The Effect of Aging and of the Development of Disease on the Ballistocardiogram

A Study of Eighty Subjects, Originally Healthy, Followed from Ten to Fourteen Years

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Second ballistocardiograms were taken on 80 subjects who were part of the series from which the original normal standards were secured in 1937, 1938 and 1939. Sixty-five of these subjects had retained good health during the long interval; by a comparison between their old and new records, the effect of "normal" aging on the ballistocardiogram has been determined. Fifteen subjects lost their health during the interval and two of them have died since the second test. The evolution of their ballistocardiograms has been compared with the development of their disabilities.

That older persons usually gave ballistocardiograms of smaller amplitude than young ones was realized early in the studies made in this laboratory. As a result, the estimate of cardiac output made from measurements of I and J wave areas diminishes with age, and so Tanner's normal standards are adjusted for age.

Experience has also demonstrated that gross abnormalities of ballistic form are common in older persons, but altogether absent or very rare in healthy young adults. Obviously, therefore, we had every reason to believe that there was a progressive change in the ballistocardiogram as age advanced, even though health commensurate with one's age might be retained. The present study was primarily designed to investigate the effect of aging on the ballistocardiogram of healthy persons with greater exactitude, to define the normal more exactly, and to obtain new information about the evolution of this record as disease began and advanced.

Certain data bearing on these interests were already available. In our files are the records secured on 200 healthy adults of all ages during the years 1937, 1938 and 1939. This series could now be edited by the subtraction of all those who became sick in the intervening years, leaving us with a series of over 100 healthy persons with whom we are still in contact. In these, good health could be defined as a state in which no serious illness of any kind occurred within a period of 10 years, a definition that we regard as very rigorous and satisfactory. Tanner made use of these data in his study and we have drawn upon them for part of this study. They permit a comparison between results secured in certain healthy young persons with those obtained in other healthy older persons.

But it seemed evident that even more interesting information concerning the effect of aging and of incipient disease on the ballistocardiogram could be secured by repeated tests...
Fig. 1. Ballistocardiograms taken before and after a 10- to 14-year interval, a pair of records for each of four subjects. The reproduction is one-half actual size.

Changes of technic during the long interval have changed the appearance of the records making comparison by inspection difficult: The single edge (black above white) of the lower record of each pair corresponds to the upper margin (also black above white) of the upper record of each pair.

The time record on the third ballistocardiogram, the longest interval 1.0 second, applies also to the first and fifth ballistocardiogram, numbering from above downward. The time record on the fourth ballistocardiogram applies also to the second, sixth, seventh, and eighth ballistocardiogram. In these later records the film ran slower than in the earlier ones and allowance must be made for this when inspecting them.

The calibration of all the ballistocardiograms is the same: 280 Gm. displaces the light spot 1.0 cm., so the amplitude of each record is directly comparable.

A simultaneous electrocardiogram, lead II, is on the second record of each pair.

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on the same subject as he was growing older. Accordingly, in the fall of 1950 and the winter of 1951, we asked every member of our original series, whose address we knew, to return for a second ballistocardiogram, and we eventually secured such "follow-up" records on 80 persons who had been similarly tested from 10 to 14 years before. The changes in the ballistocardiograms of each individual and their relation to changes in his or her health during this period forms the chief subject of this presentation. We have found that when health is retained the ballistocardiogram changes slowly as age advances; if health is lost, it is likely to change rapidly. A preliminary report has been made concerning certain features of this work.

METHODS

From the subject's viewpoint, the test made over 10 years before was repeated exactly. The same ballistocardiograph was used to obtain both old and new records. In both series no records were taken within two hours after a meal, and the subjects lay at rest for at least 15 minutes on the ballistocardiograph before a record was secured. Auscultatory estimates of blood pressure were made in both series, either just before or just after the ballistocardiograms were taken.

But certain elements of our technic had been changed in the long interval. Simultaneous electrocardiograms, recorded on the same film with the ballistocardiograms, were taken in all the new records, but only occasionally in the old ones. In both new and old records the calibration was the same, 280 Gm. deflecting the record 1 cm. Each of the new records was calibrated by a new device that allowed a weight of 280 Gm. to pull horizontally on the table for a short period, deflecting the record base line 1 cm., if the adjustment was at the usual standard, and giving an effect much like that of the usual calibration of electrocardiograms.

The technic of photography changed in the interval between the groups of tests, and examples of both methods can be found in figure 1. In the old records a wire was photographed so that the movement of a light streak on a dark background was recorded. In the new records, because of the simultaneous electrocardiogram, we photographed an edge, so that one side of the developed film is dark, the other side light, and on this light side the electrocardiogram is thrown. The moving line of the ballistocardiograms taken by the newer technic corresponds exactly to the upper edge of the ballistocardiograms of the old records, the edge from which measurements were always made. But inspection of the two types of records side by side, as in figure 1, is somewhat deceiving; one is likely to judge the old records to be of greater amplitude than the new ones, when the measurements show them to be equal. This is because one unconsciously tends to assess the amplitude of the old record not from the movement of one edge, as is correct, but from the highest peak of the upper edge to the lowest trough of the lower edge. Because of this difficulty, inspection of the actual records shown in figure 1 may be somewhat deceiving, and in figure 2 we resorted to scale drawings in which accurate comparisons can be made by inspection without optical illusion.

The speed at which the film was run also changed in the long interval. We now use a film speed closely similar to that of standard electrocardiographic technic; for the old records the film was usually run faster, another point which makes it difficult to compare new and old records by inspection alone.

With a record before us for the first time we inspected the whole of it and selected one complex as typical of the largest complexes of the respiratory cycle, and another as typical of the smallest complexes of this cycle. Only these two complexes were measured, and by averaging the heights and durations of similar waves of each an average complex was estimated. In the upper left of figure 2 this method is illustrated.

Measurement was made according to our usual routine. A base line was selected by inspection, the line the record would occupy if the heart stopped beating, and the vertical heights or depths of the H, I, J, and K waves were measured from this base line by the millimeter scale photographed on the record. We usually contented ourselves with reading to the nearest millimeter. The duration of the waves was measured in 0.01 second, along the base line,

**Fig. 1. Continued.**

First Pair: records of L. G., the upper taken at age 33 and the lower at age 47. The blood pressure was 105/70 and 105/70 at the two tests. He has maintained good health.

