Ballistocardiography
An Appraisal of Technic, Physiologic Principles, and Clinical Value

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THE various modalities used in the study of the heart and circulation contribute different types of information. Some, such as electrocardiography and fluoroscopic or roentgenographic study, have such broad spheres of usefulness that they are almost routinely employed. Other diagnostic procedures have not gained wide usage either because of expense of equipment, difficulty in clinical application, specialized nature and limited value of information provided, or because such information as is provided unnecessarily duplicates what may be learned in simpler fashion. It is the object of this survey to appraise the clinical usefulness of ballistocardiography, a technic which records the movements imparted to the body by the forces associated with contraction of the heart, and acceleration and deceleration of blood as it is ejected and moved in the large vessels. Parenthetically it may be remarked that the ballistocardiogram provides, in simple and routinely applicable fashion, a considerable body of useful information not otherwise obtainable; and hence fulfills the criteria of a valuable adjunct in examination of the heart.

I. PHYSICAL PRINCIPLES AND TECHNICS OF RECORDINGS

The principle of ballistocardiography is Newton's third law of motion, namely, for every acting force, there is an equal and opposite reacting force. Hitherto a euphemistic term, the expression "force of the heart" has become meaningful and measurable by ballistocardiography. Although clinical interest dates from Starr's important contributions,1 ballistocardiography has a fairly venerable history which has been reviewed elsewhere.2-4 A regular and reproducible procession of waves is recorded in the ballistocardiogram, the major components of which have been designated by Starr1 as the H, I, J, K, L waves. These waves are clearly associated with specific events in the cardiac cycle, but their precise qualitative, let alone quantitative, interpretation has been far from definitive for several reasons.

Both sides of the heart contribute to the ballistocardiogram in significant and continually varying degree so that it is difficult to dissociate the relative effects of right and left ventricular activity. The waves recorded are in no sense pure forces but the resultant vectors of variously and, in part, oppositely directed forces. When the heart rate is rapid, superimposition of waves reflecting forces associated with events in diastole occurs on early systolic waves of the following cycle. In consequence it becomes difficult or impossible to interpret the ballistocardiogram when tachycardia is present. Most of the ballistocardiographic technics presently employed record only those forces exerted in the longitudinal axis of the body, which best portray the major forces associated with cardiac contraction.
However, the dominant vectors associated with certain aspects of blood flow in the cardiac cycle may be exerted in other directions, and to this end ballistocardiograms may be recorded in other planes such as the lateral direction\textsuperscript{4} or multispatial vector registration.\textsuperscript{5-9}

The forces generated by expulsion of blood from the heart and propulsion in the great vessels must be transmitted through the tissues, skeleton and panniculus to the recording system. Accordingly, the compliance of the body structures, in addition to the natural period of motion of the body (which falls within the frequency spectrum of ballistocardiographic waves), impose some modifications on the waves. Needless to say body motion, such as muscular activity, must be minimized during recording. Ballistocardiograms therefore are unsatisfactory unless the subject is completely relaxed, a circumstance which makes ballistocardiography difficult in the upright position, and in aged and ill subjects, who find it difficult to lie in the recumbent position on a hard unyielding surface.

Ballistocardiographs with which most experience has been gained have employed a suspended table on which the subject lies; body movements are translated into longitudinal movements of the table, which are recorded. Multiple and important distortions are produced in the ballistocardiographic waves by the natural frequency characteristics of the recording table, as has been pointed out by Rappaport.\textsuperscript{10} The high frequency undamped table developed by Starr possesses a natural frequency of approximately 9 cycles per second. With the Starr table low frequency waves are damped and do not register with the same amplitude as higher frequency waves of the same magnitude. In one respect this confers an advantage for the very low frequency respiratory waves (approximately \(\frac{1}{2}\) cycle per second) are eliminated; if recorded they cause a wavy baseline in the ballistocardiogram and make analysis difficult. However the lower frequency waves of the cardiac cycle itself up to several cycles per second are damped so that there is a distortion in magnitude varying with the cycle frequency of the waves. In addition to the distortion in magnitude produced by the frequency response slope which affects the low frequency waves, another form of distortion which is termed differentiation is produced by introduction of the time constant. A spurious negative wave follows a steeply sloped positive wave. This causes an artefact in the K wave, the negative wave following the steep J wave upstroke, and introduces an error of real clinical significance in circumstances where the K wave is of interest, such as coarctation of the aorta, presently to be mentioned. Still another error in the Starr table is that of phase shift, whereby there is a time lag in deflection after the applied force.

To obviate the distortion inherent in the Starr table, Nickerson\textsuperscript{11} introduced a low frequency (1.5 cycles per second) critically damped table. Since low frequencies are recorded with Nickerson's method, respiratory movements are imposed on the ballistocardiographic tracing causing a wavy baseline which may make interpretation of the record difficult unless respiration is suspended. The validity of ballistocardiograms obtained with Nickerson's modification has been questioned.\textsuperscript{19} Although the frequency response differs from that in the Starr table it is not flat over the range of ballistocardiographic waves but exhibits a drooping slope, resulting in three important types of distortion, that is, reduced amplitude of the waves, increased duration of the complexes and temporal phase displacement.

