

# PHYSICAL BASIS OF THE LOW-FREQUENCY BALLISTOCARDIOGRAPH

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**T**HE circulation of the blood is a mechanical phenomenon in which the heart has the task of keeping this circulation going. The forces appearing in the body of man and animal displace the blood.

Ballistocardiography makes the attempt, by means of observation and analysis of the forces, the velocities, or the mass displacements, to gather information about the circulation, in particular of the stroke volume and of abnormalities of the heart or the large blood vessels. Several methods have already been developed for the recording of one of the three quantities: force, velocity, or mass displacement. The original model of Gordon<sup>5</sup> recording mass displacement was very simple: a light bed swung by four ropes from a trestle. Because the absence of damping of this "swing" and the respiration of the patient lying on it caused almost insurmountable difficulties, later investigators (Starr and associates<sup>10</sup> and Nickerson and Curtis<sup>9</sup>) proceeded to build their ballistocardiographs in a different way. They no longer recorded mass displacements. The original difficulties have been replaced by other ones, which made the analysis of the obtained curve more difficult and the apparatus more complicated.

As our aim is to develop a method that is physically understandable and reliably based we have again taken up the original, simple, and clear method of Gordon<sup>5</sup> and Henderson.<sup>7</sup>

In the following this "real" low-frequency method will be explained and its practical advantages will be accounted for.

## MECHANICS OF THE BALLISTOCARDIOGRAPH

A system (e.g., a patient) is conceived of that is unaffected by external forces. If the body (mass  $m_1$ ) exerts a force ( $K_1$ ) on an amount of blood (mass  $m_2$ ), then, according to the law of action and reaction, this amount of blood will exert an equal, but opposite, force ( $K_2$ ) on the body. So we have:  $K_1 = -K_2$  or  $K_1 + K_2 = 0$ . With  $K = ma$ , in which  $a$  is the acceleration, mass  $m$  obtains as a result of action of  $K$ , this will yield  $m_1 a_1 + m_2 a_2 = 0$ . From this it follows that  $m_1 v_1 + m_2 v_2 = c$ , in which  $v_1$  and  $v_2$ , respectively, are the velocities by which

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the masses  $m_1$  and  $m_2$  move as a result of the action of  $K_1$  and  $K_2$ ;  $c$  is a constant. From the last equation it follows that:

$$m_1x_1 + m_2x_2 = ct + d \quad (1)$$

in which  $x_1$  and  $x_2$  are the respective displacements of  $m_1$  and  $m_2$ ,  $d$  is a constant and  $t$  the time. If the initial velocity of the entire system is zero, then  $c = 0$ , that is, the center of gravity keeps the same position. We have here an infinitely rapid reaction, since at any moment  $m_1x_1 + m_2x_2 = d$  is exactly fulfilled.

In reality there is always a damping causing  $c$  to become 0, so the common center of gravity of body and blood has a fixed position in space.

If we imagine a patient on whom no external forces are exerted and who, therefore, is suspended freely, the displacement of the center of gravity of the blood with respect to its surroundings could be measured. Such a freely suspended system cannot be realized. It can be approximated, however, by admitting a weak binding of the system with its surroundings. If this binding of the system with its surroundings is stronger, something else can be measured instead of displacement of the center of gravity. In fact, the binding with the surroundings determines the natural frequency, that is, the number of oscillations per second that the system makes when it is brought out of equilibrium and left to itself afterwards.

It is the natural frequency that determines, among other things, what is measured. This will be illustrated by a few extreme cases (a, b, c), illustrations which, unfortunately, cannot be made entirely without mathematics.

The differential equation of a "swing" loaded with a patient is:

$$M \frac{d^2x}{dt^2} + \beta \frac{dx}{dt} + Dx = m \frac{d^2y}{dt^2}, \quad (2)$$

in which  $x$  is the displacement,  $\frac{dx}{dt}$  the velocity,  $\frac{d^2x}{dt^2}$  the acceleration, and  $M$  the

mass of patient and swing together.  $\beta \frac{dx}{dt}$  is the frictional force (caused by a

damping, applied purposely), and  $Dx$  is the restoring force driving the swing to its equilibrium position;  $m$  is the mass and  $y$  the displacement of the center of gravity of the blood ejected by the heart, so  $m \frac{d^2y}{dt^2}$  is the internal reaction force of that blood on the body.

