Three-Plane Ballistocardiography: The Effect of Age on the Longitudinal, Lateral, and Dorsoventral Ballistocardiograms

By Harold W. March, M.D.

The motions of the thorax and of the shins were recorded by a technic which gives approximately the same size waves when a given force is applied to the thorax in each of three planes. Applied to a group of men and women under 30 years of age and another group of normals over 50, the variations in form and size of the ballistocardiographic forces in three planes were recorded. During expiration and as a result of aging, the lateral systolic wave, IJ, increases in size relative to the head-foot II. It is concluded that the classic head-foot ballistocardiogram yields inadequate information of the force liberated in systole, particularly in older men.

In 1945 Hamilton and associates, in their early study of ballistic forces, utilized a high frequency bed system with freedom to record motion along the three axes of the body. Although the details of the apparatus were not published, a reconstructed diagram of their records shows clearly that when the footward I wave is inscribed, leftward and anterior motion also occurs, while the headward J is accompanied by displacement of the body to the right and posteriorly. In contrast, a variable time after the peak of K, the motion of the body becomes predominantly longitudinal and only minor deflections are recorded along the other axes. By this method the authors were able to support their conviction that the IJ stroke is derived directly from the heart’s forces, whereas the waves that follow are derived from forces directed along the aortic (longitudinal) axis.

Subsequently, both high- and low-frequency beds were modified for the purpose of studying motion in all planes, either by employing an accessory turntable or by constructing a bed with two degrees of freedom. The turntable method was not ideal, since simultaneous recording in three planes was impossible and since the position of the patient, relative to the platform, had to be changed in order to record the dorsoventral displacements. The lateral and dorsoventral traces recorded with this apparatus exhibit an I wave, directed rightward and anteriorly, and a J wave, going leftward and posteriorly. Thus, lateral motion was found to move opposite to the displacement seen in Hamilton’s diagram. Dorsoventral motion was the same. Braunstein’s two-dimensional high-frequency bed allows simultaneous longitudinal and lateral records to be taken, but he found that distortion from body rotation was introduced when freedom to move dorsoventrally was added. He has employed a cathode ray oscillograph to demonstrate the ballistic vector loop in the frontal plane. His records show an I wave, directed footward and rightward, and a J wave, returning headward and leftward.

In this laboratory, interest was aroused in multiplane recording for the purpose of studying the movement of the thorax in congenital heart disease with shunts of blood from left-to-right or from right-to-left. Lateral and dorsoventral motion of the thorax was sensed by using electromagnetic pickups fixed directly on the right lateral and anterior chest wall. These tracings usually, but not invariably, showed leftward motion with the I wave, and rightward motion with J. It was suggested that the...
rightward I recorded from tables might be the result of body torsion, which would push the table in a direction opposite to that of the actual body movement. This system was suitable only for use when respiration was suspended, and could not be used to determine how breathing affected lateral motion.

Thus, laboratory findings and common sense indicated that ballistocardiographic motion was greatest in the thorax and it appeared that the best recording system would be one that sensed lateral and dorsoventral motion from the thorax alone. For this purpose, Dock constructed a spring-opposed platform 25 by 21 inches (65 by 55 cm.) with freedom to move from side to side, contained in a frame free to move from front to back. On this platform the thorax of the supine or prone subject could be positioned. From such a platform, very satisfactory ballistocardiograms could be made, and this system has been routinely employed in this laboratory since 1953, together with the electromagnetic shin pickup for head-foot motion. The information derived from this routine study has profoundly modified our concepts of ballistocardiography. The current report offers a systematic analysis of the three-plane ballistocardiograms of a group of young and elderly normal subjects.

**Materials and Methods**

In order to characterize the variations in form and amplitude of the lateral and dorsoventral ballistocardiogram with aging, the study included two groups of asymptomatic, presumably normal individuals. The first of these was a series of 23 men and 15 women, drawn from the house staff of Kings County Hospital. Their age ranged from 20 to 29 years and the average age for the entire group was 25 years. The mean age for either sex was approximately the same as the mean for the combined group. The second group was composed of 32 individuals between the ages of 50 and 75 years, 17 men and 15 women. The average age of these subjects was 58.5 years; for the men 59.8 years and 57 years for the women. They were selected mainly from the surgical and orthopedic wards of the hospital, from among ambulatory employees and friends. In the few instances where patients were selected from the medical wards a careful study had shown no cardiovascular disease or symptom. Systolic hypertension of 150 to 160 mm. Hg with a diastolic pressure of 90 mm. or less was not considered grounds for exclusion from the study, but only two patients had such elevations. No patients were included who had abnormal electrocardiograms, enlarged cardiac silhouettes, pulmonary infiltrations, obstructive emphysema, pleural disease, anemia or deformities of the thoracic cage.

