Ballistocardiography

I. Physical Considerations

By Maurice B. Rappaport, E.E., Howard B. Sprague, M.D., and William B. Thompson, M.D.

A physical analysis is presented of the Starr, Nickerson, and Dock methods for registering the ballistocardiogram. It is shown that many forms of distortion are present. Some of the distortion may be present in the instrumentation which may be controlled, and other forms of distortion are inherent in the subject under test which are most difficult to control or evaluate. The effects which some of the uncontrollable variables have upon the amplitudes and temporal positioning of the registered ballistocardiographic waves is analyzed. The status of static and dynamic standardization procedures is discussed. A "Glossary of Technical Terms" is appended.

CONSIDERABLE confusion exists at the present time in ballistocardiography with regard to the instrumental aspect as well as the clinical interpretation of the graph. Ballistocardiographs are in use which definitely do not register identical records on the same individual and their modes of distortion are multitudinous. The purpose of this analysis and investigation is to determine and illustrate the common forms of distortion which may be introduced by instrumentation and technic and then proceed to analyze the component waves in the normal subject by simultaneously registering the ballistocardiogram with other physiologic events.

A ballistocardiogram is a graphic representation with respect to time of the motions which are imparted to the body in response to the physical movements of the heart, the ejection of blood from the heart, and the passage of the blood through the vascular system. The ballistic movements of the body as a result of cardiac action follow in principle Newton's third law of motion which states that "to every action there must be an equal and opposite reaction." The ballistic force vector which imparts the movement to the body is of variable magnitude throughout the cardiac cycle and its spatial direction changes. Furthermore, the magnitude and direction of the instantaneous spatial force vector is not necessarily equal in two normal subjects at the same instant during the cardiac cycle because of dissimilarity in anatomic positioning and the forcefulness of cardiac activity. The amount of movement imparted to the body is in turn dependent upon factors such as the compliance of the tissues between the heart and the skeletal structure, the compliance of tissues between the vascular system and the skeletal structure, the compliance of the various skeletal joints, the mode of support of the body, the compliance of the tissue between the skeletal structure and the support, and the elasticity and peripheral resistance of the vascular system.

The ballistocardiograph, in its most common form is capable of measuring the ballistic movements of the body axially only—along a line drawn from head to foot which gives the instrument one degree of freedom. The ballistic forces that exist in the body are spatial, therefore, the common forms of ballistocardiographs such as the Starr,1 Nickerson,2 and Dock,3 merely register the body movements which are produced by the projection of the instantaneous spatial vector along the head-foot axis; the projected instantaneous vector is of a lesser magnitude than the spatial vector and the body moves a lesser amount axially than in the direction of the instantaneous spatial vector. This phenomenon has been appreciated by various investigators who have constructed ballistocardiographs which are capable of registration with more than one degree of freedom,4-8 as, for example, head to foot, back to front and side to side movement. When a ballistocardiograph which is

From the Cardiac Laboratory of the Massachusetts General Hospital, Boston, Mass.
capable of measuring body movement with three degrees of freedom is used, the instantaneous spatial vector magnitude and direction may be determined.

Another ballistic factor which has been appreciated is that the spatial force vector is altered by body position. As a result, ballistocardiographs capable of registering with the subject in a standing position, instead of the usual supine position, have been constructed; Wilkins devised a tilting table so that positions between supine and standing were additionally obtainable.

The utility of a ballistocardiograph capable of three degrees of freedom for clinical investigation is apparent; however, the complexity of such an apparatus is great. In addition, a complex system of transducers for detecting head to foot, back to front, and side to side motions, simultaneously registered with one or two other physiologic events, necessitates a four or five-channel recorder. Calculation is then necessary for evaluating the instantaneous spatial vector magnitudes and directions during the cardiac cycle and plotting the locus of the spatial vectors on a three dimensional graph. Experience has indicated that a ballistocardiograph with one degree of freedom sensitive to head-foot movements is capable of giving considerable information. Furthermore, the physical principles which apply to a ballistocardiographic system with one degree of freedom also apply to a system with three degrees of freedom. For simplicity, therefore, we shall discuss the systems with one degree of freedom.

The three forms of ballistocardiograph most commonly used with one degree of freedom are the high-frequency, undamped table suggested by Starr and co-workers, the low-frequency critically damped table devised by Nickerson and Curtis and the instrument based on the method of Dock and Taubman which does not require a suspended table. Let us first consider the characteristics of the Starr ballistocardiograph and their effects upon the resultant ballistocardiogram.

The instrument is essentially a light platform which is supported by springs so that it may vibrate longitudinally (head to foot) at a natural frequency of about 9 cycles per second when a subject of average weight is placed on it. A heavier subject lowers the natural frequency of vibration somewhat whereas a lighter subject raises the over-all natural frequency. The table is undamped except for incidental damping components that may be present in the structure. Thus, if the table is deflected while supporting the subject or an equivalent mass and the deflection force suddenly released, a curve similar to the one in figure 1 will be registered. When the deflecting force is removed, the system goes into a natural oscillation which diminishes logarithmically until a resting or steady state is reached. The logarithmic decrement is caused by some friction and other incidental damping components in the system. If some damping were not present, a sinusoidal oscillation of fixed amplitude would persist which is a physical impossibility as it would be a form of perpetual motion.

All so-called undamped vibrating systems exhibit the phenomenon shown in figure 1; excellent examples are plucked violin strings, and undamped galvanometers, and plucked reeds. In figure 2 is a family of curves which show the response of a vibration system or ballistocardiograph table for various degrees of damping.* At zero cycles per second, which represents a constant displacement of the

* These curves are representative of vibrating systems and are well described in most textbooks on vibration mechanics. The ballistocardiograph table is a vibrating mechanism which falls into this classification. No accurate method has been devised actually to measure such characteristics of tables, but there is no physical reason for a table to deviate in performance.
table, the per cent response in figure 2 is 100 per cent. For example, zero cycles per second is obtained by dividing the applied frequency of zero cycles per second by the natural frequency of the table and zero divided by any finite number is zero. As the applied frequency is increased, the percentage response will vary as indicated by the family of curves. It is apparent from figure 2 that over a range of frequency from zero to at least 75 per cent of the resonant frequency, a ballistocardiograph table without substantial damping produces a deflection which is progressively increased or magnified above the true value. From a clinical standpoint this means that a ballistic wave or component of one frequency will not register with the same magnitude as another ballistic wave of a different frequency although their magnitudes are identical.