(a). If there is a strong binding  $D$  of the system with its surroundings (high natural frequency) then equation (2) is reduced to:

$$Dx = m \frac{d^2y}{dt^2}. \quad (3)$$

So the recorded deviation  $x$  gives a picture of the internal forces.

(b). If the binding to the surroundings is weak (low natural frequency) then equation (2) becomes:

$$M \frac{d^2x}{dt^2} = m \frac{d^2y}{dt^2}. \quad (4)$$

From this it follows that the recorded displacement  $x$  is proportional to the displacements  $y$  occurring within the system:  $x = my/M$ .

(c). If the system is heavily damped and weakly bound to the surroundings, then equation (2) becomes:

$$\beta \frac{dx}{dt} = m \frac{d^2y}{dt^2} \text{ and } x = \frac{m}{\beta} \frac{dy}{dt} \quad (5)$$

So the measured displacement is proportional to the velocity  $\frac{dy}{dt}$  with which the center of gravity of the ejected blood is displaced as a result of the internal forces.

Starr and associates<sup>10</sup> have made the binding of their system (that is, patient and bed) to the surroundings so strong that the natural frequency is about 10 c./sec., while others (Brown<sup>2</sup> and Brown and Pearson<sup>3</sup>) go as far as 15 c./sec., case (a). So the frequency of the ballistocardiograph is high with respect to the frequency of the heart (1 c./sec.). These authors consequently measure forces (high-frequency ballistocardiography).

Nickerson and Curtis<sup>9</sup> use a much weaker binding to the surroundings. The natural frequency is about 1 c./sec. This binding is too weak for measuring forces. It is still too strong, however, for the measuring of displacement; for the frequency is neither high nor low with respect to the frequency of the heart. As the damping in their system is not much more than critical (this case would be c) it is not quite clear what, exactly, is recorded.

The natural frequency of our swing is even lower than in Nickerson and Curtis' method, namely with or without loading 0.3 c./sec. (case b). Consequently we measure, with a reasonable approximation, the displacement of the center of gravity of the blood, resulting from the forces (low-frequency ballistocardiography). This has been applied only by others, as far as we know, many years ago (Gordon<sup>5</sup>, Henderson<sup>7</sup>). As the high-frequency ballistocardiograph measures forces and the low-frequency one displacement, the curve recorded by the first type of ballistocardiograph will be the second derivative of the curve recorded by the second type. Conversely, the twice integrated curve of the high-frequency ballistocardiograph is the curve of the low-frequency ballistocardiograph.\*

If we make records that reproduce the displacement of the center of gravity (case b), the velocity of this displacement (case c), or the internal forces (case a), it is, in general, incorrect to give the same names to the peaks of the different curves. For, as the example in Fig. 1 shows, in the different cases the peaks may appear not only on quite different points of time, but their meaning and their number also may be quite different.

\*When integrating the high-frequency ballistocardiogram it should be borne in mind that, before each integration, the base line of the curve has to be chosen in such a way that the area between the curve and the base line on the positive side for one complete heart beat is equal to the area on the negative side.

It has been stated that if the movement of the system caused by the internal forces is to be exactly measured, this system should not be bound to the surroundings. The low-frequency ballistocardiograph is not without binding. (The natural frequency is after all 0.3 c./sec., instead of 0 c./sec.) The consequence is that the lowest frequencies which may occur in the movement of the blood are partly or entirely eliminated. All higher frequencies, however, are completely represented (see the frequency characteristic: Fig. 2). When we compare this with the frequency characteristic of a high-frequency ballistocardiograph, it appears that the low frequencies entirely or partly disappear into a larger range than is the case with the low-frequency ballistocardiograph. The strong binding of the high-frequency ballistocardiograph to the surroundings is the reason why it does not react to these low frequencies. At high frequencies another decrease occurs (Fig. 2). At these frequencies the tissue of the patient acts as a damping.

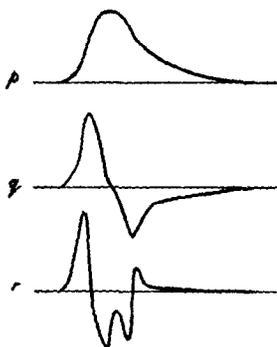


Fig. 1.