The method for recording a simultaneous three-plane ballistocardiogram together with lead II of the electrocardiogram has been described in detail elsewhere. Briefly, longitudinal motion was sensed by the Dock electromagnet on the shins with a 20 microfarad condenser in a circuit with 3,000 ohms resistance. With this pick-up, 1 mv. equals 0.055 mm. displacement at 2 cycles per second, and 0.050 mm. at 10 cycles per second. The condenser partially integrates the velocity signal, reducing fast waves due to tremor and showing less respiratory undulations, when the patient is breathing tidally than would pure displacement curves. Lateral and dorsoventral motion were sensed from the thorax, by a system of platforms mounted on stiff springs. The signals for each of these movements were picked up by appropriately placed coils and magnets, with 30 microfarad condensers in the circuits. The sensitivity of the lateral unit was adjusted when turned at right angles and recording head-foot motion, giving curves similar in form and size to those simultaneously recorded from the shins. Both lateral and dorsal systems had an output of 1.2 mv. when a force of 50,000 dynes was applied. A Sunborn 4-channel Polyvox was employed to inscribe the three ballistocardiograms, and either lead II of the electrocardiogram or the heart sounds, with sensitivity of 10 millivolts per millivolt.

All patients were ambulatory and no attempt was made to have them in a truly basal state at the time of the study. However, records were never taken less than two hours after a meal, less than an hour after smoking a cigarette, or after any physical of emotional stress. The subjects lay on the recording table until pulse and blood pressure were constant. A 12-lead electrocardiogram was recorded, and then the three-plane ballistocardiogram. In addition 24 of the 38 volunteers in the younger age group were subjected to 20 trips over the Master steps, and the ballistocardiogram was observed promptly, following exertion. Often three to five minutes would elapse before a satisfactory record could be made. Exercise was not done in the older age group. Where increase in posterior-anterior diameter of the chest was significant, fluoroscopy was performed. Patients with hyperilluminated lung fields, diminished movement of the thoracic cage, or poor diaphragmatic motion were eliminated from the study. The position of the heart and aorta in all patients was also studied either fluoroscopically or radiographically, or by both methods.


RESULTS

The data for both groups are given in table 1.

Findings in Subjects from Twenty to Twenty-nine Years of Age

Longitudinal Ballistocardiogram

There were no abnormalities of form or amplitude of the longitudinal ballistocardiogram in this group. The amplitudes for IJ were averaged in inspiration and expiration for each sex separately. For men, the range in inspiration (IJ₁) was 1.3 to 3.8 mv., and in expiration (IJₑ) was 1.0 to 3.4 mv. The mean IJ₁ was 2.5 mv., and mean IJₑ was 1.9 mv. For women, the

<table>
<thead>
<tr>
<th>No. Cases</th>
<th>Mean/Age (Years)</th>
<th>20-29 Years</th>
<th>50-75 Years</th>
<th>20-29 Years</th>
<th>50-75 Years</th>
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</thead>
<tbody>
<tr>
<td>Females</td>
<td>15</td>
<td>24.4</td>
<td>25.8</td>
<td>17</td>
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Longitudinal BCG

<table>
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<tr>
<th>Abnormals</th>
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<th>Grade I 6 (40%)</th>
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<td></td>
<td>IJₑ = 1.0-3.4</td>
<td>IJₑ = 0.9-2.3</td>
<td>IJₑ = 0.4-1.8</td>
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<tr>
<td>Mean (mv.)</td>
<td>IJ₁ = 2.5</td>
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</tr>
<tr>
<td></td>
<td>IJₑ = 1.9</td>
<td>IJₑ = 1.5</td>
<td>IJₑ = 0.8</td>
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Lateral BCG

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<tr>
<th>IJ Amplitude</th>
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<td>IJₑ = 0.5-4.3</td>
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<tr>
<td>Mean (mv.)</td>
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<td>IJ₁ = 2.3</td>
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<tr>
<td></td>
<td>IJₑ = 1.8</td>
<td>IJₑ = 1.3</td>
<td>IJₑ = 2.3</td>
</tr>
<tr>
<td>S.D. (mv.)</td>
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<td>IJ₁ = 0.55</td>
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<td>IJₑ = 0.9</td>
<td>IJₑ = 0.59</td>
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Q-BCG (sec.)

<table>
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<th>Mean Range</th>
<th>Mean Range</th>
<th>Mean Range</th>
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<tr>
<td>Q-H</td>
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<td>0.11 (0.08-0.12)</td>
<td>0.12 (0.10-0.14)</td>
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<td>Q-I</td>
<td>0.20 (0.16-0.24)</td>
<td>0.19 (0.16-0.20)</td>
<td>0.20 (0.18-0.20)</td>
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<tr>
<td>Q-J</td>
<td>0.29 (0.26-0.34)</td>
<td>0.26 (0.22-0.30)</td>
<td>0.28 (0.24-0.30)</td>
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<tr>
<td>Q-K</td>
<td>0.39 (0.36-0.42)</td>
<td>0.35 (0.32-0.38)</td>
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<tr>
<td>H-K</td>
<td>0.26 (0.22-0.30)</td>
<td>0.24 (0.22-0.30)</td>
<td>0.23 (0.22-0.26)</td>
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</table>

