Torsion Ballistocardiography: With Special Reference to Patterns in Surgically Amenable Cardiovascular Diseases

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The recoil forces generated in the circulatory system were converted into a momentum (torque) by using a table supported by a single steel bar in its center. With such a torsion ballistocardiograph, information can be obtained on the site of origin of the forces and on their direction, because the amplitude of the table is proportional to the product force times lever arm (distance from the center of rotation), and the latter can be varied by placing the subject in various positions relative to the center of rotation. The limitations of ballistocardiography in general arise mainly from the complexity of the system of three oscillators (heart, body; table) in which the elastic and damping properties of the body are presently unknown. These limitations are discussed.

I. The Mechanics of the Reaction Forces Producing the Ballistocardiogram

The pulsatile flow of blood and the periodic movement of the heart muscle impart reaction forces upon the body which are measurable either in the resulting movement of the body resting upon a stationary support (Dock's shin type of ballistocardiograph) or as the displacement of a table which is freely movable in one or more degrees of freedom and upon which the subject has been placed. A discussion of the forces involved will reveal a number of limitations inherent in the ballistocardiographic method:

1. According to Newton's laws, any accelerated mass within the body has its counterpart in a reaction force acting upon the body and consequently will contribute to the ballistocardiogram. There can be no doubt, therefore, that the ballistocardiogram reflects not only the acceleration of the blood during ventricular systole, but likewise movements of the heart muscle itself. A constant force, that is, a force of constant magnitude acting throughout the cardiac cycle, cannot be detected ballistocardiographically because it would merely affect the baseline of the system and the latter cannot be ascertained when the subject lies on the table. In cases, therefore, where a pulsatile increase in flow is superimposed upon a constant flow, the alternating component only will be reflected in the ballistocardiogram.

2. The body represents a closed system and no accelerated mass particle can escape to the outside. The law of the conservation of momentum, therefore, requires that the net sum of the reaction forces during one cardiac cycle must be zero; in other words, the sum of each mass acceleration during one cycle must be followed by a mass deceleration of equal magnitude. From Starr's classic analogy of the suspended room and the man with a waterhose it is obvious that changes in the displacement of the room depend on (a) changes in the reaction force produced by changes in the ejection of water from the nozzle, and (b) on the pattern of deceleration and on the time at which the deceleration of the water particles at the opposite wall of the room occurs. As the deceleration drives the room into the opposite direction, the time relationship between acceleration and deceleration will to a large extent determine the amplitude and pattern of the displacement of the room.

In the case of the heart the pattern of acceleration is a function of the cardiac ejection. The pattern of deceleration and the time lag or phase shift between acceleration and deceleration, however, depend on a variety of factors
such as dimensions of aorta, flow velocity, site of deceleration, filling and elasticity of the aorta and drainage through the arterioles. The ballistocardiogram resulting from the ejection of the stroke volume has, therefore, at least two components, one produced by the acceleration of the blood and, therefore, a function of the volume-velocity curve of ejection, and the other produced by the deceleration of the blood and no simple or predictable function of the ejection curve at all. The ballistocardiogram is caused by the sum of these two forces and is, therefore, neither the second or third derivative nor any other direct function of the velocity curve of cardiac ejection, and consequently the cardiac ejection curve (or the stroke volume) cannot be derived from the ballistocardiogram.

3. All forces involved are vectors; that means they are characterized by an amplitude and a direction, and at any instant of the cardiac cycle the reaction force $F$ is the vectorial sum of the forces produced by the acceleration or deceleration $a$ of the various masses $m$. In special cases there might be no resulting force $F$ at all, for example, if two masses $m_1$ and $m_2$ are accelerated in opposite directions and $m_1a_1$ equals $m_2a_2$. In this case the forces of the two masses are cancelling out each other, and the center of gravity remains at rest.

The ballistocardiogram, therefore, does not only depend on the magnitude of the force components but likewise on their direction and on their time relationship. Their spatial direction is determined by the anatomy of the heart and large vessels, and may be markedly different from individual to individual. Of the total reaction force, the head-foot ballistocardiogram picks up only an unknown fraction, namely, the force components acting in head-foot direction, and this fraction of the total force may vary individually simply due to individual variations in the anatomy of the heart and large vessels.