It has been shown by harmonic analysis that normal ballistocardiographic waves possess frequency components at least up to 10 cycles per second. The components above 6 cycles per second may be neglected without severe error according to the authors. However, a similar analysis must be made on various abnormal conditions to determine the upper frequency components that must be registered in order to produce a ballistocardiogram of accurate configuration. If a Starr table which is partially damped and possesses a natural frequency of approximately 9 cycles per second is used for the registration of normal ballistocardiograms, registrations will be made on the sections of the response curves of figure 2 from approximately resonance down to the lowest frequency component in the ballistic movement of the subject. The less the degree of damping present, the steeper will be the response curve with respect to the applied frequency.

It may be seen from figure 2 that if a partially damped table is allowed to have a resonance considerably above the highest harmonic component of the ballistic wave, the response curve will be less steep with respect to frequency. If the natural frequency is made high enough, the working spectrum can be considered flat for all practical purposes. From a theoretic standpoint this would be an excellent procedure, but from a practical standpoint some almost insurmountable obstacles appear.

For example, to increase the natural frequency of the table by a considerable amount, extremely stiff springs must be employed and the sensitivity or degree of table movement is reduced inversely as the square of frequency increase. That is, if the natural frequency is doubled, the table movement is reduced fourfold; if the natural frequency is increased tenfold the movement is reduced one hundred times. This obviously places a severe burden upon the detecting and recording systems. Furthermore, as the natural frequency is increased, the degree of damping which is incidental in the Starr table exhibits a lesser effect and a lower degree of damping results.

![Figure 2](http://circ.ahajournals.org/)

**Fig. 2.** Family of curves which are characteristic of vibrating systems. The ballistocardiograph which is such a vibrating system may be represented by these curves and the per cent response which results from an applied force at any frequency may be evaluated if the degree of damping is known.

This phenomenon tends to neutralize the gains which would result from an increase in natural frequency.

It is apparent that a Starr table with a natural frequency of approximately 9 cycles per second when loaded with an average subject does have an appreciable frequency response slope. This is readily observed when ballistocardiograms are registered with the subject breathing normally. This table will register the ballistocardiogram with but a minimal superimposed respiratory weave of the base line. When a ballistocardiogram is registered with an instrument which has a flat frequency response characteristic such as will be discussed later, the respiratory weave will
register on the same subject with an amplitude many times the magnitude of the ballistic waves. The average rate of breathing is approximately 20 per minute which corresponds to a breathing frequency of 0.3 cycles per second. An average ballistic frequency of cardiac origin is approximately 5 cycles per second. Thus, a comparison of the graphs taken with the two types of ballistocardiograph will give a rough estimate of the degree of slope of the frequency response curve. It should be mentioned at this time that because of the fairly steep frequency-response slope characteristic of the Starr table, the respiratory frequency is relatively attenuated to such a degree that the subject’s breathing does not make the ballistocardiogram unreadable as is true when a system with a flat frequency response is used.

When a ballistocardiograph has a rising frequency response characteristic in the working frequency spectrum, it may be considered as having a time constant. The steeper the slope of the curve, the shorter is the effective time constant. When the time constant is short as compared with the frequency of the ballistic waves, a form of distortion is introduced known as differentiation. To illustrate, let us assume that we have a triangular wave (fig. 3) which is to be registered. If the time constant of the recording system is long as compared with the transient wave to be measured, the triangle will register faithfully. If the time constant is short, the triangle will register as shown with a negative wave which is symmetrical but negative. In ballistocardiography this manifests itself in a form of distortion where positive waves such as the J will be followed by a deep K wave even though no K wave is present in the subject. If the time constant is somewhat longer but still too short for accurate registration of the transient wave, a partial differentiation will take place and register the negative wave but with a lesser negative magnitude. The presence of K waves in ballistocardiograms registered with undamped tables when they should not be present as in coarctation of the aorta is explainable by the differentiation principle. Deep negative waves are likewise differentiated which produce positive after waves such as an L after a deep K wave.

Another severe form of distortion, technically known as phase shift, may occur in ballistocardiograms. Phase shift is the lag of deflection behind the applied force. Figure 4 shows the angle by which the deflection lags behind the applied ballistic force for different values of underdamping and for varying frequencies relative to the resonant frequency of the ballistocardiograph.* In reading lag in degrees from figure 4 it should be kept in mind that there are 360 degrees to a complete cycle. Thus a 90 degree lag as read from the graph is equivalent to a delayed displacement or a temporal lag of one-fourth of a cycle; 45 degrees corresponds to a lag of one-eighth of a cycle. When simultaneous physiologic events are registered with relation to the ballistocardiogram and phase displacement is present in the ballistocardiogram, error in interpretation with regard to the temporal interrelationships of the component waves will result. It is obvious from figure 4 that the better the damping and the higher the natural frequency, as compared with the component frequencies present in the ballistic movements of the body, the less will be the phase displacement.

To illustrate the magnitude of phase dis-

---

* The curves of figure 4 are representative of vibrating systems and are known to students of vibration mechanics. The ballistocardiograph table is a vibrating mechanism which falls into this classification and should perform precisely as indicated by the curves.
placement in a Starr table, let us consider one with a natural frequency of 9 cycles per second when loaded with a mass equivalent to a subject and let us assume that the system is 50 per cent damped; Starr has suggested that this is an approximate value for his 9 cycle table. A 2 cycle per second wave will show a phase lag of about 14 degrees; a 4 cycle per second wave about 30 degrees; a 6 cycle per second wave about 50 degrees; an 8 cycle per second wave about 77 degrees; a 10 cycle per second wave about 103 degrees.

When a subject is placed upon a Starr table, it is next to impossible to clamp the skeletal structure to the table so that there is no relative movement possible. This is especially true because we are dealing with minute ballistic body movements; if large body movements were normal, this effect would be negligible. Thus, it is obvious that we are dealing with an over-all vibrating system of multiple component vibrations successively coupled to one another in a very complex manner. The major component vibrating systems are the heart, the body and the table. The vector sum of all the vibrating components of the subject when added to the characteristics of the table produce the resultant ballistocardiogram.

Some years after Starr devised his ballistocardiographic table, Nickerson developed a critically damped table which had a natural frequency of approximately 1.5 cycles per second when loaded with a subject of average weight. The reason Nickerson employs such a table is that he believes from certain assumptions that such a table would move in unison with the body and register a truer record of the ballistic motions of the body for the primary frequencies than is possible with the Starr table. Hamilton and his co-workers, in conclusion to their experimental observations, do not agree with Nickerson.