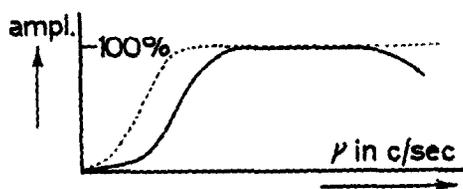


Fig. 2.

Fig. 1.—A curve chosen arbitrarily with its first and second derivative.  $p$  = coordinate;  $q$  = velocity;  $r$  = acceleration (force).

Fig. 2.—Frequency characteristics of a high-frequency (solid line) and a low-frequency (broken) ballistocardiograph (schematic).

It is clear that the difference in the frequency characteristics, as regards the low frequencies, is important when attention is paid to the respiration frequency (about 0.3 c./sec.). With the high-frequency ballistocardiograph this frequency is hardly represented, whereas it is clearly shown by the low-frequency one. For this reason it is necessary that the patient, during the recording with the low-frequency ballistocardiograph, holds his breath or that the influence of respiration is eliminated in some other way.

It has already been pointed out that the high-frequency ballistocardiograph measures forces, and the low-frequency one measures displacements. If these two types of ballistocardiograph were capable of measuring entirely correctly, they would be equal in value, because the one curve could be obtained by a mathematical operation from the other.

The curves of the high-frequency ballistocardiograph have a great uncertainty on account of the patient's movement with respect to the bed. The high-frequency ballistocardiograph is strongly bound to the surroundings, while at the same time, it weighs in the order of 70 kg. The low-frequency one has a very weak binding and weighs about 5 kg. In consequence of these two differences, the patient on the high-frequency table is far less firmly connected to it than on the low-frequency swing. With the high-frequency ballistocardiograph the binding of the patient to the bed is hard to oversee. So with the low-frequency ballistocardiograph we know more precisely what is measured than with the high-frequency ballistocardiograph.

Perhaps the simplicity of the curves obtained with the low-frequency ballistocardiograph is another advantage over the curves obtained with the high-frequency one.

Furthermore low-frequency ballistocardiography is simpler, and the displacements of the swing are greater; hence, the necessary amplification is smaller.

#### CLOSER EXAMINATION OF THE LOW-FREQUENCY BALLISTOCARDIOGRAPH

Starr and associates<sup>10</sup> do not damp their ballistocardiograph on purpose. Damping our swing has turned out to be a necessity. Not damping it would make an accurate recording impossible on account of oscillations performed by the swing after all kinds of disturbances. From the following calculations it will appear that the recorded curve has been distorted more according as the damping is heavier. The latter therefore should be as weak as admissible. From experiments it became clear that good records could still be made when the swing "overshoots" to 25 per cent. The swing after a disturbance will then do some oscillations in its natural frequency. This damping is strong enough to prevent these oscillations from lasting too long. As will be described further on, this "overshooting" can be regulated by adjusting the damping.

Any periodic phenomenon can be thought of as having been built up from a number of sinusoids, namely, of a first harmonic having the frequency of the phenomenon and the higher harmonics belonging to it. The damping shifts each sinusoid in time (phase shift) and, moreover, changes its amplitude. The changes are dependent on the frequency of the sinusoid in question (so the phase shift and change in amplitude of the first harmonic and a higher harmonic are different). The degree of damping determines how great are the phase shift and change in amplitude of every frequency. The weaker the damping, the smaller the distortion of the ballistocardiogram (Fig. 5).

In order to calculate this distortion we must know  $\beta$ . The latter can be found from the differential equation by determining the relation between damping and "overshooting." If the swing is less than critically damped, then, when displaced from its equilibrium position E (Fig. 3) and released without initial velocity, it oscillates about the latter with decreasing amplitude.

The ratio  $x/x_0$  (Fig. 3) of the amplitudes in two consecutive inversion points is called the overshooting.

The relation between damping and overshooting  $x/x_0$  we find from the differential Equation (2):

$$\frac{x}{x_0} = e^{-\frac{\pi}{\sqrt{1/\delta^2 - 1}}} \quad (6)$$

In this equation  $\delta$  is the ratio of the damping  $\beta$  to the critical damping (Fig. 4).

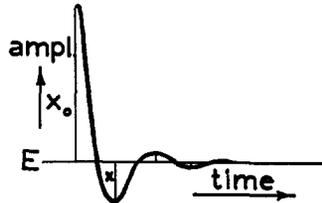


Fig. 3.—The curve written by a swing, damped periodically (overshooting 25 per cent).