Dorsoventral BCG

<table>
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<tr>
<th>IJ Amplitude</th>
<th>IJ₁ = 0.9-1.8</th>
<th>IJ₁ = 0.3-1.0</th>
<th>IJ₁ = 0.6-1.7</th>
<th>IJ₁ = 0.7-1.4</th>
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<tbody>
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<td>IJₑ = 0.3-0.8</td>
<td>IJₑ = 0.4-1.5</td>
<td>IJₑ = 0.2-1.0</td>
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<tr>
<td>Mean (mv.)</td>
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<td>IJ₁ = 0.7</td>
<td>IJ₁ = 1.1</td>
<td>IJ₁ = 0.7</td>
</tr>
<tr>
<td></td>
<td>IJₑ = 0.9</td>
<td>IJₑ = 0.6</td>
<td>IJₑ = 0.8</td>
<td>IJₑ = 0.6</td>
</tr>
</tbody>
</table>

* The range and mean amplitude for IJ in three planes for each age group by sex, in inspiration and expiration. For lateral IJ the standard deviations are included. Note that in young subjects, mean lateral IJ in expiration (IJₑ) is greater than IJ in inspiration (IJ₁) but in the elderly people, they are the same. It is significant that mean IJ in expiration (IJₑ) declines 58 per cent with age in men, when calculated from the longitudinal ballistocardiogram alone, but that the decline is only 15 per cent when mean IJ in expiration for each group is summated in three planes.
range of IJ in inspiration was 1.1 to 3.0 mv., and in expiration was 0.9 to 2.3 mv. Mean IJ, and IJF was 1.9 mv. and 1.5 mv., respectively. The overall average is equivalent to a displacement of 87 micra or 0.0035 inches.

The intrinsic difficulties in calibrating direct-body ballistocardiographs have been outlined by Bixby. In the only comparable study with a calibrated electromagnetic ballistocardiograph, the mean IJ displacement for a group of 50 normal flight personnel of both sexes between the ages of 30 and 40 years was 0.0023 inches. The mean IJ for both sexes in the current study averaged 50 per cent greater. Some of the discrepancy is due to more accurate calibration of Smith’s instrument, some to the fact that his subjects were a decade older and were studied when closer to the basal state than those in this study. The two latter factors could account for lower values of displacement.

The “Ra” ratio, \( \frac{IJ_F}{IJ} \times 100 \) was below the mean value of 72 for this age group as derived by Scarborough, in only five instances, and in no case was it below 60.

**Lateral Ballistocardiogram**

In this study, our laboratory used the conventions first suggested by the Committee on Ballistocardiographic Terminology. An upward deflection represents lateral motion, and a downward deflection indicates rightward motion. The lateral IJ in normal subjects moves from left to right, as would be expected from the rightward and headward orientation of the long axis of the heart from apex to base, and from the headward direction of IJ.

Easily measurable, lateral HIJK complexes were recorded in this group with only one exception. The form of the complexes on superficial inspection simulated the longitudinally inscribed ballistocardiogram. However, the lateral I wave is not infrequently as much as 0.02 second later than the head-foot I. The dominant stroke of the lateral complex is the leftward I wave rather than the rightward J. The leftward K is relatively small, compared to that on the head-foot trace.

Typical and average lateral ballistocardiograms are shown in figures 1 and 3A. The head-foot trace recorded simultaneously shows the relationships to the longitudinal plane, and lead II gives the relation to the electrical forces. Where ballitic form is abnormal, the electrocardiogram is essential for accurate identification of IJ in any plane.

Usually a sharp leftward, initial deflection precedes the rightward H wave. This initial component is usually small, rarely exceeding 0.5 mv. and often varies from complex to complex with respiration. At times it is absent and only a rightward H wave is seen. A true G deflection, of ventricular origin, has been observed previously in our lateral traces in the presence of complete heart block or atrial fibrillation. Where A-V conduction is normal, the initial wave (G or atrial i) is probably due in large part to the footward and leftward movement of the body as blood enters the
ventricles under the impact of atrial systole. Where A-V conduction is abnormal and atrial systole does not precede the Q wave of the electrocardiogram, G may be due to movement of the ventricle in the mediastinum as contraction sets in, but before the intraventricular pressure exceeds that in the atriums. The H wave is always represented in the lateral trace as a distinct rightward movement and is, at times, even larger than the J wave in lateral planes. In this laboratory, the H wave is ascribed to headward and rightward impact on the atrial-ventricular septum at the peak of isometric contraction.

In A-V block the atrial j wave occurs 0.24 to 0.30 second after the onset of the atrial P wave, and the headward component may be due in part to rapid return of blood to the right auricle from the inferior vena cava. But the relatively much larger rightward atrial j in lateral traces can not be due to this force, since the vein has a vertical path. It seems more probable that the reflux of blood from the ventricles, as atrial pressure falls, is the cause of both lateral and vertical j waves. With normal A-V conduction j is superimposed on H.

The normal lateral I is always leftward and its peak in about half the cases occurs 0.02 second later than that of the longitudinal I. The delay does not represent an instrumental artifact but may be related to differences in compliance of the mediastinum from one plane to another, or to true differences in peak of application of force in the two planes. The time interval from nadir of H to peak of I is most commonly 0.08 second but ranges from 0.06 to 0.10 second and would appear to be unrelated to sex or body size. The lateral HI stroke is often of greater amplitude than that of IJ.

