root of wave areas on age is the smallest we have encountered, the average of the standard deviations of men and women being 10.5 per cent of the mean values, which seems as good or better than that of most clinical methods now in use. Figure 1 gives a frequency diagram of the wave areas in different age groups, and the tendency for the results to conform to a bell-shaped curve in each of the age groups is most encouraging. This is the most satisfactory formulation that we have found, and it should be easy to identify abnormal cardiac performance by means of it.

When the square root of the amplitude of ballistocardiograms is multiplied by the pulse rate, to get a measurement related to cardiac strength per minute, the scatter of our normal standards increases significantly. The consistency of the data secured on women was disturbed by the results secured on several who, perhaps excited by the test, had unusually high pulse rates during it; but we have not omitted these results from the statistical analysis. Despite the large scatter, the use of equa-
tions given in table 2, no. 7, might well permit one to detect an important type of clinical abnormality which would be missed if attention were focused exclusively on measurements of cardiac function per beat.

The use of the product of some aspect of the ballistocardiogram amplitude and the mean blood pressure has much to commend it, and equations providing normal standards for such values are given in table 1, no. 6 and 7. Certainly any estimate of the strength of the heart would benefit by taking into account the resistance against which the blood is ejected. But, while it is easy to multiply ballistic measurements by mean blood pressure and to estimate empirical normal standards for the product, the difficulty of making a satisfactory physiological interpretation of the result is formidable.

In our cadaver experiments injections into the aorta and the pulmonary artery could be made separately, and the relation of the two effects explored. In the best experiment, the aortic ballistocardiogram was much larger, the I + J distance being twice, and the I + J wave areas almost four times the size of the corresponding deflections which followed the injection into the pulmonary artery; and the two injections were judged to be similar not only because the total amount injected was similar, but also because the contour of both injection curves was very similar. Evidently, the ballistic effect produced by the right side of the heart, while much smaller than that of the left, is far from negligible.

During life the contribution of the right ventricle to the ballistocardiogram has been judged to be considerable, because in healthy persons, that record begins to increase in amplitude at the onset of inspiration, and so at the time when the diminishing pressure in the chest would cause better filling of the right heart, and before better filling of the left heart would be expected.

In the clinic we can readily measure only the pressure which opposes the expulsion of blood from the left ventricle; but the major part of the heart's work is performed by this ventricle, and it also produces the larger part of the ballistocardiogram, so one can properly hope to secure a rough approximation of the relative magnitude of cardiac work in different subjects by multiplying the amplitude of the ballistocardiogram by the peripheral blood pressure, even though the contributions of the right side of the heart are unknown.

Another theoretical difficulty must be pointed out; the product of ballistocardiogram amplitude and mean blood pressure does not give an estimate of work in the Newtonian sense, for cardiac work of this kind is estimated from the product of cardiac output and pressure, while the ballistocardiogram wave altitudes and areas are not closely related to cardiac output unless a time factor is introduced into the calculation. It is proper to think of the amplitude of the systolic ballistic waves as related to acceleration; and the product of pressure and acceleration represents something different from Newtonian work as defined by physicists. But work as defined by the physicists is something different from what doctors have in mind when they use the word "work"; for example, according to the Newtonian conceptions, the giant Atlas, while supporting the world on his shoulders, does no work at all, a statement which would seem ridiculous to any doctor concerned with Atlas' health. So perhaps work of the Newtonian kind is not what doctors should seek when we wish to measure cardiac performance.

Because the square roots of the altitudes and areas of the ballistic I and J waves are related to acceleration, one has the right to think that the product of such values and the mean blood pressure would be related to the tension time of the heart muscle, to use a term introduced by Hartree and Hill. Tension time was employed by these authors as a measure of the performance of skeletal muscles, and I have made use of a somewhat similar idea, the product of mass and acceleration with respect to an object falling in the gravitational field, to estimate muscular work performed in supporting, lifting and lowering heights, in weight-lifting experiments. I believe that a conception of muscular performance such as this may well meet the doctors' needs more readily than the classic Newtonian conception of work; by my equations, Atlas is found to be doing very
heavy work when supporting the world. In any event, though certainly not identical with Newtonian work, the products of the square root of the I and J wave altitudes and mean blood pressure have been found to be strongly correlated with Newtonian work in our cadaver experiments, so I have not hesitated to place the normal standards for these values in table 1.