Apart from the cumbersomeness and general unavailability of the Starr and Nickerson tables, it is apparent that the interposition of the table in the recording of the ballistocardiogram introduces significant distortion. Accordingly, considerable interest has attended the introduction of more direct and much simpler methods for inscribing ballistocardiograms. It is not possible to comment individually on all the numerous ingenious recording devices, which have ranged from the bathroom scale to the seismograph in complexity. The simplest and cheapest types of apparatus, which, properly constructed, exhibit least inherent distortion characteristics, are the electromagnetic and photoelectric instruments introduced by Dock and Taubman.\textsuperscript{12}
The actual recording of the ballistocardiogram with these technics is carried out on the electrocardiograph. With both these methods, as well as a variety of modifications which have been introduced, a bar is placed across the shins with the subject lying recumbent on a rigid table or on the floor. The bar moves in unison with the body and its movements are translated into electrical potential.

The physical principles of the photoelectric instrument and electromagnetic instrument are quite different. The photoelectric type records displacement, the electromagnetic type records velocity of body motion, that is, the rate of body displacement. While the two are broadly parallel they are not synonymous, and velocity changes may precede displacement by several hundredths of a second. This is of some importance in interpreting the physiologic origin of the ballistocardiographic waves in relation to other simultaneously recorded events in the cardiac cycle. Although a pure velocity curve is theoretically desirable in registering the forces associated with cardiac ejection and blood flow it is not practicable. Unless the subject is exceptionally well relaxed artefacts are introduced with the least body motion. Recently Smith and Bryan have described a low frequency electromagnetic velocity measurement ballistocardiograph with filter circuits to eliminate body tremor components.

Voltages induced by movement of a wire coil in an electromagnetic field exhibit a steep rising response with increasing frequency in the frequency range of ballistocardiographic waves. Accordingly high frequency waves are selectively amplified much more than low frequency waves, as obtains also in the Starr table. In addition, other forms of distortion, namely, differentiation (artificial K wave) and temporal phase displacement are present as seen also on the Starr table. With the photoelectric instrument the frequency response is flat so there is no differential amplification of waves with varying frequency, and distortion due to differentiation and temporal phase displacements are likewise eliminated. Because of the difficulty in achieving a pure velocity curve, undistorted and free from artefact, in the electromagnetic ballistocardiograph, condensers varying from 20 to 70 microfarads have been introduced across the coils. The condensers have the effect of modifying the frequency response curve to make it substantially flat between 1 and 10 cycles per second, in the range of the ballistocardiographic waves. Appreciable damping is still present below 1 cycle per second which has the virtue of eliminating the very low frequency respiratory movement, although respiratory movement is still evident when a 70 microfarad condenser is employed. For routine purposes a 20 or 50 microfarad condenser is thoroughly satisfactory, and the records obtained are in effect displacement curves similar in every respect to the photoelectric curve, and relatively free of the forms of distortion mentioned. The change in the ballistocardiogram from velocity to displacement type of curve as condenser capacity is increased in the electromagnetic instrument is shown in figure 1.

Because of their simplicity, relative accuracy, and inexpensiveness, the electromagnetic and photoelectric types of ballistocardiograph appear to be the best suited for routine use as a convenient portable accessory to the electrocardiograph.

It is desirable that the amplitude of the recorded waves be sufficiently large to permit detailed inspection of their individual components. With the electromagnetic instrument amplitude is much greater with the 20 microfarad condenser than with the 50 or 70 microfarad condenser. Unless a very sensitive photo cell is employed the amplitude of waves in the photoelectric instrument may be too small to allow satisfactory interpretation. Individual instruments should be standardized by adjusting the sensitivity of the recording arm of the electrocardiograph so that in normal young adults the amplitude of the maximum ballistocardiographic deflection is between 2 and 3 cm. In this manner if appreciable reduction in wave amplitude is present in abnormal situations it will readily be apparent. If quantitative standardization is desired (which in clinical practice is of little importance) the shoulder may be struck with a 200,000 dyne blow delivered by a pendulum, which, with sensitivity of the electrocardio-
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graph set at 1 cm. deflection per millivolt, will give a deflection of 8 to 10 mm. in subjects weighing 70 Kg.12 With standardization it is possible to calculate the maximum force developed during ventricular ejection. Employing calibration of 280 Gm. to displace the recording beam 1.0 cm., Starr found the vertical amplitude from the I depth to the J peak to provide an estimate of the maximal force delivered in systole, that is, a measurement of cardiac strength.14

One further technical feature of ballistocardiography warrants mention. When ballistocardiographic patterns are abnormal it is difficult or impossible to identify the individual waves properly unless simultaneous registration is made of another event in the cardiac cycle, such as the electrocardiogram, heart sounds or arterial pulse, enabling orientation to known phases of the cardiac cycle. Multichannel instruments are not generally available but fortunately the electrocardiogram may be surmounted on the ballistocardiogram by attaching an electrocardiograph lead (such as lead I) in series or parallel circuit with the ballistocardiogram. In this manner a QRS spike will be recorded just before the ballistocardiographic waves associated with systolic contraction, permitting identification of the waves. Methods have been described to enable selective tuning of the electrocardiogram in or out of the ballistocardiograph circuit, so that the amplitude of the QRS complex may be varied as desired.15-17