The J wave is directed rightward, as well as headward and backward. Because I is a large wave, the IJ sweep in 42 per cent of these subjects was the largest lateral wave, in 11 per cent it equalled HI, while in 4 per cent HI was larger. However in the women under 30 years of age, HI was larger than HI in only 21 per cent, while it was larger than HI in 55 per cent of the young men.

Distribution curves for the amplitude of the lateral IJ waves are shown in figure 2, where the per cent of subjects is plotted against IJ amplitude in 0.1-mv. units in the manner of Soldati. The mode for the inspiratory IJ is 1.2 mv. in young men, the mode for expiratory IJ is 1.6 mv. In men the range is 0.6 to 4.3 mv. in inspiration, for women 0.2 to 2.5 mv. The mean inspiratory IJ for men was 1.5 mv. and mean expiratory IJ was 1.8 mv. This reflects the tendency in this group for lateral IJ amplitudes to increase about 20 per cent with expiration.

Except for a few unusually high values among men, the figures are quite homogeneous. One standard deviation each side of the mean embraces all but two of the IJ amplitudes in inspiration, but excludes five of these amplitudes in expiration. For women, mean inspiratory and expiratory IJ's were 1.2 mv., and 1.3 mv., respectively. No unusually high values were found in this group, but there were two very low ones. Although the mean IJ for women was less than for men, especially in expiration, the difference is not as great as the sex difference for the head-foot IJ.

Attention was given to the relation of body size and contour and of electric and radiographic position of the heart to IJ amplitude. Body contour did not appear to be a significant
factor but height and weight probably are related. Thus, the smallest lateral IJ’s (0.2, 0.4 and 0.6 mv. in inspiration) occurred in women who were 5 feet 4 inches or less in height and who weighed between 112 and 120 pounds. Tall women and men (5 feet 8½ inches, 150 pounds) had average sized IJ strokes. The largest lateral IJ waves (3.8 to 4.1 mv. in inspiration) were found in heavy-set men of about average height with a tendency to obesity, but some subjects with similar build had average deflections. Electrically the heart usually was vertical or semivertical, and anatomically it was most commonly intermediate. No significant relation of these axes with IJ could be demonstrated.

The duration of IJ is usually between 0.08 to 0.10 second, and is on the average slightly longer than for the HI duration. In four instances in which IJ duration was only 0.06 second, the patients were women, 5 feet 5 inches or less, weighing 125 pounds or less.

The lateral JK, a right to left movement, is always the smallest deflection of the systolic complex. It is most commonly 0.10 second in duration when the K peak is sharp. Often, however, this peak is blunt or indistinct or, less commonly, merges into small oscillations of the base line. Since the K deflection is believed to originate in the descending portion of the aorta, an almost purely longitudinal structure, one would not expect a significant lateral K wave.

Diastolic waves ranging from 0.7 to 2.0 mv. in amplitude were common. Occasionally a diastolic deflection, M, was the predominant wave of the lateral ballistocardiogram, (fig. 3A). Its longest slope was invariably leftward, although it overlaps in time the headward L or N wave, more commonly the former. Actually, it is inscribed after a short rightward L, and so it may be considered as the lateral M wave. Diastolic waves are now regarded as real forces, rather than as postsystolic oscillations. The leftward deflections in lateral ballistocardiograms would suggest that M is due, in this plane at least, to the ventricular diastolic inflow. No relation of large diastolic waves to physiologic third heart sounds was apparent in these young adults.

Of some interest was the occasional appearance in lateral traces of rapid deflections, coincident with the end of the electrocardiographic T wave. These presumably are due to the impact causing the second heart sound. Such waves have previously been reported in ballistocardiograms taken directly from the chest.8

Q-Ballistocardiogram Interval[s]. Time intervals from Q to H, I, J, K, and H-K time were measured, wherever reasonable accuracy was assured by the preciseness of wave form. These intervals are all somewhat shorter for women and the difference increases with the later systolic deflections. Thus mean Q-H was 0.10 and 0.11 second for men and women, respectively, and mean Q-I was 0.20 and 0.19, but for Q-J, the relative values were 0.29 and 0.26, and for Q-K 0.39 and 0.35 second. Mean H-K for men was 0.26, for women 0.24 second. These findings show the same trend as Scarborough’s figures.14 Whereas difference in sex in his study was not significant for Q-H and
Q-I times, it was slight but significant for Q-J and Q-K. This author was inclined to relate the difference to body size, especially weight. The present figures tend to support such a view, and the shortest Q-K for women also appeared in the smallest and lightest subjects. Relatively heavier women, regardless of height had Q-K times comparable to men of medium stature and weight. The longest Q-K interval (0.40 second) appeared in heavy men, regardless of height.

Effect of Exercise. In roughly two-thirds of the cases, the effect of exercise on the lateral complex was studied by having the subjects take 20 trips over the Masters steps. Respiratory artifacts often made it impossible to quantitate the immediate effects of exercise. When the records became legible the head-foot complexes usually showed IJ’s of greater amplitude than the control trace, but sometimes, at fast heart rates, they were unchanged. In either event the lateral I-J complexes became significantly reduced in size, at times markedly so and HI became more prominent. Usually, this was relative to the reduction in IJ, but occasionally an actual increase in the depth of the H wave was noted. The change in size of the diastolic waves after exercise was variable, but increases were more frequent than decreases.