Basically, the Nickerson table is similar to the Starr table with the exception of the stiffness of the suspension springs. Nickerson uses much softer springs so that the subject-loaded table drops to a natural frequency of 1.5 cycles per second. Nickerson obtains critical damping by means of an ingenious oil system which is adjustable for critical damping for each subject. By varying the opening of a valve in the oil system, the damping of the table may be varied from an underdamped to an overdamped condition. To test for the degree of damping, the operator merely deflects the table and then releases it. A kymographic registration of the table movement indicates whether critical damping is obtained. In figure 5 are representative schematic kymographic records of underdamped, critically damped and overdamped tables.

In figure 6 may be seen the frequency response curve of a critically damped Nickerson table when loaded with a weight equal to that of a human subject.* Note that from zero cycles per second and above there is a gradual diminution in the response of the ballistocardiograph with respect to frequency. For example at 1 cycle per second the response is down to 70 per cent of normal; at 1.5 cycles per second, which is the natural frequency, the response is down to 50 per cent; at 3 cycles per second the response is down to 19 per cent; and at 4 cycles per second the response is only 10 per cent. Above 4 cycles per second the

* This is a curve which may be a member of the family of curves of figure 2 and represents the special condition when critical damping is present.
BALLISTOCARDIOGRAPHY

Fig. 5. Illustrations of kymographic registrations with a Nickerson ballistocardiograph to illustrate: 
A—underdamping; B—critical damping; C—overdamping.

Fig. 6. Frequency response curve of a critically damped vibrating system whose natural frequency is 1.5 cycles per second. This curve is derived from the family of curves of figure 2 and satisfies the condition for critical damping. The critically damped Nickerson ballistocardiograph is such a vibrating system and its response with respect to frequency may thus be evaluated.

response of the instrument is nil. It has been shown that a ballistocardiograph must be capable of registering at least up to 6 cycles per second and preferably to 10 cycles per second to obtain an accurate configuration in the ballistocardiogram. Such a ballistocardiograph would have to have a frequency response curve that is flat at 100 per cent response from zero to about 10 cycles per second. If the Nickerson type table is employed with an adjustable damping mechanism, then a critically damped table with at least a natural frequency of 30 cycles per second would approximately satisfy the condition as indicated in figure 7. Note that at 10 cycles per second the response is 90 per cent of normal. It should also be noted that critically damped ballistocardiograph tables are always down to 50 per cent response at natural frequency and that all response curves droop as the frequency is increased. Actually, if a very close approximation to flat response up to 10 cycles per second is to be procured, the natural frequency would have to be considerably above 30 cycles per second.

Due to the fact that the frequency response curve of a Nickerson type table does not have a rising characteristic with frequency as does the Starr table, the former does not possess a shortened time constant. As a result, ballistic waves are not differentiated and this form of distortion is not present. However, the drooping characteristic of the 1.5-cycle natural frequency table introduces another form of distortion similar to phase displacement. Let us

Fig. 7. Frequency response curve of a critically damped table but with a natural frequency of 30 cycles per second instead of the usual 1.5 cycles per second. This curve is derived from figure 2 and satisfies the condition when critical damping is present.
consider a condition where a triangular impulse is applied to the Nickerson table. In figure 8 the abscissa is plotted in terms of time divided by the natural period of the table; deflection time is equal to half the undamped natural period. Deflection time is the time consumed by the table to traverse a deflection when an instantaneous impulse is applied. If for example the applied triangular impulse has a base which is equal to twice the natural period of the table, the response of the critically damped ballistocardiograph will be shown. It may be seen that the registered impulse is increased in width by about 10 per cent and decreased in amplitude by about 17 per cent. For impulses of longer duration, the loss in amplitude is less because loss in amplitude is inversely proportional to the width of the baseline. It may also be noted that the recorded impulse has shifted by about 25 per cent of the natural period which is the phase shift. Obviously, as the deflection time or natural frequency of the table is increased, errors due to phase shift are reduced.

Because of the drooping frequency response characteristic of the Nickerson table which falls in the working frequency spectrum of ballistocardiography, three forms of distortion are introduced, namely, reduced amplitudes of complexes, increased duration of complexes and phase displacement. Serious complications in interpretation of the ballistocardiographic complexes with respect to other simultaneously registered physiologic events may therefore be introduced.

As a result of the excellent low frequency response of the Nickerson table, respiratory weaving will be superimposed upon the ballistocardiogram in many cases with an amplitude sufficiently large to throw the kymograph recording mechanism beyond the limits of the graph. As a result, breathing must be suspended while the ballistocardiogram is being taken. In many applications the cooperation of the subject cannot be obtained and effects or variations in the ballistocardiogram cannot be evaluated during the respiratory cycle. Also, variations due to Valsalva or Mueller effects cannot always be completely avoided when the subject is required to suspend breathing.

The fact that ballistocardiographic waves may be registered directly from the body (without the use of a suspended table) while the subject is in a supine position had been observed by Nickerson's and Hamilton and co-workers. They registered the relative movements of the vertex of the head and a rigid table or support upon which the subject was allowed to rest. Dock and Taubman duplicated the procedure. Although the recorded waves appeared to be of a fair quality, head tremors, and kyphosis caused bizarre ballistocardiograms. Dock and Taubman then suggested a photoelectric and an electromagnetic method for registering relative movement between the shins and the rigid supporting table. They observed that the shins were

Fig. 8. Calculated response of a critically damped Nickerson ballistocardiograph to a triangular ballistic impulse.

more desirable as a source of ballistic movement reference because of reduced orthopneic tremor. The photoelectric method was claimed to register a displacement ballistocardiogram whereas the electromagnetic unit registered the velocity characteristic of ballistic movement. The comparatively simple technic of Dock and Taubman and the subsequent popularization of the method by Dock, has done much to stimulate interest in clinical ballistocardiography. Later, Sheehan and associates described a piezoelectric ballistocardiograph in which barium titanate was the detecting element.

When a subject is allowed to rest in a supine position on a hard surfaced rigid table, he will possess a natural frequency and a degree of
damping which is dependent upon tissue compliance and the subject's weight; the head support and the heel support exhibit modifying effects although the latter is the more marked. Dock suggests a small pillow under the head and a wooden block under the ankles so that the heel of the foot does not rest on the table. All of the data previously discussed in this report which applies to vibrating systems, such as natural frequency, damping, phase displacement, and amplitude attenuation, applies to a subject when placed on a hard-suraced rigid table. Furthermore, when the subject is placed on a Starr or Nickerson table, it is not possible to prevent the subject from exhibiting these vibrating properties with respect to the table for the small motions involved no matter how the body is supported or clamped. Therefore, it would seem that the use of a suspended table merely introduces variables or distortions in the ballistocardiogram which would not be present if the ballistic movements were registered without the use of a table. Furthermore, the use of a comparatively simple ballistocardiograph which does not require a suspended table does seem extremely enticing and applicable to routine clinical procedures.