II. ORIGIN AND PHYSIOLOGIC SIGNIFICANCE OF THE WAVES

H Wave (Presphygmic Wave). The first wave associated with contraction of the heart is an upward deflection, the H wave, which normally is relatively small and inconspicuous; in heart disease, as will presently be mentioned, it may become large in amplitude equaling or surpassing the height of the J wave. Study of the H wave with the velocity type ballistocardiograph (2 microfarad electromagnetic instrument), which possesses least time lag, together with simultaneous electrocardiogram and heart sounds recorded at high speed (75 mm. per second), indicates the following time relation-ships (fig. 1). The H wave begins .02 to .03 second, or even earlier, after the onset of electrical activation of the ventricles (onset of QRS complex), and .02 to .03 second before

![Fig. 1. Electromagnetic ballistocardiograms recorded with, (a) 2 microfarad condenser (velocity tracing), (b) 20 microfarad condenser (chiefly displacement), and (c) 70 microfarad condenser (displacement tracing). Amplitude of the waves decreases as condenser capacity is increased. In the velocity tracing (a), the J and K deflections are too rapid and large to be defined clearly in reproduction. A time lag is also introduced by the condensers. With the velocity tracing the onset of the H wave occurs .025 second after beginning of QRS complex, in the displacement tracing this interval is .04 to .05 second. Peak of H is attained in .10 second after onset of QRS in velocity tracing, in .13 second after onset of QRS in displacement tracing. Velocity tracings give a truer temporal record of ballistocardiographic waves in relation to other events of the cardiac cycle. The H wave commences .02 to .03 second before the first component of the first heart sound and is the earliest mechanical event in systole. With the velocity tracing a distinct downward wave, the G wave, is seen to precede the H wave. This begins before the onset of the QRS complex and is associated with auricular systole.](http://circ.ahajournals.org/doi/abs/10.1161/01.CIR.42.1.271)
termination of the relatively slow H upstroke is marked by the onset of a steep downstroke, the I wave, which is associated with ventricular ejection.

Various interpretations have been offered for the H wave. It has been suggested that the H wave is due to auricular contraction, but this cannot be so since H waves are observed in the presence of auricular fibrillation. There is frequently observed a distinct downward wave preceding the H wave which evidently is associated with auricular systole, and which follows the P wave and precedes the QRS complex (fig. 1). This has been termed the G wave and may be quite distinct when the heart rate is slow. The auricular components of the ballistocardiogram may be seen more distinctly in heart block where auricular and ventricular contraction are more clearly dissociated. Another explanation which has been advanced for the H wave is that it is due to the apex thrust of the heart. A clear indication that this cannot be the case is afforded by ballistocardiograms in subjects with extrasystoles. The beat following the compensatory pause after the extrasystole is more forceful than succeeding regular beats and the apex thrust is greatest, yet the H wave is smaller in beats following extrasystoles than in subsequent regular beats. Furthermore, were the H wave related to apex thrust one would not expect it to be amplified in heart disease, which occurs very frequently.

An explanation for the H wave which appears to be most valid is that it reflects forces associated with abrupt deceleration in the flow of blood returning to the heart. With the sudden rise of intraventricular pressure accompanying the onset of systole, blood flow into the ventricles is abruptly halted and this sudden deceleration is reflected in the H wave. This circumstance occurs even before the closing snap of the auriculoventricular valves which produces the first heart sound, and accordingly, where the H wave is distinct, a sensitive index is produced of the initial event in ventricular systole, that is, a rise in intraventricular pressure. Since the beginning of the succeeding I wave marks the onset of ejection, the duration of the H wave reflects the duration of the isometric or presphygmic period of ventricular contraction. The values observed, .05 to .07 second, accord well with measurements obtained by catheterization and other less direct technics.

I and J waves (Ventricular Ejection). The onset of ejection is marked by a sharp negative wave, the I wave, which represents the footward recoil of the body from acceleration of blood upwards in the pulmonary artery and ascending arch of the aorta. With impact on the crown of the two arches, the direction of forces is abruptly reversed and there is a sharp recoil of the body in the headward direction, the J wave. Accessory factors in the production of the J wave are acceleration of blood flow in the descending aorta and deceleration of flow leaving the ventricles and in the ascending arches.

The J wave normally is the dominant wave of the ballistocardiogram; its amplitude is two to three times that of the I wave. In form, both I and J waves are steep, unbroken and attain pointed summits. The peak of the J wave normally occurs between 0.22 and 0.26 second after the onset of the QRS complex of the electrocardiogram. In abnormal situations the I and J are decreased in amplitude, the I wave may not be evident, the J wave becomes slurred and notched and its peak is delayed to 0.28 second or even longer after the onset of the QRS.

The I and J waves are clearly related to ventricular ejection; indeed, much of the ballistocardiographic literature has been devoted to attempts to calculate the cardiac output from the amplitude and areas of the IJ stroke. Although a fair correlation exits, the amplitude of the I and J waves is more directly related to the velocity than to the quantity of ejection. The velocity and quantity of ejection ordinarily correlate closely but this relationship does not necessarily obtain. In shock the stroke output is markedly decreased but ejection velocity is increased. Under such circumstances cardiac output calculated by methods predicated on ejection velocity, such as the ballistocardiograph or pulse contour, give values far in excess of the actual output determined by the
Fick procedure. Conversely when ejection velocity is reduced, as in heart failure, values for output obtained by these methods are too low.  