Dorsoventral Ballistocardiogram

The dorsoventral HIJK is usually of small amplitude, but when it is large and neatly inscribed, it has a form very similar to the longitudinal ballistocardiogram (fig. 1). By the accepted convention, ventral movements are downward, and dorsal movements upward on the recording paper.

After a short, often blunt, dorsally directed H wave, the I deflection is written in a ventral direction, the J wave moves sharply backward and K returns ventrally. Even when the dorsoventral ballistocardiogram is large and distinct, the K wave is never deeper than I, although it may be of equal amplitude. The orientation of the dorsoventral IJ (IJDV) is a consequence of the fact that the apex of the heart is more ventrally located than the base and that during early systole, when the I wave is inscribed, the heart rotates clockwise and anteriorly and is thrust toward the chest wall, leftward and frontward, by the recoil from early ejection. The impact on the aortic arch and the pulmonary artery’s bifurcation thrusts the body headward, backward and rightward, causing the J wave.

In most cases, though IJDV is the dominant deflection, it is nevertheless of small amplitude and may be slurred or notched. Notching is more likely to occur in expiration, but is not limited to this phase of the respiratory cycle. The JK stroke is even more variable. It often is no more than 50 per cent of the dorsoventral IJ in amplitude, and its terminal portion may be represented merely by an undulation of the isoelectric line (fig. 3B).

The range of IJ in dorsoventral ballistocardiograms in males was from 0.9 to 1.8 mv. in inspiration, and from 0.3 to 1.6 mv. in expiration; for females, the range was from 0.3 to 1.0 mv. in inspiration, and 0.3 to 0.8 mv. in expiration. The mean inspiratory IJ for men was 1.1 mv. and mean expiration IJ was 0.9 mv. For females these values were 0.73 mv. and 0.59 mv., respectively. It is to be noted that for men the scatter is considerable and two-thirds of the inspiratory IJ values are below the mean. For women, the grouping is better and mean values are smaller. The dorsoventral IJ, like the head-foot IJ but opposite to the lateral IJ, is greater in inspiration than in expiration. It usually is larger after exercise.

Q-ballistocardiogram intervals are shorter in this plane, but H-K time agrees almost always within 0.02 second with H-K for longitudinal and lateral ballistocardiograms. The discrepancy in Q-ballistocardiogram intervals among the various planes is a result of the earlier onset of ballistic activity dorsoventrally. Whereas IJ of the lateral ballistocardiogram may be 0.02 second later than the head-foot IJ (IJHv), dorsoventral IJ is from 0.02 to 0.06 second earlier than IJ of the head-foot ballistocardiogram, usually 0.04 second. The reason for this is not clear, but it is obvious that while the body must be set into motion and slide some distance before head-foot or lateral force fully expresses itself, whether recorded directly or from a platform, dorsoventral force is applied directly to the platform on which the body lies.
Findings in Subjects Fifty to Seventy-five Years of Age

Longitudinal Ballistocardiogram (29 per cent)

In this age group only 29 per cent of the head-foot ballistocardiograms in men would be called normal, if the records were graded according to the system originally proposed by Brown.4 By these criteria 47 per cent were grade I, and the remaining 24 per cent represented grade II–IV abnormalities. The women had a higher percentage of normal traces, 47 per cent, but some of them were of very small amplitude. Forty per cent were classified grade I, and only 13 per cent were grade II and III. No grade IV records occurred in women. The most common abnormalities were absence of the I and J waves, either of very small amplitude or noted during expiration. Relatively large II, small I and J waves formed an occasional complex which Starr17 calls “early M” because the tracing in early systole looks like that letter.

When IJ was consistent and measureable, mean IJ of inspiration was 1.3 mV, and IJ of expiration was 0.84 mV, indicating smaller mean amplitudes, but less phasic variation, thereby accounting for the smaller number of abnormal traces in older women. These figures, in general, are consistent with previous studies showing high percentages of abnormal longitudinal ballistocardiograms above the age of fifty in males.9,13

Lateral Ballistocardiograms

The form of the lateral ballistocardiogram in this group is similar to that in younger normals. The distribution curve in figure 2 indicates that in older men the mode for IJ of inspiration and for IJ of expiration are both about 2.0 mV. Mean IJ of inspiration increases with age, especially in men, but the tendency for expiratory IJ to be larger than inspiratory IJ in this plane is not as consistent in this group as with the younger people. The mean lateral IJ of inspiration for men was 2.29 mV, and for expiration was 2.34 mV; for women the respective values were 1.62 and 1.61 mV. The range of amplitudes for men was considerable, inspiratory IJ varying from 0.5 to 4.6 mV, and expiratory IJ varying from 0.5 to 4.3 mV. For women the range was less, being from 0.6 to 3.0 mV for inspiratory IJ, and from 0.6 to 2.7 mV for expiratory IJ.