Second Pair: records of N. O., age 48 and 62 years. His blood pressure was 120/88 and 165/110. He has developed hypertension.

Third Pair: records of N. L., J., age 54 and 67 years. The blood pressure 128/76 and 135/85. She believed herself to be in good health, and a complete cardiac study was negative. Nevertheless the recent ballistocardiogram is far from normal.

Fourth Pair: records of P. E., aged 50 and 63. Blood pressure 136/80 and 165/85. He thinks of himself as in good health, but the deterioration of the ballistocardiogram is conspicuous.
Fig. 2. Ballistocardiographic complexes drawn to scale to illustrate (1) changes in ballistic form occurring in typical healthy persons and patients during a period of from 10 to 14 years; (2) the average changes on aging; and, (3) their physiological explanation.

Top Row, Left: The relation of the enlarged drawings to the original ballistocardiograms. The average complex, defined as the mean of typical large and small complexes of the respiratory cycle. Middle: Typical large and small complexes of N. I. O., a healthy person. The complexes in the second record can be almost superimposed on those of the record taken 14 years before. Right: from F. N. who at age 64 gave a record looking younger than his age. At 76 the record looks older, but he is still in excellent health.

Second Row, Left: from D. N. S., who showed a prominent change in the smallest complexes during the 13 years. Arrows point to I wave displaced above base line and deep K waves. Middle: from F. N. S., who showed a prominent change in the smallest complexes during the 13 years. Arrows point to I wave displaced above base line and deep K waves. Right: from F. N. who at age 64 gave a record looking younger than his age. At 76 the record looks older, but he is still in excellent health.

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by cutting out a piece of the time record and applying its edge directly to the distance being measured. As we readjusted the ballistocardiogram whenever the deflection of the light spot differed significantly from 1 cm. when the calibrating weight was applied, no correction of the vertical measurements was usually necessary.

The new records were measured in this manner soon after they had been taken. All the old records were found and remeasured except two. In these two cases we used the measurements recorded in the old record book for the I and J waves. Unfortunately H and K were not then being measured, so the averages recorded in the tables had to be obtained without these data. In a few cases items such as blood pressure or body weight were missing from the old records, deficiencies which account for the small differences in number of subjects in different tables.

The statistical analysis of the data was performed by standard methods as given in Snedecor's book. The word significant is used throughout the paper in the statistical sense, meaning that the chances are over 95 in 100 that the difference is not due to chance selection.

RESULTS

These can best be presented under two separate headings. Let us consider first the effect of aging on the ballistocardiogram as ascertained from records of those remaining in good health and, second, the effect of the development of disease as indicated by records of those whose health had failed.

PART I. THE EFFECT OF AGING WHEN HEALTH IS MAINTAINED

These studies can also be divided into two parts: first, those made on data secured from the ballistocardiograms of the old normal standard series, amended by the subtraction of all persons who had become seriously ill or had died since that time; second, those made on the persons on whom a second test was recently secured. Needless to say, the personnel of the two groups overlaps, for the first test made on all those tested twice is included in the old normal standard series in most cases.

The Effect of Aging as Estimated from Data in the Old Normal Standard Series

Ballistocardiograms were available on 27 men and 12 women aged from 40 to 49, 16 men and 7 women aged from 50 to 59, and 6 men and 3 women aged over 60 years, all of whom met the requirement of having been in good health when first tested and having survived for 10 years or longer after this test without serious illness.

The use of the I plus J distance rather than the measurement of single waves has the advantage that the considerable error of placing the base line is avoided. So in a recent publication from this laboratory normal standards were set up for the vertical distance between the trough of the I waves and the peak of the J waves (the I plus J distance) of typical large and small ballistic complexes, as a measure of cardiac strength. These standards were derived from a statistical analysis of records secured on 100 young men and women of this series from 20 to 39 years of age. By this means equations were set up which predicted the value to be expected for any subject and the likelihood of any subject's measurements falling within the normal range. Unlike the standards for cardiac output as calculated from the ballistocardiogram, this standard was not adjusted for age, in the belief that it might be more valuable for that very reason, although this is certainly a debatable point.

So the effect of age on this feature of the ballistic record (the I plus J distance) was investigated by comparing the I plus J distance found in older subjects known to have remained healthy with that predicted from data obtained on the young.
A very striking diminution of the I plus J distance occurs as age advances, the average deviations from the predicted values being —30 per cent, —40 per cent, and —49 per cent for those tested when in their 40’s, 50’s and 60’s respectively. The difference between each of these means and the predicted value is highly significant.

The Effect of Aging as Estimated from Persons Retested after a Long Interval

In studying the data secured from these cases, the scope of the investigation was enlarged. We now aimed to discover the effect of aging not only on the amplitude of the record but also on each of the major waves of the ballistocardiogram, so we accepted the error of placing the base line and examined each wave individually. Also our criteria of what constituted good health were different.

The 65 persons stated that they were in excellent health. We realize that some of them might have deceived us. Certainly all were working actively and all had been known personally to the senior author for many years and gave every appearance of good health.

Dr. Francis C. Wood most kindly volunteered to make a complete clinical study of the group. About one third have already been examined, and we plan a later communication on this aspect of our work.

Not all those admitted to this healthy group had completely negative histories. Thus there were several persons with pulmonary tuberculosis arrested for many years, one who has had an occasional attack of auricular fibrillation of short duration despite completely negative clinical findings at other times, and two who had had attacks somewhat suggestive of cardiac infarction but without any electrocardiographic confirmation. Two had taken minute doses of thyroid for many years on the advice of their physicians, although definite hypothyroidism had never been demonstrated. In several persons over 60 the blood pressure had crept up towards the hypertensive level. Especially in the older age groups, the distinction between health and disease is not always easy.

We were disappointed in the small number of persons, in their 20’s when first tested, who could be secured for a second test 10 years later. The original group consisted mostly of medical students and hospital residents, and many had moved far away from Philadelphia in the interval.

Our first step was to investigate the effect of aging on the average complex. Before beginning the statistical analysis it seemed wise to make some adjustment for the effect of differences in size of subjects. So, without setting up a regression, we merely assumed that the wave altitudes would be related to the subjects’ weight and surface area, tried both, and chose the latter. Accordingly the altitude of the waves for each subject was divided by the ratio of his or her surface area to 1.82, the latter the median surface area of the group in square meters. The statistics given in table 1 were calculated after this adjustment.