Studies of instantaneous arterial blood flow with the electromagnetic flowmeter indicate that maximum velocity is normally attained early in systole, at a time coincident with the I and J ballistocardiographic deflections. The form and amplitude of the I and J strokes may be quantitatively integrated with the instantaneous components of ejection, that is, the form of the cardiac ejection curve. Abnormalities in form and decreased amplitude of the I and J strokes accordingly signify a reduced velocity and force of ejection. As indicated by Starr and his coworkers, the ballistocardiogram is more closely related to the heart's force than to its output, and the vertical amplitude between the trough of the I and peak of the J provides an accurate index of the maximal force developed by the heart in individual systoles in giving acceleration to the flow of blood.

One of the most striking characteristics of the I and J ejection strokes is the phasic variation in amplitude with respiration. With the onset of inspiration the waves augment in amplitude, and conversely they decrease during expiration. In normal young subjects during ordinary shallow respiration the variation of amplitude is of modest degree. It is more conspicuous during deeper breathing, and in normal shallow breathing in older subjects and in those with heart disease (fig. 2).

![Fig. 2. Respiratory variation in male, age 41, with anginal syndrome. During expiration, which best reflects left ventricular activity, the identity of the waves is completely lost, in inspiration the complexes are of normal configuration. Electrocardiogram at rest (middle strip) is normal. Tracing after exercise (lower strip) shows evidence of coronary insufficiency, indicated by flattening of T wave in lead I, and semi-inversion of T wave in lead V4.](http://circ.ahajournals.org/)

Although the left ventricle is much more powerful than the right ventricle, a considerable proportion of the work of the left ventricle is expended in overcoming the arterial pressure, and this is not reflected in the IJ wave of the ballistocardiogram. There is much less disparity between the two ventricles in the forces expended in accelerating the flow of blood, which is the determinant of the I and J strokes. Consequently the left and right ventricles contribute to the I and J waves in almost equal measure, as injection experiments in cadavers have shown.
The respiratory variation in the ballistocardiographic waves is due principally to the profound influence of respiration on right ventricular filling and ejection. Ordinary respiration has much less influence on left ventricular output. The negative intrathoracic pressure accompanying inspiration sucks venous blood into the right cardiac chambers so that right ventricular output is increased 25 per cent or more. Left ventricular output varies in the inverse direction but only negligibly, so that left ventricular ejection is relatively constant (a circumstance important to circulatory efficiency), while right ventricular ejection undergoes wide swings during respiration.\textsuperscript{29, 30} The lungs serve as a buffer to equilibrate flow to the left ventricle, and during inspiration there is an increase in the volume of blood contained in the pulmonary vessels. Acceleration of this augmented quantity of blood in the pulmonary vessels during right ventricular systole, as well as altered velocity of flow in the pulmonary vessels during inspiration may be auxiliary factors in accounting for the increased IJ stroke in inspiration, in addition to increased right ventricular output. A further factor which may contribute to an augmented J amplitude in inspiration is the greater percentage of pulmonary blood flow which is directed in the footward direction with descent of the lungs and diaphragm during inspiration. An analogous effect is readily demonstrated in systemic arterial flow by recording ballistocardiograms with the arms extended above the head in the

**Fig. 3.** Deep K wave. Top strip is of subject with hypertensive heart disease. In addition to the abnormally deep and early K wave, the I wave is absent and J wave is notched. Bottom strip (high speed recording) illustrates deep K wave in subject, age 65, with arteriosclerosis of aorta and hypertension. The trough of the K wave is early (as also in the top strip) and is attained 0.05 to 0.05 second before the first component of the second heart sound. Normally the K trough occurs 0.01 to 0.02 second before the second heart sound. Exaggerated and early K waves are associated with inelasticity of the aorta. The depth of the K wave is also related to the length of the aorta. Deep K waves are seen normally in tall individuals. Note considerable respiratory variation in J wave amplitude in these two abnormal individuals.

**Fig. 4.** Coarctation of aorta. The top strip, from a male, age 30, with blood pressure 188/100, shows marked blunting of the K wave. Lower tracing, made postoperatively after surgical correction of coarctation of aorta shows normal K waves.
axis of the body and then in their normal position. The J stroke decreases as the arms are extended cephalad and increases when placed at the sides of the body.

A convincing demonstration that the intrathoracic pressure variations, with accompanying changes in right ventricular output, are the

**The K Wave (Aortic Deceleration).** The K wave, as has already been indicated, is profoundly influenced by the type of recording instrument. It is recorded with some measure of fidelity only with the displacement type of apparatus. The K is a footward wave commencing at the peak of the J and extending in

Fig. 5. Large diastolic waves. Top strip shows normal individual at rest and during Valsalva experiment. Second part of strip, during Valsalva procedure, exhibits greatly augmented L wave, associated with obstruction to return flow to heart. Middle strip in subject with 2:1 heart block reveals large waves following auricular systole (P wave) independent of ventricular activity. In some beats (latter two) the diastolic auricular ballistocardiographic waves exceed those accompanying ventricular systole. Lower strip, in subject with subclavian arteriovenous aneurysm, reveals large diastolic wave.

major factors in respiratory variation in the ballistocardiogram has been provided by Starr and Friedland who demonstrated that when the intrathoracic pressure relationships during respiration were reversed by positive pressure inspiration and passive expiratory deflation, the ballistocardiographic respiratory variation was similarly reversed in phase.

an unbroken, relatively steep slope to a deep trough at a level approximating or slightly beyond the depth of the I wave. The trough of the K wave normally precedes the onset of the second heart sound by 0.01 to 0.02 second.