Striking reciprocal relations of the lateral to the longitudinal ballistocardiogram were noted. When the head-foot trace is normal, the lateral amplitudes usually vary reciprocally with the head-foot amplitudes. Although elderly subjects may have quite large waves synchronously in two planes or even in all three planes, it is more common for lateral deflections to be large when longitudinal ones are small (fig. 4A) and for this component to be small when head-foot is large (fig. 4B). This may be apparent in any individual during each respiratory cycle, when the IJ waves in one plane become large while the other plane shows a decrease. In longitudinal traces with otherwise good form and normal respiratory variation but which exhibit the short I that Starr has ascribed to aging,18 an I of good amplitude often is present in the lateral projection.

Subjects with grade I longitudinal traces offered the best opportunities for such comparison with lateral traces. In about 85 per cent of the 14 patients of both sexes with such a head-foot classification, the lateral ballistocardiograms fell into two categories, both of which may be considered to be compatible with normal action of the ventricles. One type of record, representing the more common situation, displays lateral IJ deflections of good...
amplitude and constant form, varying little with respiration, but tending like the head-foot IJ, to decrease during expiration (figs. 4 and 5). In these patients the ratio, IJ_{Expiration} \times 100 was always well within normal limits when the accepted values for IJ_{Inspiration} head-foot IJ variation are applied to this stroke in the lateral plane. More rarely, lateral systolic complexes were more than halved during expiration, and changed more than did head-foot IJ complexes (fig. 6).

In a second category, much less frequently seen in normals, aged 50 to 65, but not rare in hypertensives or senile males, the lateral trace shows a respiratory swing in amplitude which causes the smallest IJ to be less than half the largest in each respiratory cycle. But whereas in cases where the H-F varies, the ratio IJ_{Expiration}/IJ_{Inspiration} is always less than 1, and in grade I or II records is less than 0.5, in these laterals with large variation this ratio is over 2.0. The respiratory lateral IJ becomes abnormally small during inspiration, just as the corresponding head-foot IJ becomes large. It is obvious that in these cases, total systolic force applied to the body is relatively constant during the respiratory cycle, but the vector of its application swings through a wide arc. In this group, too, belong cases with chaotic complexes in the head-foot tracing but with large systolic lateral complexes which are smaller during inspiration than expiration (fig. 7).

In two instances (14.5 per cent of the grade I longitudinal traces), the lateral deflections were small or varied excessively in form and amplitude at the same time in the respiratory cycle, when the longitudinal complexes were small or notched. Figure 6 is an example of such a case. Note that the IJ amplitude diminishes concomitantly in all three planes.

Four grade II head-foot traces were noted. Three of these had constant, large lateral IJ deflections and in two, the lateral amplitudes varied reciprocally with the head-foot IJ. In one instance, the IJ of the lateral ballistocardiogram was small and did not improve in form or amplitude in a reciprocal manner as head-foot complexes deteriorated.

Only two ballistocardiograms were classified grade III or IV. In both instances, the form and amplitude of lateral IJ were clearly normal and in one instance the IJ of the lateral ballistocardiogram was among the largest recorded (fig. 7).

Diastolic waves were seen in lateral ballistocardiograms in this group, as in the younger...
subjects. Their frequency, amplitude and orientation were not significantly different from the previous characterization given of diastolic ballistic waves in that group.

Q-BCG intervals and H-K time. The tendency for Q-J, Q-K and H-K to be longer in men than in women was not as clear for this group as in the younger subjects. This may be due in part to the more closely comparable height and weight in the older subjects of both sexes. For males, Q-H was 0.12, Q-I, 0.20, Q-J, 0.28, Q-K, 0.36 and H-K, 0.24 second. For females, Q-H was 0.12, Q-I, 0.19, Q-J, 0.27, Q-K, 0.34 and H-K, 0.22 second. As seen in table 1, there is no increase in Q-BCG time with age.

The Dorsoventral Ballistocardiogram

Motion in the dorsoventral plane in elderly patients shows no significant change when compared with the scatter for the younger age group. In contrast to lateral IJ there is no tendency for older people to have larger dorsoventral IJ, and the mean values for men (IJ\textsubscript{Inspiratory} 1.08 mv., IJ\textsubscript{Expiratory} 0.76 mv.) and women (IJ\textsubscript{Inspiratory} 0.72 mv., IJ\textsubscript{Expiratory} 0.54 mv.) were very similar to those of the young adults.

Although the dorsoventral amplitudes were generally small and the complexes indistinct, it was noted that for men there is a wide spread from the mean value. In some older men, normal or with healed infarcts, but usually with relatively large anterior-posterior diameters of the chest, IJ in lateral and IJ in head-foot ballistocardiograms may be abnormally small or deformed, whereas a prominent and well-formed dorsoventral complex may be inscribed (fig. 8). In these instances, abnormalities in other planes may be ascribable to change in the axis of force and may be less significant evidence of poor myocardial function.

As in the younger group H-K time in the dorsoventral plane usually fell within 0.02 second of the corresponding H-K for the other planes. The tendency, for I in dorsoventral ballistocardiogram to be inscribed as much as 0.04 second earlier than I in the head-foot ballistocardiogram, persists in this group.