II. PRINCIPLE OF TORSION BALLISTOCARDIOGRAPHY, METHODS AND MATERIAL

In view of the vectorial nature of the reaction forces, a torsion ballistocardiograph (TBCG), as used in this investigation, offers a number of advantages for the study of the pattern of the ballistocardiogram and its correlation with certain abnormal cardiodynamics, because with this type of ballistocardiograph one can obtain information on the direction of the forces as well as on their site of origin. In principle, the torsion ballistocardiograph consists of a table top which is not supported at the four corners but in its center only by an upright steel bar. The torsion elasticity of this steel bar permits circular movements of the table top around this center of motion. The magnitude (arc) of the circular displacement of the table as the result of an impressed force is proportional to the product of force times lever arm where the latter is the distance between the site of action of the force and the center of rotation.

The introduction of the lever arm makes the ballistocardiograph much more versatile, and by taking tracings with the subject placed in various positions relative to the center of motion one can accentuate the reaction force arising in certain parts of the vascular system. Furthermore, this principle can be used to determine grossly the unknown site of origin of a given force by observing the position where a given wave in the torsion ballistocardiograph will disappear and then will be reversed in direction.

Technical details of the torsion ballistocardiograph are presented in figure 1. The torsion bar, a round steel rod of $\frac{3}{4}$ inch diameter and 5½ inches length, is welded to the base of the instrument constructed of heavy iron girders. At the upper part, the torsion bar is surrounded by a ball bearing in order to prevent possible bending of the bar under load. The very small amount of dry friction introduced by the ball bearing was found to be negligible. An iron plate at the upper end of the torsion bar is bolted to a similar plate on the table top and all movements of the table top are only possible through the torsion elasticity of the rod. A moveable x-ray tube, not shown in the illustration, was mounted at the base of the instrument so that x-ray films could be taken when the subject was lying on the table and the distance of the various parts of the aorta
from the center of rotation could thus be determined.

The movements of the table top are arcs. However, as their amplitude is only in the order of magnitude of $\frac{3}{10}$ of an inch, they can be considered as straight lines. The displacements of the table are converted into proportional voltage by means of a condenser plate of a carrier frequency circuit, one plate of which is stationary and the other plate of which is connected to the table top in such a way that only movements of the table in the horizontal plane are recorded. The rectified output of this carrier circuit is amplified and recorded by means of the direct current amplifier of a Sanborn Polyviso recorder.

![Fig. 1. Schematic side view of the torsion ballistocardiograph.](http://circ.ahajournals.org/)

Human body and ballistocardiograph table represent an intricate system of coupled oscillators, and the mechanical characteristics of both these oscillators must be taken in account when one attempts to decide on the desirable frequency response of the ballistocardiograph table. All present day ballistocardiographs are based upon the assumption that the damping resistance of the human body exceeds the elastic and mass components of its impedance throughout the frequency range under consideration (0 to 20 cycles per second). Under this assumption the possible distorting influence of the coupling between the two oscillators, body and table, can be minimized by selecting an oscillating table which offers a great damping but a small elastic and mass resistance. Owing to the small restoring force, the amplitude frequency response of such a table will not be flat, which means that a given force will produce a greater displacement of the table at low frequencies than at higher. Such a falling frequency response, however, should not be confused with a distorted frequency response, because it is quite acceptable as long as the frequency response curve follows a defined mathematical function. The damping and the restoring force of the table used in this study were arranged in such a manner that a $1/2\pi f$ frequency response was achieved. From the equations describing vibrations it can easily be seen that such a response represents nothing else but a mechanical integration.

The $1/2\pi f$ frequency response was realized in the torsion ballistocardiograph used in these investigations by using a table with a natural undampened frequency of 4 cycles per second and a supercritical damping. The damping consists of two adjustable oil dampers which are entirely free of dry friction, and in which a piston moves with a clearance of $\frac{1}{40}$ of an inch in an oil filled cylinder. The frequency response curve of the table was determined by recording the movements of the table while a sinusoidal force of uniform magnitude was impressed upon the table at various frequencies. The force was produced by a motor driven excenter which was connected by means of a leaf spring to the table top. Each rotation of the excenter impressed a sinusoidal force of equal magnitude upon the table because the amplitude of the excenter was large in comparison to the amplitude of the table. The damping of the table was adjusted until an exact $1/2\pi f$ response of the system was obtained. Changes in the momentum of inertia of the system as
they occur due to different weight of a subject or due to different positions of the person on the table caused only negligible changes in the frequency response.