In table 1 the means of the heights and depths of the main ballistic waves of average complexes are given, for each decade of life.

<table>
<thead>
<tr>
<th>Group</th>
<th>No.</th>
<th>H Wave</th>
<th>I Wave</th>
<th>J Wave</th>
<th>K Wave</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean altitude</td>
<td>Mean depth</td>
<td>Mean altitude</td>
<td>Mean depth</td>
</tr>
<tr>
<td></td>
<td>mm.</td>
<td>mm.</td>
<td>mm.</td>
<td>mm.</td>
<td>mm.</td>
</tr>
<tr>
<td>20-29</td>
<td>15</td>
<td>1.8</td>
<td>1.0</td>
<td>5.0</td>
<td>1.1</td>
</tr>
<tr>
<td>30-39</td>
<td>30</td>
<td>1.5</td>
<td>4.7</td>
<td>1.5</td>
<td>8.0</td>
</tr>
<tr>
<td>40-49</td>
<td>38</td>
<td>1.8</td>
<td>3.9</td>
<td>1.8</td>
<td>7.6</td>
</tr>
<tr>
<td>50-59</td>
<td>26</td>
<td>1.8</td>
<td>3.7</td>
<td>1.8</td>
<td>7.6</td>
</tr>
<tr>
<td>60-over</td>
<td>19</td>
<td>1.8</td>
<td>1.2</td>
<td>2.2</td>
<td>1.2</td>
</tr>
</tbody>
</table>

* Significantly different from 20-29 year mean.

In the table each subject appears twice, the first test being in one decade, the second in another.

In this table it will be seen at once that, although the mean amplitude of H and K waves does not change significantly, there is a steady tendency for the I and J waves to diminish as age advances. The asterisks indicate which means of the older groups are significantly different from the corresponding means of the 20 to 29 year group.
The results recorded in table 2 show a slight tendency for the I and J wave durations to diminish as age advances and their waves become smaller in amplitude, but the difference is never significant. There is also a slight tendency for the H and K waves to broaden and there is a special point here which will be discussed later, but again the difference is not significant because of the size of the scatter. So we found no significant effect of aging on the duration of any main wave of the ballistocardiogram.

**Analysis by Paired Experiments**

Having two estimations, made from 10 to 14 years apart on the same subjects, the data can also be handled in another way, which presents advantages when analyzed statistically. We therefore took the measurements of the H, I, J, and K waves of the typical large and small complexes on the records secured over 10 years ago and subtracted from them the corresponding measurements from the records secured recently. We thus obtained the changes found after aging for each main wave of both large and small complexes of every subject. The statistical analysis of these differences will be found in table 3, where it will be seen that, on the average, the I waves of the youngest group did not diminish as they grew from 10 to 14 years older, but in the older subjects this diminution on aging increased progressively, the mean change of the smaller complexes always exceeding that in the larger. Also the average diminution in the J wave on aging is seen to manifest itself only in the smaller complexes, while the H and K waves show no trend in the 10 to 14 year interval. But while the changes with aging in table 3 are consistent with those shown in table 1, only a few of the former reach statistical significance. Obviously the change of the ballistocardiogram with aging is so slow that a period of longer than 10 to 14 years would be necessary to detect it.

### Table 2.—Effect of Aging on Mean Duration of Main Ballistocardiogram Waves as Estimated from the “Average Complex” of each Subject

<table>
<thead>
<tr>
<th>Group</th>
<th>No.</th>
<th>H Wave</th>
<th>I Wave</th>
<th>J Wave</th>
<th>K Wave</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean duration</td>
<td>σ</td>
<td>Mean duration</td>
<td>σ</td>
</tr>
<tr>
<td></td>
<td>sec.</td>
<td></td>
<td>sec.</td>
<td></td>
<td>sec.</td>
</tr>
<tr>
<td>20-29</td>
<td>15</td>
<td>0.062</td>
<td>0.000</td>
<td>0.067</td>
<td>0.037</td>
</tr>
<tr>
<td>30-39</td>
<td>30</td>
<td>0.051</td>
<td>0.000</td>
<td>0.062</td>
<td>0.029</td>
</tr>
<tr>
<td>40-49</td>
<td>38</td>
<td>0.053</td>
<td>0.080</td>
<td>0.057</td>
<td>0.026</td>
</tr>
<tr>
<td>50-59</td>
<td>26</td>
<td>0.070</td>
<td>0.085</td>
<td>0.058</td>
<td>0.044</td>
</tr>
<tr>
<td>60-over</td>
<td>18</td>
<td>0.079</td>
<td>0.065</td>
<td>0.054</td>
<td>0.069</td>
</tr>
</tbody>
</table>

The means of the durations of the waves in older persons are not significantly different from the means of corresponding waves in the 20 to 29 year group.

### Table 3.—Average Changes in Ballistocardiogram Wave Heights as Healthy Subjects Aged from 10 to 14 Years

| Age at First Test | No. | H Wave | I Wave | J Wave | K Wave | H Wave | I Wave | J Wave | K Wave |
|-------------------|-----|--------|--------|--------|--------|--------|--------|--------|--------|--------|
|                   |     | Mean   | σ      | Mean   | σ      | Mean   | σ      | Mean   | σ      | Mean   | σ      |
|                   | mm. | mm.    | mm.    | mm.    | mm.    | mm.    | mm.    | mm.    | mm.    | mm.    | mm.    |
| 20-29             | 14  | +0.36  | 1.5    | +0.1   | 1.31   | –0.07  | 0.67   | +0.87  | 2.4    | +0.68  | 1.08   | +1.18  | 1.33   | –1.0   | 2.3    | +0.04  | 1.62   |
| 30-39             | 22  | +0.75* | 1.3    | –0.4   | 1.8    | +1.2*  | 2.3    | +0.64* | 1.1    | +0.6*  | 1.1    | –1.0*  | 1.5    | –0.36  | 2.1    | –0.2   | 1.8    |
| 40-49             | 17  | +0.5   | 1.3    | –0.3   | 1.8    | +0.3*  | 2.7    | +0.6   | 1.9    | +0.6*  | 1.1    | –0.7   | 1.6    | 0      | 2.4    | +1.0   | 2.1    |
| 50-59             | 9   | +0.4   | 0.8    | –1.5   | 2.0    | +0.2   | 2.7    | +1.1   | 1.8    | +0.4   | 1.0    | –1.9*  | 1.1    | –1.1   | 2.0    | –0.3   | 0.7    |
| 60-over           | 3   | –0.7   | –1.2   | +1.7   | +1.3   | +0.27  | +0.3   | +1.9   | +1.6   |        |        |        |        |        |        |        |        |

* Significant for \( p = 0.05 \)
with confidence in any healthy individual, or even in a small group of healthy persons.