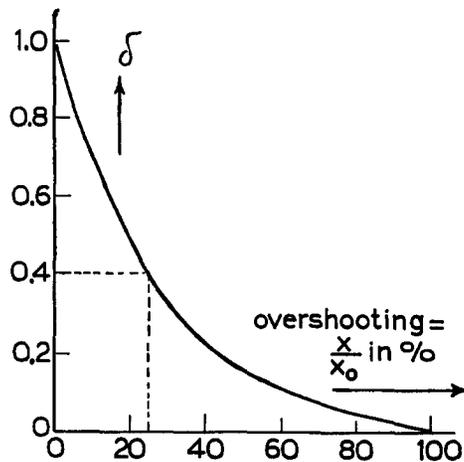


Fig. 4.—The relation between damping and overshooting.

For the phase shift  $\varphi$  we find

$$\operatorname{tg} \varphi = \frac{2 \delta \nu_0 \nu}{\nu_0^2 - \nu^2} \quad (7)$$

in which  $\nu_0$  is the natural frequency of the loaded swing and  $\nu$  is the frequency of the internal force.

From the differential equation we find also the amplitude

$$x = \frac{m}{M} \frac{\nu_0}{\sqrt{\left(1 - \frac{\nu_0^2}{\nu^2}\right)^2 + 4\delta^2 \frac{\nu_0^2}{\nu^2}}} \quad (8)$$

The phase shift as well as the amplitude can now be expressed numerically, as  $\delta$  can be calculated from the measured overshooting. From Fig. 4 it appears that with an overshooting of 25 per cent (the one usually applied by us)  $\delta = 0.4$ . The natural frequency of the loaded swing ( $\nu_0$ ) is 0.3 c./sec. The phase shift and the amplitude as functions of the frequency ( $\nu$ ) of the internal force are graphically represented in Fig. 5. In the same figure, the phase and amplitude characteristics obtained with other degrees of damping also have been drawn. It shows immediately that with the weaker damping the phase shift will be smaller. With stronger damping, however, the amplitude characteristics will be more favorable. As a compromise we chose a damping with 25 per cent overshooting. It is clear that with this overshooting very little distortion occurs in frequencies from which our curve has been built up.

If no damping were used there would be according to equation (7) no phase shift, but according to equation (8), however, there is change in amplitude.

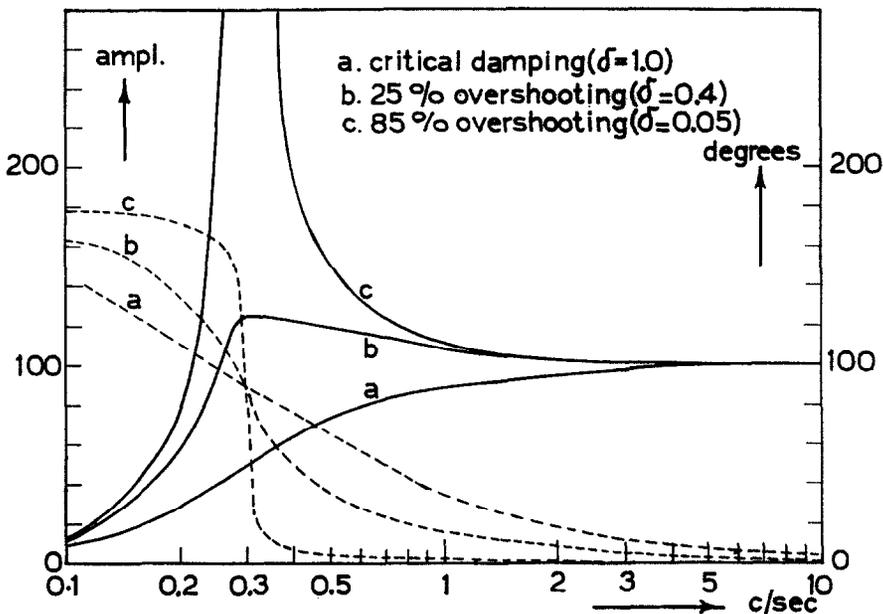


Fig. 5.—Frequency characteristics (solid line) and phase characteristics (broken) of the low-frequency ballistocardiograph with different dampings.