While small changes in the momentum of inertia (weight and position of the subject) do not affect the frequency response, they affect, of course, the sensitivity of the instrument. A calibration by applying a known force to the table top while the subject lies in position is, therefore, necessary. To this end a mass of 1500 Gm. was attached by means of a spring to the table top, and after the subject was placed upon the table the pendulum was released electrically. The sinusoidal forces impressed upon the table by the oscillating pendulum provided the calibration of the whole system. No attempts were made to express the amplitudes of the table in absolute terms, but before each torsion ballistocardiogram was taken, the attenuation of the amplifier was adjusted in such a way that the table movements due to the oscillations of the calibration pendulum produced waves of exactly 40 mm. in the tracing. Thus the sensitivity of the ballistocardiograph with the patient lying in position was identical in all tracings.

The different lever arms in various positions of the subject relative to the center of rotation, of course, must be taken in account. In each tracing the position of the subject upon the table is indicated by a schematic drawing of the aorta as seen from above. In repeated ballistocardiograms, for example, before and after surgery, the patient was placed upon the table in identical positions, and these tracings are, therefore, directly comparable.

All records were taken in midrespiration and an upward peak in the tracing represents a clockwise rotation of the table top as seen from above; a downswing represents a counterclockwise rotation. All time relations mentioned use the R wave of the electrocardiogram as the point of reference.

In most of the patients a complete cardiovascular work-up was available. Pressures were obtained from the right heart by catheterization; Sanborn electromanometers were used throughout. The electrocardiograms served as the common time reference. Heart sounds and electrocardiogram were recorded simultaneously with ballistocardiogram by means of a multichannel Polyviso direct writer, and the former were intended only as an approximate reference of the duration of systole. Throughout the records these heart sounds are indicated schematically above the electrocardiogram.

III. The Role of the Mechanical Body Impedance

It was pointed out that the torsion ballistocardiograph table used in this study (as well as all other types of ballistocardiographic instruments presently in use) is based on the assumption that the damping resistance of the human body exceeds the elastic and mass components, and that for the frequency range of interest the body impedance does not vary with the frequency. In the course of this study doubts arose as to the validity of this concept. In some individuals with a fast heart rate the ballistocardiogram was found to consist mainly of distorted sinusoidal waves of a frequency of about 5 cycles per second, and these tracings already grossly conveyed the impression of an oscillator resonating at its natural frequency. Even more suggestive were observations in patients with A-V block (fig. 2) where isolated atrial contractions produced series of waves similar to those produced by ventricular contractions. The large amplitude of these atrial waves (marked A in fig. 2) may be explained by the hypertrophy of the atrium in this patient, but it is unlikely that the reaction force due to atrial contraction is of such a long duration (500 milliseconds) and of such a complicated pattern (three up- and downswings). It was suspected, therefore, that these waves do not represent the true reaction forces of atrial systole but rather the resonating mass of the body which was excited by the atrial systole and which continued to vibrate in its resonating frequency. A Fourier analysis* of the waves supported this interpretation. As shown in table 1, the relative amplitude of the harmonics

* The authors are indebted to Dr. Paul W. Schafer and Mr. Fred Berry who made available their electronic wave analyzer.
was very similar in the waves due to the isolated atrial contractions and in those due to ventricular contractions. In both instances the predominant frequencies were those around 4.3 cycles per second, suggesting that both events excited the same resonator, namely, the body mass.

It seems, therefore, necessary to consider in some detail the factors which may modify the reaction force during its transmission from the site of origin (heart or aorta) to the site of measurement (pick up device of the ballistocardiograph table). For example, the reaction force primarily acting upon the heart is transmitted through the intrathoracic tissues to the bony structure of the thorax and from there through muscles, fat and skin to the table. All these interposed tissues have, from the standpoint of measuring the reaction force, undesirable elastic and damping properties, and it is likely that the original force $F$ will be considerably changed, both in amplitude and phase, during its transmission through these tissues.