In table 4 have been placed the average changes of pulse rate, blood pressure, and body weight which occurred in the same group of 65 healthy persons during the 10 to 14 year interval. The pulse rates of each individual tended to agree closely in the two tests and so there is no significant change in the averages of the different age groups. The average blood pressures show the well known tendency to increase

<table>
<thead>
<tr>
<th>Age at First Test</th>
<th>No.</th>
<th>Average Change in Pulse Rate</th>
<th>Average Change in Systolic B.P.</th>
<th>Average Change in Diastolic B.P.</th>
<th>Average Change in Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>per min.</td>
<td>mm. Hg</td>
<td>mm. Hg</td>
<td>lbs.</td>
</tr>
<tr>
<td>20-29</td>
<td>10</td>
<td>+3.1</td>
<td>+4.7</td>
<td>+9.0</td>
<td>+12</td>
</tr>
<tr>
<td>30-39</td>
<td>21</td>
<td>+1.5</td>
<td>+1.6</td>
<td>+7.2</td>
<td>+7</td>
</tr>
<tr>
<td>40-49</td>
<td>19</td>
<td>+0.1</td>
<td>+1.1</td>
<td>+3.3</td>
<td>+3</td>
</tr>
<tr>
<td>50-59</td>
<td>9</td>
<td>+1.9</td>
<td>+1.0</td>
<td>+7.7</td>
<td>-8</td>
</tr>
<tr>
<td>60-over</td>
<td>3</td>
<td>-3.0</td>
<td>-4.3</td>
<td>-1.6</td>
<td>0</td>
</tr>
</tbody>
</table>

as age advances, and it is of interest that the average increase is greater in the older age groups excepting the eldest which, containing only three persons, neither adds nor subtracts anything significant, and is placed in the table only to complete the record. It is also of interest to note that the younger people tended to gain weight during the interval and the older ones to lose it; but the scatter is large and mean changes are not significantly different from zero.

Other Changes Found on Aging

In some cases in the later decades of life the I wave becomes not only diminished in size but displaced upward so that its point fails to pass the base line. Figure 1 gives three good examples of this and, in the three records of D. N. S., given in figure 2, the evolution of the abnormality could be followed. In the typical smallest complexes of the respiratory cycle when he was 55 the I wave, though small, clearly goes below the record’s base line; when he was 63 it just touches the base line; when he was 68 its trough is well above the base line. Despite this developing ballistic abnormality this subject appeared to be in good health for his age and a careful and complete cardiac examination by Dr. Francis C. Wood did not disclose any abnormality detectable by the usual clinical methods of examination.

Such upward displacements of the I wave have been encountered only in the later decades of life in this study of healthy persons, but in records taken on the sick they are not uncommon. Thus we encountered them quite frequently in records secured soon after surgical operation in persons over 50 years of age. The abnormality often disappeared as the patients recovered from the effects of the operation. We have as yet no conclusive data on its clinical importance, but the absence of anything similar in hundreds of records of healthy young adults arouses our concern for the future of those who have this abnormality.

A second change in contour developed by certain subjects when reaching their fifth or sixth decade is less conspicuous and probably less important. In these the L-wave peak fails to reach the base line, making K appear unusually broad. The smaller complexes of subject N. L. K. shown in figure 1 are good examples. We first became aware of this abnormality when measuring the duration of K waves, and in table 2 the average duration of K is increased in the eldest age groups because of its occasional presence, the duration of K having been defined as the time between the intersection of the JK downstroke with the base line, and the record’s return to the base line.

It is of interest that these two changes with aging are in a way the reverse of one another; the first abnormality suggests a force pushing the record up at the beginning of systole and the second a force pushing it down at the beginning of diastole. In this clinical paper we will not pause to speculate about the nature and origin of these forces but, needless to say, the cases showing such abnormalities will be followed with unusual interest.

Normal Standards for the Contour of Ballistocardiograms

The statistics given in tables 1 and 2 may be used as empiric normal standards for the individual waves of the ballistocardiograms secured from high frequency instruments such
as are used in this clinic. To assess the normality or abnormality of any wave of the record of a patient being investigated one would proceed to measure typical large and small complexes in the usual manner, and average the heights and depths of corresponding waves. If the instrument's calibration differs from that we employ (280 Gm. displaces our light spot 1 cm.), one must make proportional correction for this. One then corrects for size of subject by multiplying each vertical measurement by 1.82 divided by the surface area of the subject concerned; the result can now be compared with the data in table 1 for subjects of corresponding age, the normal range being defined as some multiple of the standard deviation laid off on each side of the mean. Two is the multiple that convention has assigned for such defining the limits of normality but the convention arose under conditions very different from those of medical practice and smaller values might well be found more useful. And indeed, many abnormalities of ballistic contour are so obvious that they can be recognized with confidence by inspection alone. Nevertheless, the data contained in tables 1 and 2 define the contour of the records of healthy adults of different ages and permit us to go on with increased confidence to a study of the records of those who failed to maintain good health during the interval of years encompassed by our study.

**PART II. CONCERNING FIFTEEN SUBJECTS WHO FAILED TO MAINTAIN GOOD HEALTH**

In the light of the experience with aging in healthy persons, let us now consider the ballistocardiograms and the clinical histories of those whose good health did not continue. No attempt will be made to present all the cases who have been followed for over 10 years in this clinic. The cases here described are all persons whom we thought of as healthy when we invited them to come for the first test over 10 years ago.