Thus the general character of satisfactory normal standards for amplitude of ballistocardiograms now seems clear and the small scatter of our best formulations has reassured us about several features of our procedure.

It has long been known that the deviation of duplicate ballistocardiograms taken by our apparatus and technique, in individuals on the same day, and on different days, was small.2, 9, 14 and the results contained in this presentation demonstrate that there is also a satisfactory stability of the physiological function we are measuring from person to person. Also, since the male subjects studied ranged from 280 pounds to 125 pounds in weight, and from 74 to 61 inches in height; and the females from 183 pounds to 97 pounds in weight, and from 71 to 52 inches in height, it seems evident that differences in body size and configuration play no important role in the amplitude of ballistocardiograms secured by our apparatus and technique, a conclusion in accord with Tanner's results. It also seems evident that inevitable small differences in technique, such as different pressures of the heels against the footplate, also cause no noteworthy differences of result. In short, the ability to get such stable values in a large and diverse series of healthy persons has greatly increased our confidence in the ability of our method to detect abnormality due to disease.

Consideration of the results of the statistical analysis summarized in tables 1 and 2 has enabled us to design a simple procedure for the routine detection of abnormality of amplitude of ballistocardiograms, which has proven both useful and easy to apply. From the results recorded in table 1, no. 1, I have constructed table 3, which permits one to determine the normality of the amplitude of the ballistocardiogram of any subject, in terms of that of the healthy young adults of the selected series, without a calculation. To apply the method, one should proceed as follows:

With the whole ballistocardiogram before one, one selects by inspection a typical large and a typical small complex of the respiratory cycle, and measures the vertical distance between the tips of the I and J waves of each complex. If the ballistocardiogram is calibrated as my instruments are, 10 mm. of deflection representing 280 Gm. of force, the sum of the two vertical IJ distances is found in column 1 or 4 of table 3, and the normality of

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**TABLE 3.—This Permits Ready Detection of the Abnormality of the Amplitude of any Record, by Comparison with that of Healthy Young Adults**

<table>
<thead>
<tr>
<th>Sum of Amplitudes of Typical Large and Small Complexes (I + J)</th>
<th>Relation to Means of Healthy Young Adults</th>
<th>Sum of Amplitudes of Typical Large and Small Complexes (I + J)</th>
<th>Relation to Means of Healthy Young Adults</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males</td>
<td>Females</td>
<td></td>
</tr>
<tr>
<td><strong>mm. (std. calibration)</strong></td>
<td><strong>Force, gms.</strong></td>
<td><strong>%</strong></td>
<td><strong>%</strong></td>
</tr>
<tr>
<td>60</td>
<td>1680</td>
<td>+43</td>
<td>+77</td>
</tr>
<tr>
<td>59</td>
<td>1652</td>
<td>+42</td>
<td>+76</td>
</tr>
<tr>
<td>58</td>
<td>1625</td>
<td>+40</td>
<td>+74</td>
</tr>
<tr>
<td>57</td>
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Normal limits mean ± 2σ = +21% to -21% for males.
Normal limits mean ± 2σ = +22% to -22% for females.
the result in terms of the deviation from the expected value is found by moving over to the column marked "Men" or "Women," depending on the sex of the subject. The calculation involved in making the table dispenses with the necessity of taking the square root when it is used.

For example, if the sum of \( I + J + I_2 + J_2 \) altitudes = 32 mm., and the subject is male, we find that this result is 4 per cent above the expected value. If \( I + J + I_2 + J_2 \) altitudes = 15 mm., and the subject is a woman, the answer is \(-11\) per cent. If one chooses to use \( 2\sigma \) as normal limits, these are, for males, \( \pm 21\) per cent; for females, \( \pm 22\) per cent.

If the ballistocardiogram is not calibrated as are my own instruments, one can enter table 3 by the force equivalent to the sum of the deflections of the large and small waves, by using the second and fifth columns of table 3; and obtain the same result for instruments which are standardized against force.