Unfortunately, however, this procedure of registering ballistocardiograms is not free of error. In the first place, the natural frequency of the body falls in the spectral region of the ballistic frequency components. Therefore, the frequency response as a function of the ratio of the applied frequency to natural frequency for different degrees of damping is not flat. The degree of damping is not the same for all persons which additionally complicates the situation. With optimal technic, considerably less than 50 per cent damping is obtainable on the average subject which introduces differentiation effects and phase distortion. The type of foot support definitely affects the magnitude, damping and the temporal positioning of the component waves in the ballistocardiogram. An inflated plastic cushion, a feather pillow, wooden block and a sand bag as a foot support will affect the natural frequency and damping of the body differently. The higher the natural frequency, the more accurate will be the registered ballistocardiogram. A sand bag, as suggested by Herzman, when placed under the ankles appears to produce the best condition. Due to the high degree of compliance of the joints leading to the head, the support under the head produces a lesser effect upon over-all damping and natural frequency. A padded table lowers the effective natural frequency markedly and reduces the degree of damping. Therefore, the best one can do is use the technic which will produce the highest natural frequency and maximum damping. In figure 9 may be seen the effects of technic upon damping and natural frequency.

Instrumental characteristics which are unsuitable for ballistocardiography can introduce distortion of a magnitude much greater than one must put up with in the subject. Fortunately, instrumental characteristics are completely controllable but inadequate consideration has been given to this phase of the subject. Many forms of ballistocardiograph which do not employ the suspended table are in use and an analysis of their characteristics is in order.

Let us first consider the ballistocardiograph originally suggested by Dock and Taubman. Basically, their apparatus consisted of a coil of fine wire which was placed in a magnetic field. Relative movement between the coil and the magnet was accomplished by supporting the coil on a hinged mechanism which was activated by a cross bar located on the subject's shins. The rest of the mechanism was placed on the table between the subject's legs. The coil was connected to an electrocardiograph and the potentials generated in the coil as a result of ballistic movements was registered.

The magnitude of the voltage generated in the coil may be expressed by the formula

\[ e = N \frac{d\phi}{dt} \text{ abvolts} = 10^{-4}N \frac{d\phi}{dt} \text{ volts} \quad (1) \]

where \( e \) = voltage generated in the coil as a result of ballistic movement
\( N \) = number of turns of wire in the coil
\( \phi \) = flux linkages or magnetic lines of force which surround the coil
\( t \) = time

According to formula 1, the voltage which is
induced in the coil as a result of relative movement with respect to the fixed magnetic field is equal to the product of the number of

![Diagram](image)

**Fig. 9.** The effects of technic upon natural frequency and damping. Records A through F were taken on a 135 pound male 5 feet 8 inches tall. The sensitivity of the recorder was lowered so that ballistocardiograms would not register. The subject was deflected along the long axis (head-foot) and suddenly released. Record A was taken with a plastic pillow under the head and a sand bag under the ankles. The natural frequency is approximately 4.10 cycles per second. The ratio between adjacent positive and negative lobes is 1.7 to 1 which represents marked underdamping. A 5 to 1 ratio would represent 50 percent damping; the higher the ratio the better is the damping. Record B was registered with the pillow removed, the natural frequency is unchanged but the lobe ratio is 3.2 to 1. Record C was taken with a plastic pillow under the head and a wooden block under the ankles. The natural frequency is 3.35 cycles per second and the lobe ratio is 1.7 to 1; with pillow removed (D) the natural frequency is unchanged and the lobe ratio is 2.2 to 1. Record E was taken with plastic pillows under the head and ankles. The natural frequency is 3.13 cycles per second and the lobe ratio is 2.2 to 1; with head pillow removed (F) the natural frequency is unchanged and the lobe ratio is 2.1 to 1. Record G was registered on another subject with a pillow under the head; heels were allowed to extend beyond the bounds of the table. The natural frequency is 3.85 cycles per second and the lobe ratio is 1.1 to 1.

and, therefore, the voltage is higher even though the magnitude of relative movements is constant. The response curve (pure velocity) of such an instrument possesses a rising characteristic with respect to frequency as shown in figure 10.

From the material previously discussed, it should be apparent that the original Dock-Taubman instrument shows the following effects:

1. It does not register all of the component ballistic frequencies with amplitudes which are independent of frequency.
2. The instrument measures velocity rather than displacement. Actually, when the subject’s response is vectorially added to

![Diagram](image)

**Fig. 10.** Curves which show the frequency response relationships between displacement and velocity. In addition, the calculated response of the Dock magnetic ballistocardiograph which is equalized by 50 microfarad and 20 microfarad condensers is shown.

that of the instrument response, the over-all response is no longer a pure velocity curve.

3. Marked differentiation is introduced in the ballistocardiogram.
4. Marked phase displacement is present.
5. No limitation to high frequency response is present.
6. No weave is superimposed upon the ballistocardiogram due to respiration.
7. The configuration of the ballistocardiogram resembles one obtained on the same subject with a Starr table.

The original design of the Dock-Taubman ballistocardiograph had a rather serious mechanical defect. The hinged mechanism had sufficient friction to effect the true movement of the hinge with the result that some of the registered waves appeared truncated. The
modified design of the Dock magnetic ballistocardiograph\textsuperscript{16} overcomes this defect by the elimination of the hinge. In addition, the modified instrument introduces what is electrically known as equalization by the addition of a 50 microfarad condenser across the coil. Equalization modifies the slope of the frequency response curve to make it approach the response of a displacement type ballistocardiograph (fig. 10); a displacement ballistocardiograph has a flat frequency-response curve. Equalization accomplished with 50 microfarad and 20 microfarad condensers shunting the coil in the Dock magnetic ballistocardiograph is shown. It may be seen that when 50 microfarads are used, the frequency-response curve begins to approach the pure displacement curve from 1 cycle per second to the upper limits of the frequency component waves that may be found in ballistic impulses. From figure 10, it may also be seen that the larger the condenser, the closer will be the approach to pure displacement type registration. The more important characteristics of the most recent version of the Dock ballistocardiograph are

1. It possesses a fair approximation to a displacement characteristic for ballistic frequencies.
2. The larger the capacity of the shunting condenser, the better is the approximation to true displacement type registration.
3. The larger the capacity of the shunting condenser, the less is the attenuation effect upon respiration frequencies. As a result, the more will be the respiratory wave which will superimpose itself upon the ballistocardiograph.
4. Phase displacement which is introduced by the instrument diminishes as the shunting capacity is increased. There is some phase displacement present when a 50 microfarad condenser is used but not of sufficient magnitude to be serious.
5. Distortion due to differentiation is present but small when a 50 microfarad condenser is used.
6. The ability of the instrument to register higher ballistic frequencies is not impaired by equalization.
7. The configuration of the registered ballistocardiograph will not be similar to one taken on the Starr table or the original unequalized Dock-Taubman apparatus.