Discussion

In this study, the lateral IJ wave of young adults seemed almost equal in force to the head-foot systolic wave and the chief difference was that the J wave is larger in the longitudinal and the I wave in the lateral plane. Also, while the head-foot waves normally are largest during the inspiratory phase, the lateral waves are largest during expiration. It should be noted that with the use of blocks on each side in order to obtain good transmission of lateral forces and to prevent the thorax from rolling on the platform, the lateral systolic waves are much closer in size to the head-foot waves than had been suggested by earlier studies in this laboratory and elsewhere. There is little doubt that the system, described here, transmits to the table a higher percentage of lateral than of longitudinal force. Effective vertical blocks at the shoulders and pubis probably would be needed to correct this instrumental difference.

Study of the anatomy of the outflow tracts in angiocardiograms indicates that the right ventricle can exert very little lateral force and that the left ventricle normally has its axis of ejection close to 45 degrees to the right of the vertical axis of the spine. Therefore, the normal lateral force probably varies from one-third to two-thirds, the longitudinal thrust during recoil from ejection (I wave) and from one-fifth to one-third during impact on the arch or bifurcation of the great arteries. Quantitative photoelectric records from the base of the sternum show about three to five times more longitudinal than lateral displacement in nor-
mal young subjects, but since the rib cage is more easily moved longitudinally than laterally, this probably minimizes the effect of the lateral thrust.

Even with our present method, which tends to exaggerate the relative force of the lateral and front-back thrusts, as compared with longitudinal ones, it is apparent that most young adults and many elderly people have relatively large head-foot ballistocardiographic waves and relatively small dorsoventral ones. The lateral waves, which average somewhat smaller than head-foot waves in young adults, become relatively large, however, in the elderly subjects. Relatively large back-front waves are encountered rarely and only in deep-chested older subjects with small head-foot waves.

Age causes a much greater decrease in the head-foot waves inscribed during expiration than in those during inspiration. In this study, the smallest IJ in the cycle was 42 per cent as large in those over 50, as compared with the smallest waves in those 20 to 30 years old. A comparison of the lateral waves inscribed synchronously with these small waves, showed that they were 22 per cent larger in the old group as compared with the younger one. In the younger group, the lateral waves average a 30 per cent increase during expiration than during inspiration, when the smallest head-foot waves are inscribed. In older people, the average lateral IJ is larger than in younger ones, but its change during the respiratory cycle is less. It may decrease in amplitude during the expiratory phase in older subjects, but very rarely does so in the younger ones.

The causes for the change in vectors with age are not fully understood, but the cause for the increase in the lateral waves during expiration is apparent. The rise of the diaphragm results in upward motion of the apex and the axis of ejection of the left ventricle becomes more transverse at the same time that the stroke volume increases, due to increased filling as blood is forced out of the pulmonary veins by decrease in lung volume. In young people, the diaphragm moves more than in elderly or emphysematous ones, so that one would expect a larger respiratory change in axis in young people than in the aged and also a greater change in men than in women, since costal breathing is relatively great, diaphragmatic breathing less in women.

The most important factor in the increase in lateral waves in older men undoubtedly is the tortuosity of the aorta. As this vessel becomes longer and bows farther to the right in its ascending portion, the axis of ejection of the left ventricle becomes more transverse. There is a general, but not a consistent, relationship between the tortuosity of the ascending parts of the aorta and large lateral IJ waves; the exceptions are usually in subjects with large IJ waves, but no striking prominence of the ascending aorta. Although a significant number of individuals who have predominantly laterally directed ballistocardiograms do have dilated, tortuous aortas, such a vector change may be present in individuals whose ascending aortas on radiographic examination do not appear to be different from those of young people. Conversely, the arch is dilated in some patients whose lateral complexes are very small. However, since the initial portion of this vessel is concealed in the mediastinal shadow, angiocardiograms are needed to show whether the angle of ejection from the ventricle lies transversely.

Physiologic considerations, thus far unstudied, may also have a role in the genesis of a large lateral IJ wave. The position of the A-V atrial-ventricular septum at the time the IJ stroke is inscribed may play a role in determining the size of the HIJ complex, for with early ectopic beats the head-foot IJ is often much smaller than in the normal beat, while the lateral HIJ, with slightly shifted time of occurrence of its peaks, is as large as in the normal cycles.

There may also be some effect of age on the relative velocity of ejection from each ventricle. A delay in aortic ejection, relative to pulmonic ejection, would cause recoil from left ventricular ejection to coincide with impact on the pulmonary artery bifurcation and explain a large I wave laterally, when the head-foot I wave is absent. Study of the three-plane ballistocardiogram in bundle branch block might be profitable, although the failure of Samet to observe consistent delay in ejection from the
ventricle with "delayed activation" makes timing of ejection essential in each case.

So far, as the effect of age on the force of systolic thrust is concerned, the mean head-foot IJ wave decrease is very much greater than that of the sum of the thrusts in three planes. This sum, for the beat with the largest head-foot IJ waves is about as large in our subjects over 50 as in those under 30, while the sum of forces during the beats with the smallest head-foot IJ was only 15 per cent less in the elderly subjects than in the young ones, although in the head-foot IJ for these beats, the mean decrease in size was 58 per cent.