1. **Persons Who Became Ill but Whose Ballistocardiograms Remained Normal**

Case II. *N. P.* was a housewife, 42 years of age when first tested in 1939. At that time she considered herself in good health save for an occasional attack of pollen or dust asthma which had started in 1930. She was known to be sensitive to a large number of substances, including dusts, foods, and pollens. In 1939 her ballistocardiogram was altogether normal.

In the 12-year interval the asthma has increased greatly in severity and on several occasions in recent years she had been forced to enter the hospital to be given oxygen. When tested in July, 1951, she was receiving epinephrine subcutaneously about 0.3 to 0.4 cc. about every four hours to keep her free of attacks, and was preparing to leave the city for the mountains to avoid the late summer pollens. Despite all this her recent (1951) ballistocardiogram was altogether normal and extraordinarily similar in appearance to the previous (1939) record; no wave measurement differed by more than 1 mm. from that of the record secured 12 years before. The similarity of pulse rates (70 and 76) and of blood pressures (120/70 and 120/64) in the two tests suggests she was not under the influence of epinephrine in the last.

Case K. J. M., a teacher, considered himself in good health when tested in 1939 when he was 42 years old. His ballistocardiogram was altogether normal at that time.

In 1943 he had a severe illness and was admitted to the hospital with what was diagnosed as Addison's disease. Since that time he has had the standard maintenance therapy for this condition which has been varied according to his needs. When tested in June, 1951, he was carrying three pellets, originally 75 mg. of desoxycorticosterone each, which had been implanted in his back on Jan. 20, 1951. He was also taking 6 mg. of cortisone daily, and 20 mg. Paredrine three times daily by mouth; and extra salt with his meals. He was working actively and considered himself in reasonable health. His blood pressure at the time of our test was 130/85, almost exactly what it had been before he became ill. The ballistocardiogram was altogether normal and indeed the I and J waves of the last tracing averaged 1 mm. larger than those of the preceding one, despite very similar pulse rates, 67 and 70, at the two tests.

Both these subjects have therefore suffered from severe and prolonged ill health without any detectable deterioration in their ballistocardiograms.

Case F. G. E., a doctor, long in medical practice, was first examined in 1939 when he was 60 years of age. At that time he gave a history of an attack of cardiac infarction two years before. He never thought of himself as seriously ill, but consultation with the physician who had cared for him, an old friend of the senior author, disclosed that there was no doubt whatever concerning diagnosis and that the electrocardiogram had been typical of this condition. Despite this history his ballistocardiogram in 1939 (fig. 2) was not only altogether normal but looked like that of a much younger man. At that time this result was thought of as being an instance
when the ballistocardiogram had failed to detect cardiac damage which was almost certainly present. But during the 12-year interval the subject's health has remained excellent, with one reservation. Two years ago he went into auricular fibrillation and remained in this arrhythmia for several weeks, reverting spontaneously to normal rhythm. He was started on digitalis at this time and has continued to take it, although the arrhythmia has not recurred. In contrast to this transient episode of ill health let me put the fact that within the last few months, at the age of 72, he made an 82 on one of Philadelphia's most difficult golf courses. Taken in 1951, his ballistocardiogram differs from the previous record only by the changes characteristic of aging. It still looks like the record of a younger man.

In this case a normal ballistocardiogram was followed by continuing good health despite an ominous history. Among those who have had their difficulties and maintained normal ballistocardiograms we must also mention B. I., a female subject, in good health when first tested at the age of 28, who has proudly borne five healthy children in the 14-year interval. Her ballistocardiogram after all this, completely normal, can be almost superimposed on that secured during nulliparity.

II. Subjects Attaining Advanced Age

Case K. V.'s first record, taken in 1938 when she was 74 years old, was reproduced in a previous publication. It was normal in form but extremely small in amplitude. She developed mild but typical angina pectoris on exertion about four years later and has had occasional attacks since.

This patient is still alive, aged 87. She has continued to suffer from arthritis of the knees, which has increased in severity, and she now is able to walk only a few steps on crutches. She is very feeble and spends much of the day in bed, the rest in her wheelchair. Leading this restricted life, she has not had an anginal attack for over a year. The ballistocardiogram taken in 1951 resembles the earlier one in that it is still of extremely small amplitude, but the form has now become highly abnormal. In the majority of complexes the II wave dominates the excursions, in the smaller complexes it is double the height of J; in many complexes I does not reach the base line; in many J is less than 1 mm. in height. No complexes could be passed as normal.

Case F. E. S., a housewife, was first tested in 1937 at the age of 69. She had a history of rheumatic fever in childhood and a murmur suggestive of mitral stenosis could be heard when she lay on her left side, according to her cardiac consultant; many examiners had failed to hear it. About three years before this test, under great mental strain during the last illness of her husband, she had her first transient attack of auricular fibrillation and she continued to have these attacks, usually of only a few hours duration, at occasional intervals. Despite this, when in normal rhythm, she was extremely strong and active for her years and had far less shortness of breath on exertion than most younger people. The first ballistocardiogram taken during normal sinus rhythm in 1937 was of small amplitude but otherwise normal in form. The blood pressure was 120/70.

During the interval her general health has continued excellent, although the attacks of auricular fibrillation continued. Eventually, probably about two years ago, she went into permanent aurricular fibrillation. She has never been in congestive failure. At present, aged 84, she is taking digitalis and still has no undue shortness of breath, but she is definitely slowing up both mentally and physically. The ballistocardiogram taken in 1951 shows no complexes that are normal in form.

In these two cases both health and ballistocardiograms are plainly deteriorating.

In contrast are the history and records of E. N. (fig. 2) who, when aged 63, had the ballistocardiogram of a much younger person. His good health has continued; at 75 his record does show changes of the aging heart type, the I waves are smaller and the K waves deeper than when he was younger. At present he prides himself on walking between five and six miles every day, and certainly both his vigor and his ballistocardiogram are those of a much younger man.

III. Patients Developing Ill Health of a Doubtful Character

Case P. E., a carpenter, had no complaints when his first ballistocardiogram was taken at the age of 50. He had, however, suffered from an attack of pain of an indefinite sort for which the diagnosis of cardiac infarction was considered but abandoned after electrocardiographic studies were negative. His ballistocardiogram was altogether normal. His blood pressure was 130/80. Both ballistocardiograms are shown in figure 1.