Dock and Taubman also described a photoelectric ballistocardiograph which was used on the shins. The essential difference between the original electromagnetic ballistocardiograph and the photoelectric apparatus is the substation of a photoelectric cell and light bulb with an occluding vane for the coil and magnet. The vane was attached to the hinge and ballistic body movements varied the amount of light falling on the cell which modulated the photoelectric cell. The cell was in turn connected to the electrocardiograph with a condenser located in one of the two connecting wires. The authors called their photoelectric method a displacement type ballistocardiograph. Although a photoelectric system such as used by Dock and Taubman is a displacement system, the addition of the series condenser for the purpose of eliminating respiratory waves introduced a rising frequency-response characteristic in the ballistic frequency spectrum. As a result, the instrument did not register displacement ballistocardiograms with the resultant forms of distortion inherent in such a system.

The piezoelectric or barium titanate crystal described by Sheehan and associates\textsuperscript{13,14} when used as a sensing element in ballistocardiography possesses rather interesting properties. The more commonly used piezoelectric crystal made of rochelle salt is more sensitive than barium titanate but it is not as stable as a function of temperature, and it is permanently damaged if exposed to temperatures above 115 F., or if located for prolonged periods in excessively low or high humidities.

Piezoelectric crystals possess the property of generating electrical voltages when squeezed or twisted, and the magnitude of the voltage is proportional to the applied force. The electrical potentials are led off from the crystal by means of metal foil electrodes which are cemented to the opposite faces of the crystal. The combination of crystal and electrodes with zero pressure or twist applied may be considered a condenser with a finite capacity. When physical pressure or twist is applied,
the crystal acts like a generator with a condenser in series with it. The electrical energy which is developed in a piezoelectric crystal is extremely small although the voltage generated may be of fair magnitude.

When a piezoelectric crystal is used for ballistocardiographic purposes, it is cemented to a cantilever which is flexed. A cross bar is placed on the shins and the movement of the cross bar deflects the cantilever, one end of which is rigidly fastened to the table. In turn, the piezoelectric crystal is flexed and a voltage which is proportionate to movement is generated across the crystal electrodes. This voltage is applied to an amplifier type electrocardiograph and registered as one would an electrocardiographic lead. A string machine cannot be used because the energy generated by the crystal is too small to deflect the string. If an amplifier is interposed between crystal and string, the combination will function.

The electrical loading which the amplifier presents to the crystal may be considered as resistive and the voltage which is delivered to the amplifier is equal to the voltage generated by the crystal minus the voltage drop across the effective capacity of the crystal. The distortion which may be introduced by the effective capacity of the crystal is dependent upon the rate at which the voltage which is generated by the crystal varies and upon the relative values of the crystal capacity and the amplifier input resistance. The product of the crystal capacity and the input resistance of the amplifier is the time constant in seconds if the capacity is expressed in microfarads and the resistance in megohms.

In order for the ballistic voltages to be applied to the amplifier with a configuration nearly equal to the voltages generated by the crystal, it is necessary that the time constant be of the order of at least a second. Otherwise, errors due to differentiation effects, relative amplitude distortion of the component frequencies and phase displacement will be present. The capacity of a usual crystal element is equal to approximately several thousandths of a microfarad. In order to attain a time constant of about 1 second or more, the resistance in the circuit would have to approach impractical values. The piezoelectric ballistocardiographs described in the literature possess time constants which introduce the distortions described.

A piezoelectric ballistocardiograph may be designed with an adequate time constant and still retain a reasonable value of resistance by shunting the crystal with a large condenser. The resultant sensitivity is very markedly reduced but by proper design it may be possible to attain adequate voltages from such a system.

Another source of trouble with the piezoelectric method is the necessity for making direct contact between table and subject via the instrument. If the compliance of the instrument is not high, the ballistocardiogram may be distorted. We have observed that even a moderately high degree of compliance may introduce distortion in the ballistocardiogram. Most of the distortion is probably due to the shifting of the tissue over the tibia when a retarding force is present.

For our studies we devised a photoelectric type ballistocardiograph which differed from the Dock-Taubman arrangement. Instead of a cross bar, we used a considerably heavier apparatus across the shins. Our cross bar has built into it an optical system which allows a rectangular field of light to be thrown upon half the sensitive portion of a barrier layer photoelectric cell. The photoelectric cell is allowed to rest on the table and the relative movement of the field of light and the cell varies the amount of light which falls upon the photosensitive element of the cell. The voltage which is generated by the cell is proportional to the amount of light which strikes the photosensitive element thereby making the system a pure displacement ballistocardiograph. The output of the cell is connected to an amplifier type electrocardiograph. The only physical connection between the cross bar and the stationary cell is a beam of light which does not introduce compliance effects nor the difficulties with the Dock-Taubman hinge.

Another important difference between our photoelectric ballistocardiograph and the Dock-

Taubman arrangement is in the filter system. The latter introduced a condenser in series with the photoelectric cell and the electrocardiograph to eliminate respiration wave of the ballistocardiographic base line. When a condenser is introduced which adequately attenuates the respiratory wave, the time constant is shortened sufficiently to introduce the errors previously discussed. Our instrument circumvents the time constant effects by allowing the operator directly to couple the photoelectric cell to the electrocardiograph by means of a toggle switch. In one position of the switch, the pure displacement response of figure 10 is attained and the subject must suspend breathing when ballistocardiograms are registered. Error due to differentiation, frequency-amplitude attenuation and phase displacement are not present in the instrument although it cannot be eliminated in the subject because of the low natural frequency and underdamping which must be contended with. The most precise ballistocardiogram is obtained if Valsalva and Mueller effects are minimized and if the best possible technic is used which produces the maximal natural frequency and damping of the subject with pure displacement registration.