At the present time, it seems justifiable to consider as normal all tracings in which the form of the complexes is not bizarre and the ratio IJ_{Head-Foot} + IJ_{Lateral} (expiratory) × 100/ IJ_{Head-Foot} + IJ_{Lateral} (inspiratory) is over 60. This would give less than 10 per cent of abnormal traces in our group of normals over 50 years of age, while applying delallia and Brown's original system of grading to the head-foot traces, with a ratio below 50 considered abnormal, 64 per cent of our subjects had abnormal head-foot traces.

The percentage of presumably normal tracings rises sharply when three-plane rather than head-foot traces are used in the study of normal people past the fifth decade, but there is also a rise in the per cent of normal tracings, obtained from those with healed infarction of the heart. Since the normal three-plane traces are most often found in patients who are asymptomatic after recovery, this method of classification gives better agreement with clinical findings, as well as far fewer false positives in elderly normals, than does any classification based on head-foot tracings alone. However, one may well regard as abnormal traces in which there are extreme even though reciprocal, changes in the lateral complexes. The case shown by Dock (fig. 4) gives a ratio over 100, but shows a decrease in lateral IJ waves during inspiration which suggests a paradoxic pulse, since it is much greater than anything seen in records from normals. Even in three-plane ballistocardiography, one must look at the traces and not depend on measured amplitudes or ratios alone.

Summary

1. Simultaneous three-plane ballistocardiograms have been inscribed in a group of 38 men and women under 30 years, and in another group of 32 people over 50 years. History, complete physical examination, chest roentgenograms and 12-lead electrocardiograms showed no evidence of cardiac or pulmonary disease in any of these subjects.

2. The sensing systems used gave approximately equal signals to equal forces applied to the thorax in three planes.

3. The normal variations in form and size of the ballistic waves are described and the range and mean values of the main systolic wave, IJ, are given for the two sexes in each age group.

4. The IJ wave is directed headward, rightward and backward; its peaks occur earlier in the backward, and later in the rightward direction than in the classic head-foot trace.

5. The IJ wave decreases more during expiration in the head-foot than in the dorsoventral tracing, in young people. A respiratory decrease, in head-foot IJ, is marked in older subjects, but in the dorsal wave is about the same in the elderly as in the young and is greater in men than in women in both groups.

6. The lateral IJ increases during expiration and with age. The expiratory increase is more marked in young men, and is barely evident in many older subjects. However, some older normal subjects, with very great expiratory decreases in longitudinal IJ waves, have striking increases in the lateral waves inscribed by the same heart beats.

7. It would appear that in young individuals, the ballistic systolic forces are predominantly longitudinal, but with age, the force vector changes and in middle aged or elderly individuals, it may have an almost purely lateral representation.

8. In three-plane ballistocardiograms with small amplitude or abnormal head-foot tracings in which lateral IJ is uniformly large or increases during the part of the respiratory cycle when head-foot IJ becomes abnormally small, changes in direction of ejection rather than in cardiac force are probably determining
the character of the record. The causes of these changes are unsettled, but elevation of the diaphragm with expiration, a more transverse position of the heart and greater aortic tortuosity in the aged deserve study. Other factors, such as change in the time interval between the onset of the pulmonary and aortic pulse waves, may also prove to be significant in causing this sign of aging.

(9) The ratio \([IJ_{Head-Foot} + IJ_{Lateral} (Expiratory)] / [IJ_{Head-Foot} + IJ_{Lateral} (Inspiratory)] \times 100\) has been introduced for the purpose of grading three-plane ballistocardiograms. In 38 subjects, 20 to 29 years old, the mean value for this ratio is 91 and the lowest is 81. In only 3 of the 32 subjects over 50 years of age was this ratio below 60, whereas in 20 of these subjects the ratio \([IJ_{Head-Foot} (Expiratory)] / [IJ_{Head-Foot} (Inspiratory)] \times 100\) was below 50 and would therefore be considered abnormal according to the Brown convention.

(10) Any conclusions as to force of ventricular systole in subjects over 40 years old must be fallacious if based on classic head-foot ballistic waves alone, for the vector of force changes more than the total force of systole in older subjects, especially in males. Study of the total ballistic forces is not adequate unless body motion is recorded in at least the lateral and head-foot planes. Ideally, it should be registered in all three planes, with the lateral and dorsoventral force recorded from the thorax.

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Summario in Interlingua

Le motiones del thorace e del tibia esseva registrate per medio de un technique che resulta in undas de approximativamente le mesme dimensiones quando un fortia identic es applicate al thorace in le un o in le altere del tres planos. Le registrationes esseva executeate pro un gruppo de masculos e femininas de etates de infra 30 annos e pro un altere gruppo de individuos normal de etates de supra 50 annos, e le variationes de forma e dimension del fortias ballistocardiographic esseva studiate.

Durante le expiration e como effecto de etates plus avantiae, le unda systolic laterale IJ augmenta su dimensiones in comparison con le unda capite-pede IJ. Se impone le conclusion que le classic ballistocardiogramma capite-pede rende inadequate informationes super le fortias liberate in le phase systolic, specialmente in masculos de etates plus avantiate.

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THREE-PLANE BALLISTOCARDIOGRAPHY


Three-Plane Ballistocardiography: The Effect of Age on the Longitudinal, Lateral, and Dorsoventral Ballistocardiograms

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