The use of this table suffices to determine the normality or abnormality of the amplitude of the great majority of records with sufficient accuracy for most clinical work but, if one wishes to obtain further information, or to discover whether an abnormality indicated by the use of table 3 can be accounted for by the patient's age, one can use the equations of table 2, no. 9, to give an expected value, to which the area of the I and J waves found in the patient's record can be compared.

For example: if one finds that in a male, age 53, a typical large complex has an I wave altitude of 5 mm., a duration of 0.08 second, and a J wave altitude of 10 mm., and a duration of 0.10 second; and that in the typical small complex, \( I_1 = 4 \) mm. and 0.06 second, \( J_1 = 8 \) mm. and 0.08 second, then:

\[
\begin{align*}
\text{Area } I &= \frac{1}{2} \times (5 \times 0.08) = 0.20 \text{ mm. second} \\
\text{Area } J &= \frac{1}{2} \times (10 \times 0.10) = 0.50 \text{ mm. second} \\
\text{Area } I_1 &= \frac{1}{2} \times (4 \times 0.06) = 0.12 \text{ mm. second} \\
\text{Area } J_1 &= \frac{1}{2} \times (8 \times 0.08) = 0.32 \text{ mm. second}
\end{align*}
\]

and \( I + J + I_1 + J_1 = 1.14 \) mm. sec. and

\[
\sqrt[4]{I + J + I_1 + J_1} = 1.07. \text{ The expected}
\]

\[
\sqrt[4]{0.0071(53)} + 1.4 = 1.02
\]

The difference between found and expected values = 1.07 \(-1.02\) = 0.05.

Since the standard deviation about the regression is 0.142, \( t = \frac{0.05}{0.142} = 0.35 \). This value being less than 2, the difference is not significant, and the result is within normal limits. If \( t \) exceeds 2, the chances of abnormality exceed 20 to 1, and this defines the conventional limits of normality.

The other regression equations in table 2 could be used similarly, if one felt the need of information of the kind they supply.

I hope that I have not confused readers by using the sum of measurements of large and small complexes, rather than their average, in constructing these normal standards. This was done simply to save the step of averaging. Needless to say, the average is of greater theoretical interest, but the use of the sum suffices equally well to distinguish normal from abnormal amplitudes.

Finally one must ask oneself the question: To how many of the different types of ballisto-
cardiograms now in use, would these standards be applicable? I fully expect that the general form of the equations which have so diminished the scatter of our results, defines important physiological relations, the knowledge of which will prove useful in designing normal standards for results secured by any of these instruments. I am also hopeful that the standards themselves will be found useful for assessing results secured by instruments that can be standardized against force, which includes not only resisted tables calibrated by a suspended mass, the type I employ, but also nonresisted tables whose acceleration is recorded and which are calibrated by means of the acceleration of a pendulum. In theory, these two types should give similar records. At the moment, it is hard to say whether these standards will prove to be applicable to results secured by the Dock method or not, but I am hopeful that they may, when the means of calibrating these instruments have been improved. But these standards could not be applied to results secured by tables of the Nickerson type, without a major revision.

Nevertheless, as factors such as weight of the table make a difference in the amplitude of records taken by resisted tables, and as there may well be other disturbing factors not yet clearly identified, it seems wise to recommend that all workers in the field confirm the applicability of my data to their results by comparing my averages with those secured in
normal subjects by their own instruments. For example, the mean values of the I and J wave altitudes of healthy men and women between 20 and 49 years of age in the ample data of Scarborough and his coworkers indicate a $\sqrt{I + J + I_2 + J_2}$ about 15 per cent higher than the values we obtained, a difference probably to be attributed to the heavier table used by these authors, as adding weight to my own table increases the amplitude of my records. It should be easy to adjust the normal standards given in this paper to compensate for differences such as this.

**Summary**

To obtain new and improved normal standards for the amplitude of ballistocardiograms, as a measure of force of the cardiac beat, we have restudied results secured in a series of 146 healthy persons tested over 15 years ago. The great majority of these subjects have been carefully followed ever since and those who subsequently developed cardiovascular disease have been eliminated. To secure greater numbers for certain aspects of the analysis, 48 healthy persons, tested at later dates, have been added, but to allow time for the development of unrecognized cardiac disease in the added group, no results secured in tests made within the last five years have been included.