Suspended respiration is not always practical in clinical ballistocardiography and a means for minimizing distortion consistent with optimal attenuation of the respiratory frequencies is a necessity. In order to accomplish this, we devised a resistance-capacitance type parallel-T network attenuator which is interposed between the photoelectric cell and the electrocardiograph by throwing the toggle switch in the opposite direction. This type of attenuator when designed to produce maximum attenuation at 0.3 cycle per second, which corresponds to a respiratory rate of 20 per minute, produces a much flatter frequency response curve than is possible with a series condenser except in the respiratory-frequency spectrum. The curve will fall between the 50 microfarad and the 20 microfarad curves of figure 10 in the ballistic frequency spectrum (1 cycle per second and above) and attenuate the respiratory frequencies (1 cycle per second and below) to a greater degree. Our experiences have shown that although such a response does not completely eliminate distortion, it makes possible the registration of a clinically usable ballistocardiogram in the presence of respiration.

We have also observed that either a very light cross bar or a moderately heavy one gives best results. A moderately heavy cross bar reduces the relative movement between tibia and cross bar during ballistic body movements. The maximal weight that may be used is consistent with subject comfort only. The very light cross bar will apparently also ride on the shin without relative movement with the tibia. Considerable distortion may be introduced if the heavy cross bar is allowed to rest on muscle.

Amplifier type electrocardiographs are resistance-capacity coupled and thereby possess a time constant of at least 2 seconds or equivalent. The frequency response curve is good down to 1 cycle per second. The droop in response below 1 cycle per second is too gradual to attenuate effectively the respiratory frequencies. Such a frequency-response characteristic does not distort the ballistocardiogram.

An experiment was performed to illustrate the effects of phase shift, amplitude distortion and differentiation for varying time constants. A typical ballistocardiogram was generated by means of a rotating disc whose circumference was cut out in polar coordinates. The rotating disc in turn modulated light which fell on the photosensitive surface of a photoelectric cell through an appropriate optical system. The output from the photoelectric cell was allowed to pass through electrical circuits of differing time constant and were simultaneously registered on a four-channel recorder. The resultant record is shown in figure 11. The "control" would be equivalent to a pure displacement ballistocardiogram as registered with a photoelectric ballistocardiograph and no condenser or filter interposed between the cell and the recorder or electrocardiographic apparatus. The paper speed was 50 mm. per second and each time line increment represents 0.02 second. The record with an 0.025 second time constant represents velocity recording, and the 0.1 second recording is an approximation
of a commercially available piezoelectric ballistic cardiograph. Note the effects upon amplitude, differentiation effects and temporal relationships. The effect of underdamping and low natural frequency of the human body would further modify the ballistocardiogram. Figure 11 merely illustrates the form of distortion which an improperly designed Dock type of instrument will introduce.

The customary procedure which has been used to date in calibrating a Starr or a Nickerson ballistocardiograph is to apply a longitudinal force to the table (head-foot direction) and observe or register the magnitude of deflection. The longitudinal force is produced by means of a suspended weight; a pulley is used to change the gravitational pull on the known weight to a longitudinal pull. The recording mechanism which registers the table movement may be in the form of a Hamilton manometer, a strain gauge or capacitance transducer, or any other sensing element which is capable of registering table movement down to zero cycles per second which represents a constantly applied force. The amplitudes of the registered ballistocardiographic waves are then evaluated on the basis that if a force of X grams produces a deflection of Y millimeters in standardization, a ballistic wave may then be evaluated.

This calibration procedure is known as static calibration and may lead to gross error in evaluating the ballistocardiogram. We have shown that the frequency response curves of both the Starr and the Nickerson ballistocardiographs are not flat. That is, as the applied force varies its frequency, the response of the ballistocardiograph changes. The ballistocardiogram is composed of waves of differing frequency and they will register with different amplitudes even though the magnitude of the applied force may be unaltered. Unless the over-all frequency response of the ballistocardiograph is known and the frequency components of each ballistic wave are determined, the static calibration relationship to the ballistic force in the head-foot direction cannot be inter-related. In addition, a further complication is introduced when a live subject is placed on the ballistocardiographic table.

We have shown that it is impossible to clamp the skeletal structure to the table so that no relative movement is possible. We have also shown that a subject in the usual position possesses a frequency response which is not

![Fig. 11. Simultaneously registered ballistocardiograms to illustrate the effects of phase shift, amplitude distortion and differentiation for varying time constants. The indicated time constants may be found in ballistocardiographs presently in use.](image-url)
flat with respect to frequency and that there is considerable variation from one person to another. The over-all frequency response curve of the table must be added vectorially to that of the subject and the resultant evaluated. This is definitely not a clinically feasible procedure.

The true calibration must be obtained under dynamic conditions and there is no known simple procedure for doing this. Starr has tried dynamic calibration (described in his first paper on ballistocardiography) where he imposed impacts simulating the ballistocardiogram into the heads of cadavers lying on a table and these impacts were delivered at increasing rates. The trouble with this procedure is that a great deal of calculation must be introduced before a very rough approximation is obtainable with respect to the overall response on each subject. This again is not a practical clinical procedure!

Let us assume that a simple dynamic calibration procedure were possible. Further modifications due to the spatial force vector projections along the head-foot axis and compliance effects would be present. It is our opinion that calibration procedures with regard to amplitude in the ballistocardiogram from a clinical standpoint should be treated with extreme caution.

Ballistocardiograms which are registered from the shins may be statically calibrated even though the systems are completely insensitive to constantly applied deflections. A simple procedure is to push on the subject's head with a scale calibrated in grams at a slowly changing rate. The maximal push in grams and the amount of deflection registered is the calibration. Here again the frequency response of the instrument must be vectorially added to that of the subject, and the over-all treatment is identical to that of the table method. Obviously, the accuracy is no better nor worse than the static calibration procedure with the suspended table and is just as involved.

About all that is justifiable from a calibration standpoint with both the table and shin ballistocardiographs is to maintain over-all instrumental sensitivity at a known or constant value for the observation of gross ballistic changes only. An instrument such as we have used satisfies this condition because the light intensity is fixed, the photoelectric cell is inherently of constant sensitivity and the electrocardiographic recorder sensitivity is adjustable to a predetermined value. If further check on sensitivity is desired, the calibration procedure which we have described may be used. However, the reading of amplitude relationships other than gross changes must be done with extreme caution on all of the ballistocardiographic systems we have discussed.