A diagram illustrating these factors is given in figure 3. Action and reaction are symbolized by an excenter with one force accelerating the blood and its reaction force acting upon the heart. The intrathoracic tissues are indicated as the "interior coupling" consisting of an elasticity (spring) and a damping. The muscles, fat and skin between the skeleton of the body and the ballistocardiograph table are indicated in the same fashion as "exterior coupling," and finally the table itself has mass, damping, and elastic characteristics which are known while the characteristics of the exterior and interior coupling are unknown. This diagram represents a simplification of the actual conditions, and can be complicated at will by adding, for example, coupled oscillators representing head, arms, and other parts, but this simplification already reveals the very great importance of these factors. Those unfamiliar with such a system may underestimate the influence of the elasticities and dampings, but it must be understood that for any given pattern of force impressed upon

**Table 1.—Harmonic Analysis of the Torsion Ballistocardiogram of Figure 2a.**

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the system almost any conceivable pattern can be obtained at the writing arm of the table simply by varying the elasticities, dampers and masses of the system. Applied to the ballistocardiographic method this means that even if one knows the characteristics of one’s table or measuring device, the recorded ballistocardiogram may have little resemblance to the pattern of the reaction force which one wants to measure.

As long as the damping resistance of the exterior coupling exceeds the elastic and mass resistance, only the amplitude of the ballistocardiogram can be corrected electrically or graphically.

For the time being, caution must be exercised in analyzing ballistocardiograms, and it is unwarranted to correlate each spike or deflection of the tracing with a circulatory event. In this study, therefore, more emphasis was placed upon the comparative analysis of the torsion ballistocardiogram in the same individual before and after cardiac surgery, because it is likely that the body impedance in one individual does not change significantly within a few days or weeks.

IV. CLINICAL OBSERVATIONS

1. The Normal Torsion Ballistocardiogram

A representative example of a normal torsion ballistocardiogram is given in figure 4. The series 4a–e shows tracings where the midline of the subject was placed at various points of the BB’ table axis, and the diagram with each tracing indicates schematically the position of the aorta relative to the axis of the table. The figures in the diagrams represent the distance of the subject’s midline from the AA’ axis in centimeters. In figure 4a the longitudinal forces act with a long lever arm and this position is similar to the conventional head-foot ballistocardiogram, that is, a headward force produces an upward deflection of the record.

The transverse forces where studied in the series 4f–k, where the longitudinal force was suppressed and the transverse forces were recorded with various lever arms. The position of the aorta relative to the center of rotation is indicated in the schematic diagrams and the figures represent the distance between arch of aorta and center of rotation in centimeters.

The most conspicuous wave in the transverse series is the large downswing (fig. 4f) which occurs in early diastole and reaches its maximum at 640 milliseconds (after the R wave of the electrocardiogram). The downswing is followed by an upward wave at 840 milliseconds. The waves were present in all normal subjects provided the heart rate was slow enough, otherwise these waves may be fused with and superimposed upon waves related to atrial systole. These waves must originate in or close by the
heart because they disappear when the heart is placed close to the center of rotation, and they are reversed when the subject is shifted farther towards the other end of the table (fig. 4i–k). These waves are distinct from the K wave in the longitudinal series, which occurred at 540 milliseconds (fig. 4a). Besides this time difference, the K wave is absent in patients with coarctation of the aorta while the transverse waves are present in these patients (fig. 8).

The direction of the forces producing these waves and their site of origin suggest that they are related to the filling of the heart during early diastole, and the downswing (fig. 4f) at 640 milliseconds would be produced by the rapid inflow of the blood into the ventricle and the upswing at 840 milliseconds by the deceleration of this blood inside the ventricle. The amplitude of these waves may seem to be too large to be caused by the diastolic filling of the heart, as compared with the acceleration of the blood during cardiac ejection. However, Rushmer and Thal have shown by a cinefluorographic method that the filling of the ventricle during early diastole occurs more rapidly than its emptying during systole and our observations are in good agreement with the findings of these authors.

2. Auricular Systole and Isometric Ventricular Contraction

Tracings of patients with A-V block lend themselves to the study of the contribution of atrial systole to the ballistocardiogram. Figure 2 is an example of markedly hypertrophic atrium and has been discussed above. The contraction of a hypertrophic atrium in mitral

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**Fig. 4 (a–k).** Electrocardiogram and torsion ballistocardiogram of a normal subject in various positions relative to the center of rotation as indicated in the diagram at the left of the tracings.