The K wave, unlike the I and J waves, is due entirely to the systemic circulation. Its trough is coincident with the peak of the femoral
pulse curve.\textsuperscript{22} It is caused by deceleration of blood flow in the descending aorta as it is slowed by the peripheral resistance and as ejection velocity falls off at the end of systole. When peripheral resistance is decreased by producing reactive hyperemia of the lower extremities the K wave decreases in amplitude.\textsuperscript{18} Conversely the K wave is increased in amplitude and attains an earlier trough with increased peripheral resistance and arterial inelasticity as in hypertension, and arteriosclerosis of the aorta associated with aging (fig. 3). The depth of the K wave is directly related to the length of the descending aorta. When the length of the descending aorta is greatly shortened, as in model experiments and clinically in coarctation of the aorta,\textsuperscript{19, 33, 34} the amount of blood in the descending aorta undergoing abrupt deceleration is greatly reduced and the K wave may disappear (fig. 4). This is a useful diagnostic sign in intraluminal obstruction of the descending aorta.\textsuperscript{35, 36}

\textbf{L Wave, and Diastolic Waves (M, and others).} Originally considered as resulting from body after vibrations, the L wave and subsequent waves in diastole are now recognized to be associated with circulatory forces. The L wave is a relatively slow wave representing headward thrust which begins at the trough of the K wave. It is of variable form and amplitude, reaching a plateau rather than a sharp peak at a height considerably below the peak of the J wave. The L and subsequent diastolic waves in the ballistocardiogram are considered by Hamilton\textsuperscript{19} to represent forces in the aorta. These waves are of complex origin and cannot be ascribed to any single phenomenon of blood flow. In some measure, at least, these waves must be associated with return flow to, and filling of, the heart; for in abnormal situations such as gallop rhythm, mitral valvular disease, constrictive pericarditis, myocarditis, heart failure, the Valsalva experiment, and arteriovenous aneurysm the L wave and subsequent waves may be of great amplitude and even exceed the IJ wave of ventricular ejection (figs. 5 and 6).

\textbf{III. Clinical Interpretation of the Ballistocardiogram}

If the ballistocardiogram is to attain status as a clinical instrument in the diagnosis of heart disease some criteria for interpretation are necessary. It is desirable to relate such criteria and terminology, so far as is possible, to specific circulatory phenomena.

Certainly any scheme of interpreting the ballistocardiogram must take account of respiratory variation, exaggeration of which is the commonest abnormality encountered in heart disease. It has already been indicated that respiratory variation in the ballistocardiogram is due to phasic changes in right ventricular filling and ejection. At first glance it seems paradoxical that respiratory variation, which is primarily due to right ventricular changes, should be so conspicuous in types of heart disease such as coronary disease which principally involve the left ventricle. Although the right and left ventricles contribute to the formation of the I and J waves in almost equal
degree, the right ventricular component is much larger in inspiration, the left greater in expiration.

The levo and dextro ballistocardiogram components of the IJ wave may be separated in large measure by a modified Valsalva maneuver. If a subject exhales, after a deep inspiration, against a resistance of 23 cm. water, the marked increase in intrathoracic pressure abruptly halts filling and emptying of and abnormal in form. With the sudden fall in intrathoracic pressure on termination of this maneuver and the succeeding inspiration, the right ventricle is filled and its ejection is large, while left ventricular ejection is still small. At this point a dextro ballistocardiogram is recorded.

In effect, to a less complete degree than obtained in the Valsalva procedure, the ballistocardiogram during inspiration is a dextro

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**Fig. 7.** Ballistocardiographic changes following exercise in male, age 46, with previous posterior wall infarct. The ballistocardiogram, markedly abnormal at rest (note phasic variation in IJ waves), became abnormal five minutes after exercise (thirty 18 inch ascents in two minutes) to such a degree that no identification of the waves is possible. The electrocardiogram, normal at rest showed no significant changes in serial tracings after exercise. This illustrates that there is no necessary correlation between the electrocardiogram and ballistocardiogram in coronary disease.

the right ventricle, while left ventricular ejection is actually augmented for a few beats until the pulmonary vascular bed is drained. Consequently at the beginning of expiration against pressure a levo ballistocardiogram is obtained, that is, the IJ stroke represents almost pure left ventricular ejection. In normal individuals the normal form of the I and J waves is maintained though amplitude is reduced, in subjects with heart disease the complexes become greatly reduced in amplitude ballistocardiogram and during expiration it is a levo ballistocardiogram. Abnormalities in the force of left ventricular ejection are masked during inspiration and become revealed only in expiration when right ventricular ejection is reduced. These circumstances appear to explain adequately the reason for the exaggerated respiratory variation in heart disease involving the left ventricle (figs. 2, 3, 7, 8). When the I and J waves are grossly abnormal both in inspiration and expiration it
must be assumed that there is a general impairment in the force of cardiac ejection involving the right as well as the left ventricle.

Inasmuch as the Valsalva maneuver appears to afford a better dissociation than normal respiration (which varies in depth in different subjects) a modified Valsalva test may be employed in ballistocardiography to provide an index of the force of the right and left ventricular ejection individually. If subjects exhale through a tube whose orifice is placed in water at a depth of 15 to 25 cm., a steady exhalation may be carried out without undue straining and without distortion of the ballistocardiogram by somatic tremor.