Normal standards have been defined by statistical analysis of these results. These standards can only be applied to ballistocardiograms from instruments which can properly be calibrated in terms of force. The absolute values for cardiac force or for the other aspects of cardiac function measured by the ballistocardiogram cannot be given at this time but the relation of results secured on any subject to the normal can be readily determined.

New knowledge of the genesis of the ballistocardiogram has resulted in marked improvement over our previous normal standards, for in the results here described the scatter about the mean is smaller, the standard deviation about the mean being close to 10 per cent of the mean value in the most promising formulations.

For use as a screening test, a table is given in which the normality of the I and J wave altitudes, in terms of results secured on healthy young adults, can be read off without a computation.

Regression equations defining the effects of age on the normal values are also given, the amplitude of the record diminishes as age advances, as is well known, and these equations can be used to determine the normality or abnormality of the values secured in any patient.

When measurements of the square root of the amplitude of ballistocardiograms are multiplied by the pulse rate, a product is secured which might well have clinical value. Normal standards for this product are given, but the scatter of the results secured exceeds that when the amplitudes alone are used.

When measurements related to the square root of the amplitude of ballistocardiograms are multiplied by the mean blood pressure, the correlation of the product with age is no longer significant for either men or women between 20 and 50 years of age. The relation of this product to the work of the heart is discussed, and formulae defining the normal values are given.

**Summario in Interlingua**

Pro obtenere nove e meliorate standards pro le amplitude ballistocardiographic interpretate como mesura del fortia del pulso cardiac, nos ha re-examinate le resultatos obtenite un serie de 146 subjectos in bon stato de sanitate plus que 15 annos retro. Le grande majoritate de iste subjectos continuava ab ille tempore sub caute surveliantia, e omne illes qui subse-quentemente disveloppava morbo cardiovascular esseva eliminate. Pro disponere de plus satisfacente numeros de casos pro certe aspec-tes de nostre analyse, nos ha includite in illo 48 personas in bon stato de sanitate qui esseva subjicite a examines ballistocardiographic a un tempore plus recente. Sed a fin de permitter un sufficiente lapso de tempore pro le disveloppa-mento de non-recognoscite morbo cardiac, nulle resultatos obtenite in examines durante le passate cinque annos esseva includite in le gruppo additional.

Standards normal esseva definite per le
analyse statistic de iste resultatos. Le standards assi obtenite es valide solo pro ballistocardiogrammas facite con instrumentos que perimite un adequate calibration de fortia cardiac. Valores absolute de fortia cardiac e de altere aspectos del functionamento cardiac mesurate per le ballistocardiograph non pote esser determine con nostre presente technicas; sed le resultatos obtenite in un date subjecto es prompte—e facilemente exprimibile in relation al norma.

Nostre meliorate comprenzion del genese del ballistocardiogramma ha resultate in un marcate melioration de nostre previe standards normal. In le resultatos hie descritise le dispersion circa le valor median es plus parve que in previe studios: le deviation standard ab le valores median es vicin a 10 procento del valor median in le plus promittente formulaciones.

Pro facilitar le classification preliminari de ballistocardiogrammas nos ha summarisate le resultatos obtenite ab juvene adultos in bon stato de sanitate in un tabula per medio del qual le normalitate del altitude del undas I e J es verificabile sin computation.

Nos etiam presenta equationes de regression le quales defini le effectos del etate del subjecto super le valores normal. Il es ben cognoscite que le amplitude del registration regrede quando le etate del subjecto se avantia, e nostre equationes de regression pote esser usate pro determinar le normalitate o anormalitate del valores obtenite ab ule patiente.

Quando mesuraciones del radice quadrato del amplitude de ballistocardiogrammas es multiplicate per le rapiditate del pulso, le producto resultantte es possibilemente de valor clinic. Nos presenta standards normal pro iste producto, sed le dispersion del resultatos obtenite exceede le dispersion del amplitudes simple.

Quando mesuraciones del radice quadrato del amplitude de ballistocardiogrammas es multiplicate per le valores median del pression sanguine, le correlation del producto con le etate del subjectos cessa esser significative pro homines e feminas inter 20 e 50 annos de etate. Es discutite le relation de iste producto al labor del corde. Nos presenta formulas que defini lor valores normal.

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Normal Standards for Amplitude of Ballistocardiograms Calibrated by Force
ISAAC STARR

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