Stenosis produces marked recoil forces in the transverse direction, as shown in figure 5b, and figure 7b as a larger upswing almost synchronous with the R wave of the electrocardiogram. This wave must be produced by a force acting from the left to the right at heart level and is definitely related to the atrial contraction because it disappears when such a patient goes into atrial fibrillation as demonstrated in figure 5. The left side tracings represent a patient with severe mitral stenosis in atrial fibrillation and the right side tracing the same patient after conversion to a normal sinus rhythm, and one clearly notes in the left hand tracings the absence of the large wave which is so prominent in the right side tracing. This atrial wave in patients with mitral steno-
sis became smaller and more delayed in some cases following valvulotomy, but remained unchanged in others (fig. 7), and there was no correlation with the success or failure of the operation. It is doubtful whether the acceleration of the blood during atrial systole is responsible for this atrial wave; we are rather inclined to believe that the movement of the heart muscle itself, especially in those cases with hypertrophic atria, and possibly the interruption of the venous inflow, are the main factors in producing the mentioned wave.

Especially interesting changes were found in four cases of constrictive pericarditis before and after pericardiolysis and they demonstrate an entirely different wave occurring during atrial systole.

Figure 6 shows the torsion ballistocardiogram and right heart pressures of a 14 year old boy with constrictive pericarditis before and after pericardiolysis. The marked increase in the amplitude of the ventricular complex in figure 6a after pericardiolysis is very obvious. The position in figure 6b accentuates the transverse forces and the postoperative tracing shows the large downswing at 600 milliseconds and all the other features of a normal tracing. In the preoperative tracing this downswing is much smaller, of shorter duration and is followed by a large upswing which is the largest wave of the whole tracing, and this wave disappeared after surgery. The start of this remarkable wave coincides with the P wave of the electrocardiogram, but it reaches its peak (at 70 milliseconds before the R wave) earlier than the peak of the right atrial pressure. We do not believe that this wave is related to the acceleration of the blood from the atrium towards the ventricle but rather to the deceleration of the inrushing blood due to the inextensibility of the ventricles.

3. The Ventricular Systole

The relationship between the I and J wave of the ballistocardiogram and cardiac ejection is obscured by a number of factors, of which the distortion of the reaction forces during their transmission through the body tissues and the role of the deceleration already have been discussed. The summation or interference of waves produced by the atrial contraction with those of the ventricular systole has been mentioned in connection with figure 2. Among the other factors which must be considered are the reaction forces originating in the pulmonary circulation, the movement of the center of gravity of the heart muscle, and the opposite direction of the blood movement in the ascending and descending aorta.

Little is known of the contribution of the
pulmonary circulation to the ballistocardiogram. Theoretically, one would expect significant longitudinal forces from the ejection of blood from the right ventricle because the accelerated masses are the same in both ventricles. The transverse forces due to a normal pulmonary circulation are probably not reflected in the torsion ballistocardiogram because the left and right pulmonary artery very likely produce similar and opposite reaction forces which cancel each other. In patients with unilateral pneumonectomy, however, the remaining transverse forces of the opposite side should be demonstrable. Considerable abnormalities were found in the torsion ballistocardiogram of three patients following pneumonectomy. However, these abnormalities did not show a general trend and could not be related to the pulmonary circulation only, but it is probable that unilateral pneumonectomy induces a great variety of changes, especially by positional alterations of the heart and great vessels.

Another important factor affecting the ventricular complex of the ballistocardiogram is the movement of the heart muscle itself. The mass of the heart is considerable compared with the mass of the stroke volume, and, judging from the apex beat, its acceleration and deceleration is likewise significant. We have no way to ascertain the magnitude of these forces because the border movements as measured by

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Fig. 6. Torsion ballistocardiogram in constrictive pericarditis (left tracings) and after pericardiolyis. The tracings represent from top to bottom: electrocardiogram, right atrial pressure, right ventricular pressure, torsion ballistocardiogram and heart sounds.
means of electrokymographic or roentgen kymographic methods do not necessarily provide information on the movement of the center of gravity of the heart. Concentric contractions, for example, would not change the center of gravity at all. We tried to obtain information on the reaction forces contributed by the heart movements by comparing torsion ballistocardiograms of patients with advanced mitral stenosis before and after valvulotomy. In these cases the stroke volume was increased significantly after valvulotomy (as measured by the Fick method) and, therefore, an increase in the reaction forces attributable to ejection of the stroke volume could be expected, while the mass of the heart remained unchanged. The reaction forces due to the heart movement should, therefore, remain approximately the same before and after valvulotomy, and any changes in the tracing would rather be due to the increased stroke volume. Figure 7 shows the torsion ballistocardiogram of a patient with rheumatic mitral stenosis (grade III) before and after valvulotomy. In the position in which