#### THE RELATION BETWEEN DISPLACEMENT OF CENTER OF GRAVITY AND THE DISTENSIBILITY OF THE BLOOD VESSELS

With every contraction of the left ventricle blood is pushed into the aorta. The latter is temporarily distended by it. This distention starts at the heart, goes on to the periphery, and is damped out. When considering some small part of an artery we find that during distention there is more blood in it than when the distention has passed. This distention goes along the artery and acts as if an extra mass were moving along the artery with the velocity of the pulse wave.

This is true for the aorta and for all other arteries. So in consequence of the contraction of the two ventricles and the distensibility of the arteries, a periodic mass displacement occurs in the body and hence "displacement of the center of gravity."

If the patient is laid on a low-frequency ballistocardiograph, then, because the common center of gravity keeps the same position, the movement of the whole body, followed more or less by the swing, can be recorded. (Fig. 7 is an example.)

We have seen that the mass displacement on account of the pulse wave gives a displacement to the body in the opposite direction. A constant filling of a blood vessel would not give the swing a displacement even when the blood is moving, as no change in mass distribution in the blood vessel would occur.

The pulse wave is found mainly in the aorta and the pulmonary artery as they distend most, and to a lesser degree also in their large branches. As there is a venous pulse the veins also contribute, but how much? Also, the displacement of tissue on account of the pulse wave and the displacement of the heart cause mass displacement.

Every mass displacement along each blood vessel in which this phenomenon occurs causes an opposite displacement of the swing. The sum of the different effects is measured. That is the reason why analyzing the curve is difficult. From this it follows that the form of the curve is determined for the greater part by the anatomical structure of the patient.

#### THE INSTRUMENT

Our ballistocardiograph consists of a bed (200 by 80 cm.) suspended from the ceiling on four wire ropes of equal length (300 cm.) and 12 mm.<sup>2</sup> in diameter. The wire ropes have been fixed to points of suspension in such a way as to run parallel. The advantage of parallel ropes is that the bed always keeps the same position regardless of the place the patient occupies on it.

The bed consists of a steel tube bent rectangularly. In this frame a piece of canvas has been stretched. At the foot-end there is a vertical plate enabling the patient's feet to make firm contact and securing a better fixation of the swing to the patient. An adjustable damping device is located at the head-end and foot-end. The damping is supplied by making horizontal aluminum plates of 14 by 8 cm. move in shallow boxes filled with treacle. These plates are strongly attached to the frame, while the distance, between each plate and the bottom of the box belonging to it, is adjusted by moving the box containing treacle vertically. A stronger damping can be obtained by decreasing the distance between plate and bottom of the box. In that case, with the same velocity, a greater gradient in velocity is caused in the treacle between plate and bottom and, therefore, a stronger damping. Conversely the damping can be made weaker by increasing the distance between plate and bottom.

The total mass of the swing, the attached footplate, and the damping device is 5 kg. The damping is adjusted in such a way that the swing with patient overshoots 25 per cent ( $\delta = 0.4$ ) and then the movement in the longitudinal axis

of the patient is recorded.\* A weaker damping gives too much waving in the curves, while on the other hand, the damping should be kept as light as admissible to make the distortion as small as possible. With every patient the damping has to be adjusted anew, because there will be a difference in the mass of this patient plus swing, thus, in the strain of the wire ropes and in the bending of the swing, and hence, in the thickness of the layer of treacle.

In order to record the movement of the ballistocardiograph we have used until now two methods (out of many possibilities) which we shall call (a) the mirror method and (b) the phototube method.

(a) *The Mirror Method.*—A small brass plate is soldered to a vertical steel wire which is stretched between two fixed points. On this plate a little mirror is fixed, and in the plate a number of holes are drilled in a horizontal line. If the brass plate is first turned in such a way around the wire as an axis of rotation, so that a thread now connecting swing and wing is taut, then the to-and-fro movement of the swing will cause the mirror to turn round. (The directive force, caused by the steel wire and acting on the brass plate, is strong enough to record even the highest frequencies that are of interest.) The rotation of the mirror and with it the swing movement can be recorded; the mirror is illuminated from a fixed direction by a slitlike source. The image of the slit, formed by the reflected lightbeam is received by a film moving perpendicularly to the to-and-fro movement of the image of the slit. The amplification can be regulated by making use of different holes drilled in the brass plate. It is equal to twice the distance torsion wire-film over the distance torsion wire-hole in the plate. For testing purposes the swing may be given a known displacement and the appertaining deflection of the light spot recorded. The usual amplification is about 200 times.