When tested in 1950 he was 63 years old and his ballistocardiogram had deteriorated in an alarming fashion. Although the pulse rates in the two tests were very similar, 58 and 63, the size of the complexes had diminished greatly, the I and J waves of the larger complexes being 4 and 5 mm. smaller, the J wave of the small complex 5 mm. smaller than in the old record. At this time his blood pressure was 165/85.

Dr. Francis Wood examined this patient for us in ignorance of the ballistic findings, and refused to pass him as completely healthy. The blood pressure he obtained during his examination was higher than that we found after a 15 minute rest period on the ballistocardiograph, and he was impressed with the fact that the subject, an important hospital main-
tence man well known to all of us, appeared to lack vigor and to move slowly and guardedly as one watched him at his work. But no other positive objective evidence of cardiovascular abnormality was discovered. Needless to say, the course of this subject will be followed with great interest.

Two other persons in our series have also developed ill health of a doubtful character together with a marked deterioration of their ballistocardiograms. We have decided to await developments before reporting their cases in detail.

IV. Subjects Developing Hypertension

Subject N. O., a teacher, had suffered from pulmonary tuberculosis as a young man. Under appropriate treatment it was completely arrested, and activity has never recurred. He has learned to lead a life appropriate to this condition, taking no strenuous exercise, and much more rest than the average person. He considered himself in excellent condition when first tested in 1937 at the age of 48. His blood pressure at that time was 120/88. This ballistocardiogram shown in figure 1 attracted attention at once because, while the waves were all normal in form, the amplitude was very small. Indeed, for his age and weight, it was one of the very smallest records we had encountered in a healthy person up to that time.

During the interval he has continued in good health, and aside from some dizzy spells, still thinks of himself as in excellent condition. However, when tested in 1951 at the age of 62, there had been a marked change in the ballistocardiogram (fig. 1), the H wave being preceded by an unusually deep G wave, while the I wave never reached the base line. No normal complexes were seen. The blood pressure was 165/110 at the end of his 15 minute rest period, so he now has a definite hypertension.

This experience is interesting from two points of view. In the first place, here is a subject with an unusually small ballistocardiogram who has developed hypertension rather than coronary disease as so many of these cases do. And second, at the time of the first test, the cardiac output, as calculated from the ballistocardiogram, was unusually low; so, to maintain the normal blood pressure then found, he must have had increased peripheral resistance at that time. The thought that people might develop the abnormality of hypertension, increased peripheral resistance, before the blood pressure rises is a challenging one.

Subject I. H., a physician, was unusually strong and vigorous when tested in 1937 at the age of 25. At this test his blood pressure was 138/85. In the interval, several years ago, hypertension was discovered. He is completely without symptoms and continues to practice very actively. At the time of his ballistocardiogram in 1951 his blood pressure was 200/120. Both these records have been illustrated in figure 2, where it will be seen at once that there has been a great diminution of the size of the I waves in the interval. No one in the healthy series suffered such a large I wave change as occurred in this patient. At the age of 39 he has a record which looks like that of an elderly man.

The records of Subject S. J. are also illustrated in figure 2, and they are of interest as a continuation of the story of hypertension. S. J. was completely asymptomatic when he came to be tested in 1941 at the age of 63, and he was ignorant that his blood pressure was elevated (180/100). At that time his ballistocardiogram showed an abnormally short I wave, a deep K, and indeed it looks very much like the second record of I. H.

Unfortunately, during the 10-year interval, S. J. has become completely incapacitated. He has been in congestive failure three times and when tested in 1950 was in auricular fibrillation and receiving both digitalis and mercurial diuretics. The illustration in figure 2 showing only a large and small complex does not give a fair idea of the abnormality of his record, for the largest complexes of the respiratory cycles were the only ones which could be passed as normal. The intermediate ones resembled the small complexes illustrated and the ratios of normal to abnormal complexes throughout the record was 1 to 5.

By combining the experience in the last two cases one may anticipate the changes in the ballistocardiograms which might occur as the hypertensive syndrome advances for a period of 20 years.

V. Subjects Developing Coronary Heart Disease

Subject F. E., a maiden lady of 59 when first examined in 1938, considered herself to be in excellent health. However, her ballistocardiogram was definitely abnormal, every J wave showing two peaks about 0.08 second apart. Her blood pressure at that time was 160/85.

During the 12-year interval she has developed angina pectoris. The onset is rather hard to date but during the past year she has had typical attacks on only moderate exertion, such as rapid climbing of one flight of stairs. Her doctor writes that an x-ray film shows the heart to be normal in size, that the electrocardiogram is essentially normal, and that the patient is taking nitroglycerin occasionally to relieve her attacks. Interestingly enough the recent ballistocardiogram does not show the split J wave which was such a prominent feature of the first record; but only an occasional complex was normal, the I wave being absent or shallow in the majority. The blood pressure is now 180/100.

This patient was not included in our first and second follow-up series on healthy persons because her blood pressure was elevated at the first test. But she evidently belongs to the ever growing group of patients whose ballistic abnormality preceded the clinical picture of coronary heart disease.
Subject S. C. has been mentioned before.\textsuperscript{8} Secured in 1937 when the subject was 44 years old, the ballistocardiogram was entirely normal in form and larger than was to be expected from the subject's age and weight. Indeed, with a pulse rate of 81 and a blood pressure of 120/80, the calculated cardiac output exceeded the young adult mean by 20 per cent, a value exceeded by only one subject in his age group.

During the interval this subject had several attacks which might well have been angina pectoris after very unusual exertion, as was described.\textsuperscript{8} This experience was recorded as the most divergent black dot in figure 2 of the previous report,\textsuperscript{4} indicating a subject who, contrary to the general experience, had developed evidence of coronary heart disease despite a large ballistocardiogram of normal form.

Since that report the subject has had no more attacks suggestive of angina pectoris, and has continued to work very actively. However the ballistocardiogram taken in 1951 shows more diminution in size than any other in our series. At a pulse rate of 54 and a blood pressure of 135/79 the I and J waves of the large complexes have diminished by 2 and 6 mm. in altitude; in the small complexes they have diminished 1 and 4 mm. respectively. When the time-amplitude estimate of cardiac output used in the preceding paper\textsuperscript{8} is employed, using the subject's actual weight, the deviation from the young adult mean is now -44 per cent. So the findings on this patient which diverged from the rest of the data in 1937 now conform with them. If a black dot to represent the present findings is placed on figure 2 of the previous paper,\textsuperscript{8} it now appears among the other black dots.