Conclusions

1. The ballistic force vector which imparts the movement to the body is of variable magnitude throughout the cardiac cycle and its spatial direction changes.

2. The amount of movement which is imparted to the body by the spatial force vector of cardiac origin is dependent upon factors such as the compliance of the tissues between the heart and the skeletal structure, the compliance of tissues between the vascular system and the skeletal structure, the compliance of the various skeletal joints, the mode of support of the body, the compliance of the tissue between the skeletal structure and the support, and the elasticity and peripheral resistances of the vascular system.

3. The ballistocardiograph, in its common form is capable of measuring ballistic body movements along the long axis of the body only. Ballistic forces that exist in the body are spatial, therefore, the projection of the instantaneous spatial vector along the long axis of the body is measured. The projected instantaneous vector is of a lesser magnitude than the spatial vector and the body moves a lesser amount along the long axis than in the direction of the instantaneous spatial vector. Unless the ballistic body movements are known in three dimensions, quantitative estimations of cardiac output are unwarranted.

4. Modifications to body movement which are introduced by anatomic compliances (item 2) hinder the exact evaluation of cardiac output from the ballistocardiogram. Thus, only gross
changes in cardiac output in the same person may be crudely estimated.

5. There are three basic types of ballistocardiograph presently in use, namely, the so-called high frequency undamped Starr table, the low frequency critically damped Nickerson table, and the method popularized by Dock which does not require a suspended table.

6. The Starr table introduces several forms of distortion, namely, amplitude distortion with respect to frequency, phase displacement, and differentiation effects.

7. The Nickerson table does not introduce differentiation but is incapable of registering the higher frequency components, exhibits phase and duration distortion and amplitude distortion with respect to frequency.

8. The original Dock-Taubman ballistocardiographs introduced amplitude distortion with respect to frequency, phase displacement and differentiation effects. The more recent Dock electromagnetic type with equilibration has some of these distortions present but of a lesser amount.

9. The photoelectric ballistocardiograph of our design permits the selection of pure displacement or distortionless response or, with the introduction of a parallel-T network attenuator, an amount of distortion approximately equal to that registered with the more recent Dock equalized-electromagnetic ballistocardiograph. However, the parallel-T network attenuates the respiratory weave more efficiently.

10. When a subject is allowed to rest in a supine position on a hard-surfaced, rigid table, he will possess a natural frequency and a degree of damping which is dependent upon the tissue compliance, weight and the mode of support of the heels and head. The natural frequency falls in the frequency spectrum encountered in ballistocardiography which introduces distortion which cannot be eliminated. Furthermore, the degree of damping is variable and the subject is well underdamped which contributes to the magnitude of distortion.

11. When a subject is placed on a Starr or Nickerson table, it is impossible to prevent the subject from exhibiting a natural period of vibration independent of the table no matter how well the body is supported or clamped for the minute ballistic movements. Therefore, the response characteristics of the body must be vectorially added to the characteristics of the table. In such case, table distortions are introduced.

12. Extreme caution must be taken to keep the compliance high when the cross bar across the subject's shins is mechanically coupled to a stationary object. Too low a compliance may introduce a slight relative movement between tibia and cross bar which will distort the ballistocardiogram.

13. There is no known way of attenuating respiration weave without slightly distorting the ballistocardiogram. The parallel-T network attenuator allows a close approach only. Suspended respiration is not always practical. Therefore, with the present knowledge of the art, we believe that both methods should be made available to the operator and the distortions which may result taken into consideration.

14. In evaluating ballistocardiograms, especially when simultaneously registered with other physiologic events or when measuring the duration of ballistic complexes, the degree of subject damping and the natural frequency should be determined. With these data available, reference may be made to the graphs discussed in this paper and the approximate amount of temporal displacement of the registered ballistic complexes may be estimated and the necessary correction factor may thus be made.

15. Ballistic body movement may be measured in terms of magnitude (displacement), body speed (velocity) and the acceleration which the body experiences in attaining the speed of traversal. Mathematically, body motion may be represented as a vector quantity which possesses magnitude and direction; velocity is the derivative of displacement, and acceleration is the derivative of velocity. Each of the three forms of measurement supplies distinct and pertinent information which must be properly evaluated and interpreted. Instruments which markedly modify the intended characteristic so that the performance is neither true displacement, velocity or ac-
CELERATION will confuse ballistocardiographic interpretation.

16. Suspended table type ballistocardiographs such as the Starr and the Nickerson are generally calibrated by applying a constant force in the head-foot direction. This is known as static calibration. Due to the fact that neither the Starr or Nickerson ballistocardiographs have equal sensitivity of deflection throughout the frequency spectrum encountered in ballistocardiography, static calibration is quite meaningless for the estimation of the ballistic force which is responsible for the production of a ballistocardiographic wave.

17. A further complication in the use of static calibration is that it does not take into consideration the relative movements of the patient with respect to the suspended bed. The response characteristics of the subject must be vectorially added to the characteristics of the bed.

18. A calibration method is described for shin type ballistocardiographs but its accuracy is limited by the same factors which affect the table type ballistocardiograph.

19. Dynamic ballistocardiographic calibration is necessary for the evaluation of the ballistic forces of cardiac action. Unfortunately there is no simple clinical method known. Until such a method is developed, it is not advisable to make quantitative amplitude measurements in ballistocardiography.

20. The physical analysis presented definitely indicates that there are inherent distortions present in ballistocardiography. When making physiologic and clinical application, it is most important to keep in mind the limitations of the method. To date, it is our belief that the art has been hindered by the many fantastic claims made in the literature without due consideration to the inter-relationships of the physical and physiologic principles involved.

SUMARIO ESPAÑOL

Un análisis físico se presenta del método de Starr, Nickerson y Dock de registrar el balistocardiograma. Se demuestra que muchas formas de distorsión están presentes. Alguna de la distorsión puede estar presente debido a la instrumentación que puede ser controlada, y otras formas de distorsión son inherentes al sujeto que se está examinando, estas últimas son más difíciles de controlar y evaluar. El efecto que algunos de los variables no controlables tienen en la amplitud y posición temporal de las ondas balistocardiográficas se analizan. El estado de la normalización estática y dinámica de los procedimientos se discute. Un glosario de las voces técnicas se incluye.

GLOSSARY* OF TECHNICAL TERMS

ACCELERATION BALLISTOCARDIOM: a graphic registration of the acceleration which the body experiences. The temporal relationships of the component waves are different than in a velocity or a displacement ballistocardiogram.

ATTENUATION: the process of lessening or diminishing the amount of force or stimulation or the recorded effects.