In interpretation of the ballistocardiogram, to recapitulate, the first and most important aspect to be studied and described is the force of ventricular ejection, and more specifically right and left ventricular ejection individually as indicated by the IJ wave in inspiration (right ventricle), and in expiration (left ventricle), during continuous breathing. Such information may be provided more adequately by a modified Valsalva procedure. As has already been mentioned the form and time relationships of the J wave are important as well as its amplitude. When ejection velocity and force are impaired, abnormality of the ventricular component of the ballistic complexes is revealed not only by decreased amplitude of the IJ stroke, but by disappearance of the I wave, slurring and notchng of the J wave, and delayed attainment of the J peak.

A simplified scheme of grading the ballistocardiogram has been employed by Brown, Hoffman and de Lalla,37 which places primary emphasis on respiratory variation. Four grades of abnormality are scored:

Grade 1—Regularity of complexes is preserved.
Amplitude in inspiration is normal, in
expiration amplitude is decreased and varies in definitiveness.
Grade 2—One half or more of the complexes are abnormal, mainly in expiration. The inspiratory amplitude is decreased somewhat also.
Grade 3—Abnormalities are present in inspiration as well as expiration, but the complexes are still identifiable.
Grade 4—All the waves are unidentifiable and of low amplitude.

The second factor in the ballistocardiogram which should be inspected and described after noting the IJ wave and respiratory variation is the K wave, the wave of aortic deceleration. It should be observed whether the K wave is unusually shallow or deep, and the timing of its trough, either in relation to the second heart sound, or if heart sounds are not recorded, the time interval from the onset of ventricular ejection (peak of H wave) should be studied. As has already been mentioned the K wave is shallow or absent in coarctation of the aorta, and it is accentuated and attains an early trough in hypertension and arteriosclerosis (figs. 3 and 4).

The third factor in analysis of the ballistocardiogram pertains to waves associated with return flow, the L waves, and subsequent diastolic waves. The H wave falls into this category, for although related to the onset of ventricular systole (presphygmic period) it is due to the abrupt deceleration of blood flow returning to the heart. Abnormally large H, L and diastolic waves are frequently observed in heart disease and may at times be the only abnormality present (figs. 5 and 6).

In summary, then, interpretation of the ballistocardiogram may be conveniently subdivided into three aspects: (1) force of left and right ventricular ejection (IJ wave), (2) aortic wave (the K wave), and (3) waves of return flow (H, L and diastolic waves).

Abnormalities in Ejection

Clinical interest in ballistocardiography has focussed particularly on investigation of its usefulness in coronary artery disease. The succinct observations of Starr and Wood, who were the first to study this problem extensively, will not be repeated but will merit rereading.

Numerous studies have confirmed and extended the observations of Starr and Wood. Notwithstanding the varying techniques employed and the absence of uniform criteria of interpretation, there has been a surprising unanimity in the ballistocardiographic findings in coronary disease among different investigators. These may be summarized briefly as follows:

In acute myocardial infarction, the ballistocardiogram is quite regularly abnormal. During recovery, the ballistocardiogram tends to improve, particularly in younger subjects in whom it often reverts to normal form. Normal ballistocardiograms following coronary occlusion are helpful in indicating restoration of functional integrity of the contractile mechanism of the myocardium. In angina pectoris and in asymptomatic coronary artery disease likewise, the ballistocardiogram is almost invariably abnormal. Subjects with normal resting electrocardiograms who manifest electrocardiographic evidence of coronary insufficiency following exercise or anoxemia commonly exhibit abnormal ballistocardiograms at rest. Following exercise or anoxemia or meals in such individuals, the ballistocardiogram tends to become increasingly abnormal.

Inevitably, despite Starr and Wood's injunction that the ballistocardiogram and electrocardiogram measure different activities of the heart, comparisons have been drawn of their relative value in the diagnosis of coronary disease. There seems little doubt that abnormalities occur more commonly in the ballistocardiogram than in the electrocardiogram, both at rest and after stress (fig. 7). The sensitivity of the ballistocardiogram, however, imposes very serious limitations on its practical diagnostic value. Ballistocardiographic patterns encountered in coronary artery disease are illustrated in figures 2 and 8.

The Effect of Aging. Several studies on large groups of presumably normal individuals have uniformly shown a rapid increase of abnormal ballistocardiographic patterns with advancing age. Employing Brown's grade 2
or over as indicative of significant abnormality, Franco found over 50 per cent of ballistocardiograms abnormal among 317 normal individuals without any evidence of cardiovascular disease, whose ages ranged from 35 to 64. Above the age of 45 over one-third of male subjects exhibited abnormal patterns, and above the age of 60 years tracings were abnormal in the majority of cases.

Starr and Hildreth have itemized the changes in the individual waves with aging.

Their data provide useful empiric normal standards for the amplitudes and ratios of the individual waves of ballistocardiograms recorded by high frequency instruments. Standards for the low frequency, critically damped displacement ballistocardiograph have been presented by Jones, and for low frequency velocity ballistocardiograms by Smith and Bryan. In successive decades from age 20 to age 60 and over, Starr and Hildreth found the I wave decreased from 5.0 mm. to 2.2 mm., the J amplitude decreased from 8.6 mm. to 5.4 mm. The decrease in I depth occurs earlier and is of greater degree than the decrease in J amplitude. The amplitudes of the H wave, mean 1.8 mm., and depth of the K wave, mean 5.2 mm., do not alter between ages 20 and 29 and age 60 and over groups. However, the relative amplitudes of the H and K waves in proportion to the I and J become significantly increased with age.