One wonders if the high finding of 1937 could have been due to excitement, despite normal pulse rate and blood pressures. In making experiments on normal subjects the senior author has seen many instances in which increased cardiac output attributed to excitement has manifested itself without conspicuous changes in pulse rate or blood pressure. The fact that errors of this kind can creep into ballistocardiographic work, despite the painless and unalarming nature of the test, must always be kept in mind.

Subject H. C. B., a distinguished physiologist, was in excellent health when first tested in 1937 when aged 52. Indeed he was a person of unusual vigor and took great interest in performing physiologic experiments, often very rigorous ones, on himself. He had long been aware that there was a prolonged P-R interval on his electrocardiogram. His ballistocardiogram at this time was altogether normal.

An utterly fearless person, during the war he supervised and conducted research in aviation medicine and was especially concerned with the construction and testing of equipment to make it possible to live and fly a plane at extreme altitudes. On one occasion the senior author (outside the chamber) collaborated in testing equipment which permitted us to get H. C. B., alone in the chamber, up to a simulated altitude of 52,000 feet, which was the limit of the motor's power, an experiment which alarmed the senior author but not the subject. This experiment was concluded without untoward incident, but the number of times H. C. B. had blacked out in less successful experiments was very great, and I mention this in tribute to a courageous and self-sacrificing man, who never spared himself when the interests of others were concerned.

In 1948 when exercise tests were being conducted in this laboratory by Dr. Makinson,\textsuperscript{9} H. C. B. was tested both before and after exercise. The resting record was altogether normal, but after exercise there was slurring of the J wave in the smaller complexes in records taken 10, 60, 100, 135, and 175 seconds after exercise had been completed. That taken 245 seconds after exercise was normal once more. The subject did not experience any distress whatsoever during the performance of the test. His health at this time was excellent.

In the summer of 1949 in very hot weather during a scientific meeting, he challenged several much younger colleagues to a race at underwater swimming in the hotel pool, a sport in which he was most interested and extremely proficient. He won the race easily. But that night he had an attack of precordial pain, which he suspected was due to coronary occlusion. Nevertheless, next day he started to drive his car from Atlanta to Philadelphia. On his arrival the electrocardiogram showed changes in the T wave which had not been present before, and sedimentation rate was increased, so he was admitted to the University Hospital.

His symptoms were never severe and, after a short period, both the electrocardiogram and sedimentation rate returned to their previous states and recovery seemed to be complete. He was judged to have had a minimal myocardial lesion.

Though he had pain of an indefinite character at intervals, he worked hard all the next winter. A ballistocardiogram taken at rest at this time was altogether normal and indistinguishable from the earlier records. He was not tested after exercise.

In July, 1951, planning to attend the International Physiological Congress, he had some indefinite pain in his upper abdomen just before leaving which both he and his physician thought might well be indigestion and, as his electrocardiogram was unchanged, he decided to sail. Several days later he was found dead in the bathroom of the trans-Atlantic liner.

This case is cited as our most conspicuous example of a failure to detect abnormality in a subject who died a sudden and almost certainly a cardiac death, by ballistocardiograms taken at rest. Both symptoms and electrocardiographic changes suggested that the lesion was minimal, and it is to
be noted that a test made after exercise brought out an abnormality in the ballistocardiogram.

Subject T. I., was a teacher who believed himself to be in good health when first tested in 1937 at the age of 50. A person of high emotional tension, he had difficulty relaxing during the test and the slight elevation of blood pressure found, 160/90, was attributed (rightly) to this, because hypertension did not persist. The ballistocardiogram taken at this time (fig. 2) attracted attention because of its unusually small size for his age and weight, his cardiac output, referred to ideal weight, being estimated as −38 per cent below the healthy young adult mean. At the time of our first follow-up study he was still in good health.

Unfortunately he suffered from a severe attack of cardiac infarction in 1949 at the age of 62 and was for many weeks in the University Hospital. A ballistocardiogram taken about six weeks after the infarction showed the bizarre complexes illustrated in figure 2, where one should note not only the very high H wave common in coronary cases, but also the large I and J waves, which are most unusual in this condition. Convalescence was slow and difficult, and he suffered from severe attacks of breathlessness for some months. It was over a year before he attempted to return to work, and after working at half pace for several months, the onset of congestive failure forced him to come to the hospital in February, 1951. Rapid improvement followed the use of mercurial diuretics and just before discharge he gave the last ballistocardiogram shown under his initials in figure 2. No normal complexes were seen.

Placed on digitalis and mercurials regularly, he improved until he was able to do light work, but in the early summer he developed severe congestive failure despite therapy. He came to the hospital with marked pulmonary congestion, hemoptysis, marked hepatic enlargement, and edema of the legs as the predominating symptoms. He died suddenly the next morning.

At necropsy the heart showed hypertrophy and dilatation, and there was a large infarct involving the apex and the lower part of the anterior wall of the left ventricle. The sections showed evidence of both a healed and an acute lesion. Both coronary arteries contained numerous atheromatises and calcified plaques, which practically occluded the left anterior descending branch. The lungs showed a massive infarct of the right lower lobe and passive congestion. The kidneys showed mild benign nephrosclerosis; the liver and spleen, passive congestion. The thyroid was nodular but not enlarged. There was marked atherosclerosis of the aorta and other arteries.

In this case the ominous nature of the first ballistocardiogram was borne out by subsequent events, and after the first infarction neither the ballistocardiogram nor his health ever approached normal.

Discussion

The average effect of aging on the ballistocardiogram is shown in the lowest row of figure 2, where average complexes for each decade have been placed. The difference between the records of most healthy young and healthy old people can be recognized at a glance; in the “young” ballistocardiogram the two conspicuous downward points, I and K, are approximately equal in size, while in the “old” record I is conspicuously shorter than K. Comparison of the initial ballistocardiograms of subject L. G., aged 33, and subject P. E., aged 50, in figure 1 shows this difference clearly. If one knows that the subject is healthy one can make a fair guess as to his age by inspecting his ballistocardiogram.