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**Fig. 7.** Electrocardiogram and torsion ballistocardiogram in a patient with pronounced mitral stenosis before and after valvulotomy.
the longitudinal forces are accentuated (fig. 7a),
the ventricular complex was small and of abnor-
mal pattern, and the change towards normal
after surgery is impressive. (Owing to the
small complexes before valvulotomy, a greater
amplification was used in the tracings dem-
onstrated in figure 7. The sensitivity of the bal-
istocardiograph was 1.5 times that used in
these waves are related to the heart movement
itself, both at the beginning of ejection and at
the beginning of relaxation. In the same figure
7b it will be noted that the deep downswing,
normally seen in early diastole and attributed
to the diastolic filling of the heart, is almost
absent. After valvulotomy this wave appears
in normal amplitude and pattern.

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The pre- and postoperative torsion ballisto-
cardiogram in patients with aortic coarctation
should provide information on another prob-
lematic point of the ballistocardiogram, namely
the opposite direction of the flow of blood in
the ascending and descending aorta. Instead
of explaining the ballistocardiographic waves
by analyzing the possible force components in
various parts of the heart and vessels, one can
more generally consider the ballistocardi-
ographic deflections as caused by shifts of the

Fig. 8. Electrocardiogram and torsion ballistocardiogram in a patient with aortic coarctation be-
fore (upper tracings) and after insertion of a homologous graft.
center of gravity within the whole body. These shifts of the center of gravity, either in headward or in footward direction, are, of course, mainly produced by shifts in the blood content of the large vessels. From this viewpoint, the I wave must be produced by a shift of the center of gravity into headward direction, and the J wave by one into footward direction. As blood flows at all times in both directions, the shifts of the center of gravity responsible for the I wave must be due to the fact that during the I wave a greater amount of blood is accelerated headwards than toward the feet, and the reverse conditions must prevail during the J wave. The validity of this concept can be examined in patients with aortic coarctation where one would expect the following changes: (a) a greater than normal flow headward during the first half of the systole and consequently a deeper I wave and longer duration of this wave, (b) a delayed and less accelerated (collaterals of smaller caliber) flow footward, and, therefore, a smaller and possibly delayed J wave and the absence of the K wave.

These expected abnormalities were actually observed in all of nine patients with aortic coarctation and were found to be reversible in most of the patients following surgery. Examples are given in figures 8 and 9. Figure 8 represents the torsion ballistocardiogram of a 14 year old girl with a marked coarctation of the aorta, approximately 2 cm. in length. A direct end-to-end anastomosis could not be accomplished and a frozen homologous piece of aorta, 5 cm. in length and 15 mm. in diameter, was inserted by end to side anastomosis to the aortic arch. The blood pressure before surgery was 190/120 in the arm and unobtainable in the legs, and after surgery 135/75 in the arm and 110/70 in the leg.

The ratio of the amplitudes I and J which is in normal subjects around 1 to 1.2 was in this case of coarctation 1 to 0.62 before and 1 to 1 after surgery. It will be noted, however, that
the tracing taken three months after surgery is still abnormal, although the blood pressure in the lower extremity was 110/70 mm. Hg.

The persistence of ballistocardiographic abnormalities after surgery in cases of coarctation has been described by Murphy, and we believe that in this case the necessity to insert a graft into the aorta is responsible for the abnormalities in the postoperative tracings.

Figure 9 shows a tracing of a 34 year old man with aortic coarctation and a blood pressure of 160/90 in the upper and 120/90 in the lower extremity before and 130/80 and 125/80 respectively after a complete excision of the coarctation and end-to-end anastomosis was performed. The I to J ratio was 1 to 0.65 before and 1 to 1 after surgery.

4. The Early Diastole

Significant abnormalities of the torsion ballistocardiographic waves in early diastole were observed in patients with patent ductus arteriosus and with aortic insufficiency.