AXIALLY: when used in ballistocardiography, the head-foot direction along the body.

CANTILEVER: a projecting beam which is supported only at one end.

COMPLIANCE: the physical yielding characteristic of matter when a force is applied to it. The compliance of matter is generally expressed in centimeters per dyne.

CONDENSER: an electrical device which is used in electrical circuits for holding or storing an electrical charge.

CRITICAL DAMPING: (See damping.) when a certain predetermined amount of friction is introduced in an object such as a ballistocardiographic table and a force is instantaneously applied to the table, the table will deflect with a dead beat; it will neither overshoot nor consume excessive time in reaching its destination.

DAMPING: the introduction of friction in a mechanical system and resistance in an electrical system.

DEFLECTION TIME: the time consumed by an object such as a ballistocardiographic table to traverse a deflection when a constant force is suddenly applied.

DISPLACEMENT BALLISTOCARDIOM: a graphic registration of the magnitude of body movement which results from cardiac action recorded with respect to time.

DYNE: a unit of force in the metric system of physical units. It is such a force that under its influence an object whose mass is 1 Gm. would experience during each second an increase in velocity of 1 cm. per second.

* This has been introduced at the request of the Editor who was of the opinion that some of the definitions would be helpful to some readers who are not familiar with the field of vibration mechanics and some of the other fields referred to in this paper.
Equalization: an electrical procedure for modifying the effective frequency response of a system in order to compensate for the inherent deficiency of one or more components of the system.

Frequency response curve: a performance graph of a vibrating system such as a ballistocardiograph table in which the axis of abscissas is expressed in cycles per second and the axis of ordinates represents the corresponding response of the table to an applied force of constant magnitude at different frequencies. A flat frequency response occurs when the vibratory response of the system does not change with the frequency of the applied force.

Frequency spectrum: the distribution of vibrating energy with respect to frequency.

Harmonic: a component vibration of a complex wave which is an integral multiple of the fundamental frequency of the complex wave. For example, a component whose frequency is twice the fundamental frequency is called the second harmonic.

Instantaneous ballistic spatial vector: a three dimensional mathematical entity which represents the magnitude and direction of a force of cardiac origin at any instant during the cardiac cycle which is applied to the body. A spatial force such as this generally has components in the head-foot, side to side and anterior-posterior directions.

Lobe ratio: the amplitude ratio of sinusoids or waves of a simple harmonic motion or a sine wave.

Logarithmic: a mathematical term which is related to the exponent of that power of a fixed number called the base which equals a given number called the antilogarithm. If a geometric curve is plotted from a logarithmic equation, it is called a logarithmic curve.

Logarithmic decrement: a logarithmic curve which diminishes with respect to time.

Microfarad: a farad is the electrical term which expresses the capacity of a condenser for storing an electrical charge. A microfarad is one millionth of a farad. The farad is too large a value to be applied to the usual electrical condenser and avoid fractional numbers.

Magnetic transducer: a device which changes mechanical movement into electricity by means of relative motion between a magnetic field and a coil of wire.

Natural frequency: the frequency of vibration or oscillation of a vibratory system at which resonance exists. The unit of measurement is the cycle per second.

Overdamping: when a force is suddenly applied to an overdamped vibratory system, the system will deflect and consume more time in reaching its destination than if the system were critically damped.

Phase shift: the displacement in degrees between two waves of the same frequency. For example, if a vibratory system is excited by a sinusoidally varying force and the resulting deflection is also sinusoidal or simple harmonic motion, and if a displacement or lag exists between the deflection and the applied force or the two sinusoids, the lag measured in degrees is the phase shift.

Photoelectric transducer: a device which converts light energy into equivalent electrical energy.

Piezoelectric transducer: a device which converts mechanical force into electricity by flexing a crystal made of material such as rochelle salt, barium titanate or quartz.

Resonant frequency: same as natural frequency.

Resonance: occurs whenever there is impressed upon a body the frequency at which it would vibrate if set in motion and then left to itself.

Respiratory weave: when a ballistocardiograph is sensitive to the very low frequencies which make up the pneumogram, a pneumogram will be superimposed upon the ballistocardiogram. The slowly changing pneumographic pattern is called the respiratory weave.

Spatial ballistic force vector: a three dimensional mathematical entity which represents the magnitude and direction of a force of cardiac origin which produces body movement in a ballistocardiographic sense.

Sinusoidal oscillation: a vibration which is simple harmonic motion. When the magnitude of the oscillation is plotted in the form of a graph against time, the resultant curve is a sine wave. An example of such motion is the movement of a pendulum.

Time constant: a mathematical term which represents the rate of charge or discharge of a condenser through a resistance. The larger the condenser and/or the resistance, the larger will be the time constant.

Transducer: a device designed to receive energy such as mechanical and convert it into equivalent energy of another form such as electrical. A microphone is a transducer, because, by means of it, acoustic energy is transformed into equivalent electrical energy.

Undamped natural period: equal to two times the deflection time of a vibratory system such as a ballistocardiograph table when a force is instantaneously applied.

Undamped: when a force is instantaneously applied to an underdamped vibratory system, the system will deflect and overshoot its destination and then return to its destination.

Velocity ballistocardiogram: a graphic representation of the speed with which the body moves as a result of the forces produced by cardiac action when recorded with respect to time.

REFERENCES

cardiac output in man, and of abnormalities in cardiac function, from the hearts recoil and the bloods impact; the ballistocardiogram. Am. J. Physiol. 127: 1, 1939.


3 Dock, W., and Taubman, F.: Some technics for recording the ballistocardiogram directly from the body. Am. J. Physiol. 142: 1, 1944.


9 Starr, I., and Rawson, A. J.: The vertical ballistocardiograph; changes in the cardiac output on assuming the erect posture, with a further theoretical study of the blood's impacts. Am. J. Physiol. 133: 461, 1941.

10 —, and —: The vertical ballistocardiograph; experiments on the changes in the circulation on arising; with a further study of ballistic theory. Am. J. Physiol. 134: 403, 1941.


15 Hertzman, V. O.: Personal communication.


Ballistocardiography: I. Physical Considerations
MAURICE B. RAPPAORT, HOWARD B. SPRAGUE and WILLIAM B. THOMPSON

Circulation. 1953;7:229-246
doi: 10.1161/01.CIR.7.2.229
Circulation is published by the American Heart Association. 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1953 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circ.ahajournals.org/content/7/2/229

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation is online at:
http://circ.ahajournals.org/subscriptions/