Measurements show that as age advances, the average I wave slowly diminishes in size until, in records secured in subjects in their 60’s, it is less than half the depth found in records obtained on subjects in their 20’s. The average J wave diminishes also as age advances, but at a slower rate; in subjects in the 60’s it is 62 per cent of the height found in subjects in the 20’s. The altitude of the average H wave, the depth of K, and the duration of all the waves do not change significantly as age advances.

We believe that the physiologic implications of the changes in the ballistocardiogram which occur on aging are thoroughly understood from the results of experiments in which cardiac action was simulated in cadavers. The meaning of the change in the I wave characteristic of aging is illustrated in figure 2. To produce a deep I wave experimentally the blood leaving the heart must be rapidly accelerated early in systole, and to do this requires strength. A shallow I wave and a smaller J wave occur when there is little early acceleration of “blood”; and to produce this less strength is required. So our results show that as the heart grows older it lifts its load more slowly.

In healthy young persons these changes take place slowly; those found in a 10-year period are not significant in our data. But this very slowness of change is an important fact; it means that if a rapid change occurs in any subject’s ballistocardiogram it should not be
attributed to natural causes; disease should be suspected if no obvious physiologic or pharmacologic cause is found.

In healthy persons over 50 years of age when first tested, these changes take place more rapidly. In most subjects they are qualitatively identical with those of younger persons, diminution of the depth of the I and height of the J waves, but in some a further change of contour has occurred, the I wave being displaced upward until its lowest point fails to reach the base line, a form long judged abnormal because it has never been seen in healthy young adults. This abnormality has not been found in any healthy person of our series under 60 years of age, but most of those showing it give every appearance of health commensurate with their years and, in several cases, a complete cardiographic examination by Dr. Francis C. Wood disclosed nothing abnormal. Needless to say, these cases will be followed with much interest.

As disease begins and advances the changes in the ballistic contour which may develop are many and varied, but in addition to other abnormalities, diminution of the I wave, far beyond that expected for the patient's age, is a very frequent finding, and if the blood pressure has remained the same, we have a right to believe that these hearts have weakened. Diminution of the I wave may be the sole finding, as in the case of F. N. of figure 2, but in many subjects other abnormalities of contour are also evident. One of the cases described (D. N. S.) has now provided direct evidence for what was previously a belief, that, as disease or age advances, ballistic abnormalities first appear in the smallest complexes of the respiratory cycle, and then as if by spreading to the adjacent small complexes, involve increasingly large proportions of the record, the largest complexes being spared until last. So our data support the view that when the heart begins to weaken it does not contract with normal strength in that part of the respiratory cycle in which it is least well filled, a conception in accord with Starling's law. When searching for the first manifestation of cardiac weakness in any case one should scrutinize the smallest complexes of the ballistic record.

Indeed the experience described in this paper leads us to suggest a new conception. Evidence of the kind illustrated in that part of figure 2 entitled "Meaning of the Change in Form as Age Advances" has led us to believe that the heart weakening from age or disease has a recourse open to it that has not been realized. By changing the manner of systolic ejection of blood so that acceleration is kept at a minimum, the load of the heart is lifted more slowly, and by this means a heart lacking in strength can secure the greatest cardiac output possible to it, and so perhaps maintain its cardiac output unimpaired. However, this change in cardiac function can be detected by the change in the form of the ballistocardiogram, and since this adaptation may permit the heart's function, that of pumping blood, to remain essentially unimpaired, we see a reasonable explanation for the observation that the ballistic record can detect myocardial abnormality very early in the course of disease, and may detect it before the development of symptoms or of other clinical evidence of myocardial dysfunction.

That changes in the ballistic record of resting subjects do not always precede the onset of serious cardiac disease should surprise no one; in our experience with H. C. B. we have reported a conspicuous example of such a failure. Certainly such failures should be expected in any lesion too small to cause a detectable diminution of the strength of the cardiac contraction, but such a small lesion still might kill by inciting fibrillation of the ventricles. Doubtless ballistocardiograms taken routinely after exercise will increase our ability to detect cardiac abnormality, as was the case in this instance. All our methods are still in their infancy and the search for both better instruments and better ways of using ballistocardiograms must be actively continued.

In conclusion, as an answer to many questions from practicing physicians, let us give a brief statement of our idea of the place of the ballistocardiogram among the other clinical methods. Giving information about the motion of the blood, its data, combined with knowledge of blood pressure, are related to the power of the heart, but the best method of combining the two to get a useful single numerical value
is still in doubt. The relationship between the ballistocardiogram and the electrocardiogram can be vividly presented to most readers by rough analogy to the gasoline engine. The electrocardiogram gives information about the spark, the ballistocardiogram about the explosion. Abnormality of one is often associated with abnormality of the other, but this is by no means always true. The utility of the ballistocardiogram stems from the fact that it contributes so much to our knowledge of the heart's "explosion."

SUMMARY AND CONCLUSIONS
1. Second ballistocardiograms have been secured on a group of 80 subjects who, as part of the normal standard series, had undergone this test from 10 to 14 years before.
2. In this 10- to 14-year interval 65 of these subjects continued in good health. The records of these subjects have provided normal standards for the size and duration of the major ballistic waves. The changes during the interval have allowed us to estimate the effect of aging on the ballistic record. The principal effect is a steady diminution in depth of the I wave, with a lesser diminution of the J wave.
3. Our physiologic interpretation of this change of ballistic form is that, as age advances, the heart lifts its load more slowly. By such an adaptation a normal cardiac output could be maintained for a time by a heart whose power was diminishing, and a weak heart could secure the maximum cardiac output possible to it.
4. In the same interval 15 of our subjects have lost their health. The clinical histories of most of these patients are given in detail and the relations between their illnesses and the changes occurring in their ballistic records have been discussed.

ACKNOWLEDGMENTS
We are especially indebted to Dr. F. C. Wood, who made extensive clinical examinations on a great many of these subjects; to Dr. C. C. Wolfert, Dr. Edward Rose, and Dr. W. D. Stroud, who made their findings in certain cases available to us; and to Mrs. Grace S. Metz for technical assistance in taking ballistocardiograms.

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Circulation. 1952;5:481-495
doi: 10.1161/01.CIR.5.4.481

Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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