The changes in the ballistocardiogram with aging are identical with those due to coronary disease (fig. 9). They pose the question whether such changes indicate that older individuals, presumably normal, have some degree of coronary disease and impaired myocardial function. Certainly this is compatible with observations that arteriosclerosis can be demonstrated clinically in a majority of subjects over the age of 50 years. Even more pertinent are the extensive pathologic studies of White, Edwards and Dry, who demonstrated the presence of a severe grade of coronary artery sclerosis in well over two-thirds of subjects above the age of 50. Any middle-aged commuter running for a train will testify that his heart is not what it once was, and this apparently is what the ballistocardiogram reveals.

The factors which contribute to impairment of the ballistocardiographic waves with age are several. Primary perhaps is the decrease in cardiac strength. Among older normal subjects Jones found the maximal systolic force was reduced by over one-third compared with the force in young normal subjects. The changes in the waves with aging, observed by Jones, were qualitatively as well as quantitatively almost identical with those in a group of cases with coronary disease. In addition to a decrease in cardiac force another cause for reduced wave amplitude in older subjects lies in their decreased cardiac output.

Extra-cardiac factors, too, may contribute to the development of ballistocardiographic abnormalities with aging, specifically, an increased width and decreased elasticity of the aorta. The capacity of the aorta in older subjects is fully double that in younger age groups, and it is to be emphasized that movement of the blood volume in the aorta contributes to the ballistocardiogram in important measure. In shock, for example, where the arterial blood volume is greatly reduced, the velocity of ejection and blood flow in the aorta is increased, and the ballistocardiographic waves yield values of stroke output much greater than
the actual output determined by the Fick method.\textsuperscript{25, 26} A similar disparity obtains in ballistocardiograms recorded in the erect position, in which circumstance the amplitude of the waves is increased despite a reduction in cardiac ejection. The importance of aortic capacity and distensibility in determining blood flow in the aorta and the complexity of aortic blood flow have received recent emphasis.\textsuperscript{24, 25, 26, 60, 61}

It is evident that ballistocardiograms must be interpreted with reservations and with due consideration to the age of the subject. Abnormal ballistocardiograms in young individuals below the age of 40 are significant. In older subjects on the other hand, while an abnormal ballistocardiogram is not too meaningful, a normal pattern is helpful in indicating integrity in the force of ventricular ejection. It is among young subjects that the effects caused by disease processes, such as myocardial infarction, may be most clearly defined and studied.

\textit{Myocardial Disease and Heart Failure}. The ballistocardiographic changes encountered in coronary disease are not specific for this condition, for any disorder associated with impaired force of ventricular ejection produces like abnormalities. As previously mentioned, these include diminution or disappearance of the I wave, significant decrease in amplitude, slurring and delayed attainment of the J peak. Such abnormalities are particularly evident in expiration which most completely reflects left ventricular ejection velocity, relatively free of right ventricular contribution to the ballistocardiogram. In addition, large diastolic waves, (the L wave and after waves) are frequently present associated with abnormal return flow to the heart, as well as a prominent H wave reflecting sudden deceleration of return flow to the heart with the onset of ventricular contraction.

These abnormalities are found not only in coronary disease, but also in rheumatic carditis, other types of myocarditis, metabolic cardiopathies such as beri-beri and myxedema, and cardiac failure. The presence of a relatively normal ballistocardiographic pattern with high amplitude J wave in subjects who are in manifest cardiac decompensation should arouse suspicion of a high output type of failure, associated with such causes as hyperthyroidism, anemia or aortic insufficiency.

\textit{Valvular Disease}. Valvular lesions affect the ballistocardiogram by virtue of their influence on the velocity and quantity of ejection, and the development of myocardial failure. When cardiac decompensation ensues, the ballistocardiograph exhibits abnormalities of the I and J waves as in other types of myocardial disease, and large H, L and after waves may be present associated with abnormalities in return flow and cardiac filling (fig. 6). Mitral valvular disease does not produce any specific alterations of the ballistocardiogram, other than decreased amplitude of the IJ stroke in mitral stenosis, which reflects decreased stroke output. When mitral insufficiency is marked the amplitude of the I wave may be greatly decreased, and the J peak may be delayed.

In aortic insufficiency, the IJ stroke may be of huge amplitude. This is due not only to the augmented stroke volume, but, as the authors have observed with a velocity type of recording instrument, to a greatly increased velocity of left ventricular ejection. Whereas normally the J peak is attained 0.22 to 0.26 second from the onset of the QRS, in aortic insufficiency the J peak may be reached as early as 0.20 second. Another abnormality observed in aortic insufficiency is a widening and notching of the K downstroke, which is probably related to the altered character and direction of the blood flow in the aorta.

In aortic stenosis, the I wave may be unusually wide and large (fig. 10). Normally, the ballistic effect of expulsion of blood into the ascending aorta (which causes the I wave) is very rapidly succeeded by the counter effect of impact of the ejected blood on the aortic arch, which together with acceleration of the blood flow in the descending aorta produce the J wave. Retardation of the latter events in aortic stenosis causes the I wave to be less precipitously opposed ballistically so that it becomes accentuated.