In all of seven patients with patent ductus the changes illustrated in figure 10 were found, namely an upward wave in early diastole. Normally, the upswing of the J wave is terminated at the end of systole and returned to the baseline, but in all cases of patent ductus a strong positive wave was observed at that time. This wave was especially marked in the position demonstrated in figure 10b, where it occurred 380 milliseconds after the R wave; that is, it must be caused by a force acting from right to left, but with a headward component as noticed in figure 10a. After ligation of the ductus, this wave disappeared in all cases. The vector of this force would agree with the direction of blood flow through the patent ductus; it seems doubtful, however, whether this flow can produce a wave of this magnitude.

Marked abnormalities, especially in the transverse forces, were noticed in patients with aortic regurgitation as shown in figure 11. These tracings are at the same time a good example of the usefulness of recording the torsion ballistocardiogram in various positions, because the tracing in figure 11a would pass as normal. This position is similar to the conventional head-foot position, and the ventricular complex is well developed and of normal amplitude although the patient was suffering from rather advanced aortic insufficiency. In the positions
accentuating the transverse forces, gross abnormalities will be noted, namely, the large negative wave at 400 in figure 11d and its positive counterpart in the position demonstrated in figure 11c. It is possible that these waves are related to the reversal of flow in the aorta at the closure of the aortic valve and to the regurgitation of the blood.

V. Conclusions

It will be noted that the ballistocardiogram, as a diagnostic aid, is rather superfluous in a number of diseases demonstrated here because they can easily be diagnosed by other means. It was not the aim of this investigation to evaluate the clinical application of the instrument but to investigate more fundamentally how certain defined changes in hemodynamics and especially in the same subject are reflected in the ballistocardiographic tracings. The reproducible and defined response observed in the majority of cases is encouraging in quantitative and qualitative respect. The marked changes in the torsion ballistocardiogram towards normal after valvulotomy in cases of mitral stenosis and the good correlation with other parameters of follow-up studies in these patients seem to justify hopes that the ballistocardiogram eventually may provide semi-quantitative information on cardiac function.

It is obvious, from the discussion of the physical principles, that the determination of the stroke volume cannot be achieved under any circumstances by means of the ballistocardiogram, and formulas which use nonmeasurable correction constants are more apt to obscure the results than to elucidate the situation. The amplitude of the I and J wave should, therefore, be expressed in gram-centimeter-seconds\(^{-2}\) or as fractions of a known calibration force which had been impressed upon the table while the patient was lying upon the table, and one should have a clear understanding that no wave of the ballistocardiogram represents a single and defined physiologic event, for example, the recoil produced by cardiac ejection.

In view of the vectorial nature of the reaction forces, the recording in at least two directions, that is, the longitudinal and the transverse, seems imperative. The torsional system used in this investigation has the additional advantage that, by means of the effective lever arm, information can be obtained on the site of origin of the forces. With this method more attention can be given to the study of waves other than those of the ventricular complex, and the demonstrated examples of pathologic patterns of these diastolic waves suggest their diagnostic significance.

However, in both approaches, for the quantitative measurement of the cardiac force as well as for the study of the pattern of the ballistocardiogram, it will be necessary to eliminate to a greater extent the influence of the mechanical impedance of the body which has been discussed in detail. Thus, the quantitative determination of the components of the mechanical body impedance for the frequency range of 0 through 20 cycles per second seems to be the most urgent step in advancing the ballistocardiographic method.

Acknowledgments

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Sumario Español

Las fuerzas de reculada generadas en el sistema circulatorio fueron convertidas en momento (torque) usando un tablón sostenido en el centro por una sola barra de acero. Con un balistocardiógrafo de torsión de tal descripción, se puede obtener información del sitio de origen de las fuerzas y de su dirección, debido a que la amplitud del tablón es proporcional al producto de la fuerza por el brazo de palanca (i.e., distancia del centro de rotación), y el último puede ser variado moviendo el sujeto en diferentes posiciones relativas al centro de rotación. Las limitaciones de la balistocardiografía en general suscitan de la complejidad de el
sistema de tres osciladores (corazón, cuerpo y tablón) en el cual las propiedades elásticas y apagadoras del cuerpo en el presente son desconocidas. Estas limitaciones se discuten.

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