It is to be emphasized that the ballistocardiographic changes in valvular disease occur only when the hemodynamic effects of the lesions are marked. Consequently, the ballistocardiog-
gram is of little or no practical diagnostic importance in valvular disorders.

Abnormalities in Aortic Flow, and in Cardiac Filling and Return Flow

Abnormalities in aortic flow are revealed by changes in the K wave, and abnormalities in cardiac filling and return flow by increased prominence of the H, L and after waves. Comment has already been made on clinical disorders involving these waves under analysis of the factors involved in their origin. Although characteristic changes occur in the K waves in hypertension, arteriosclerosis and coarctation of the aorta, and in the H, L and after waves in constrictive pericarditis, arteriovenous aneurysm, rheumatic heart disease and congestive heart failure. It may reasonably be stated that such ballistocardiographic changes are of

Fig. 10. Deep, slurred I wave in aortic stenosis. Top strip is that of male, age 46, with calcified aortic valve and auricular flutter. Lower strip, of another subject with aortic stenosis, shows normal I waves during inspiration, but during expiration, which best reflects left ventricular ejection, the I waves are slurred and widened.

Fig. 11. Upper left strip, from subject with hypertensive heart disease, is relatively normal except for diminished I wave. Lower left strip shows development of grossly abnormal waves immediately after cold pressor test in which blood pressure rose from 190/140 to 218/160. In upper right strip after intravenous administration of hydergine (mixture of hydrogenated ergot alkaloids) tracing is similar to control. Rise in blood pressure on performance of cold pressor test was prevented and no deterioration of ballistocardiographic complexes occurred as in control test.
relatively little practical importance, and serve only to complement more fundamental diagnostic criteria.

**Effect of Drugs on the Ballistocardiogram**

Reflecting the force of ventricular ejection in a sensitive manner, the ballistocardiogram provides a felicitous method for the study of the effects of drugs on cardiac function (fig. 11). Among agents which have been thus investigated are digitalis, quinidine, epinephrine, sympatholytic agents, visammin, nitroglycerin and other nitrites, surgery and changes in blood volume, and nicotine. The ballistocardiogram lends itself particularly well to demonstration of the effects of thyroid hormone in myxedema, thiamine in beri-beri heart disease, and in general to observation of the effects of treatment on cardiac function. The ballistocardiogram may indeed provide an objective diagnostic sign, since response to thiamine is a clinical criterion whereby diagnosis is established.

**Conclusions**

It is difficult to view a new clinical procedure such as ballistocardiography in its proper perspective. Ballistocardiograms may be recorded in a variety of ways, and recording technics have been so simplified that the procedure readily lends itself to general employment. However, physical and physiologic principles are complex and as yet in part unresolved. The ballistocardiograph is unique in providing information concerning aspects of cardiac function not revealed by other diagnostic procedures, namely, an index of the force of the heart and velocity of ejection.

The regular procession of waves characterizing the normal ballistocardiogram relate to specific events in the cardiac cycle. The I and J waves, which are of principal interest, reflect the velocity and force of ventricular ejection. Phasic respiratory variation in amplitude of the I and J waves, modest in normal subjects, is accentuated in heart disease. In effect the ballistocardiogram during inspiration is a right ventricular or dextro ballistocardiogram, and during expiration a left ventricular or levo-ballistocardiogram. Abnormalities in the force of left ventricular ejection are masked during inspiration and may be revealed only in the expiratory phase of breathing when right ventricular ejection is reduced. This appears to explain adequately the reason for exaggerated respiratory variation in heart disease, which is perhaps the most striking feature of abnormal ballistocardiograms. Cycles exhibiting abnormal form show diminution or absence of the I wave and decreased amplitude, slurring and delayed attainment of the J peak. These evidences of impaired force of ventricular ejection are the first and most important aspect to which attention should be addressed in studying the ballistocardiogram. Abnormalities in the ballistocardiogram occur quite regularly in coronary disease and other disorders impairing myocardial function. The sensitivity of the ballistocardiographic method, however, imposes very serious limitations on its practical diagnostic value, for there is a rapidly increasing frequency incidence of abnormal ballistocardiographic patterns with advancing age, so that abnormalities are not too meaningful in older subjects.

The second factor in the ballistocardiogram which should be inspected and described is the K wave, which reflects deceleration of blood flow in the descending aorta in the latter part of systole. The K wave is shallow or absent in coarctation of the aorta and it is accentuated and attains an early trough in hypertension and arteriosclerosis of the aorta.

The third factor in analysis of the ballistocardiogram pertains to waves associated with return flow and cardiac filling, the L wave and subsequent diastolic waves. The H wave falls in this category, for although related to the onset of ventricular systole, it is due to the abrupt deceleration of blood flow returning to the heart as ventricular contraction begins. Abnormally large H, L and diastolic waves are frequently observed in myocardial disease, rheumatic heart disease, heart failure, constrictive pericarditis and arteriovenous aneurysm.

Although the ballistocardiogram supplies interesting information regarding cardiac func-
tion, it must be concluded that its specific diagnostic applications are limited. It does not replace any existing procedures in the study of heart disease, but by providing information regarding the force of contraction and blood flow, it complements other procedures in examination of the heart. Its most useful sphere of application appears to be in providing a sensitive index of the force of the heart both in heart disease and in investigating the effects of pharmacologic agents on cardiac function.

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