With this method the distortion of the curve is negligible and the apparatus is very simple.

(b) *The Phototube Method.*—A circuit is formed, consisting of a phototube, a voltage supply, and a resistance. If light is made to fall on the phototube, a current will start in the circuit. Between the terminals of the resistance a voltage will arise that is proportional to the amount of incident light. If the amount of light incident on the phototube is variable, then the current in the circuit will vary with it, and hence the voltage over the resistance. The optics belonging to the phototube are schematically represented in Fig. 6.

The filament of the illuminating lamp is projected on the phototube, so as to eliminate the influence of possible differences in sensitivity over the surface of the phototube. If, in fact, a part of the lightbeam is screened off in the place of the arrow in Fig. 6, a complete image of the filament still is obtained, but this image is more feebly illuminated over the entire surface. Moreover, with this optical arrangement the lightbeam is homogeneous in the neighborhood of the arrow.

A screen is attached to the swing. When the swing is in zero position, it has its edge in about the middle of the lightbeam, at the place indicated by the arrow

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\*The device used also enables recording the lateral movement.

in Fig. 6. In this place we have the image of the first lens opening, a square diaphragm (size 26 mm.) giving a square image. (The image is one-fourth the size of the object in order to obtain a greater sensitivity). When the swing is moving, then alternatively more and less light is transmitted to the phototube. In this way variations of voltage on the resistance in the phototube circuit are obtained, which, connected with an electrocardiograph, make the latter write a curve representing the movement of the swing.\*

As existing types of electrocardiographs with a sufficiently long R-C time can be made use of, this method of recording is directly suitable for application in hospitals. By means of suitable apparatus ballistocardiograms can be made synchronous with electrocardiograms and phonocardiograms.

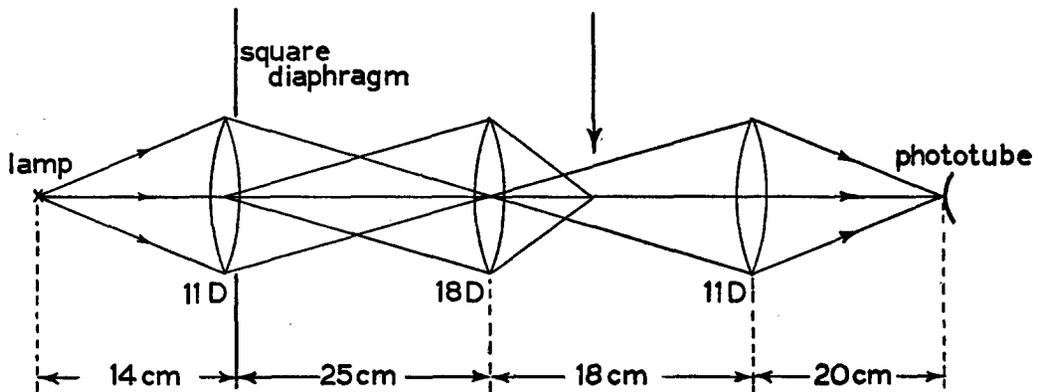


Fig. 6.—The optics of the phototube.

The homogeneity of the lightbeam has been examined. For this purpose the phototube was replaced by a thermopile, connected with a galvanometer. A screen (in the place of the arrow in Fig. 6) was moved through the beam with equal steps. At every position of the screen the galvanometer was read. From this it appeared that the middle 4 mm. out of the total width (7 mm.) were homogeneous within 1.5 per cent. This not only holds for the place of the arrow but also for the places 2 cm. in the direction of lamp and phototube, respectively. So on adjusting the screen it is not necessary to take care that the screen is exactly in the middle of the lightbeam and in the place of the arrow.

The sensitivity of the entire design (i.e., inclusive of the amplification of the electrocardiograph) can be calibrated by fixing a thin wire (0.1 mm. in diameter) to the screen in such a way that it comes into the beam parallel to the vertical edge of the screen. (The diameter of the wire has been made this small, because the movement of the ballistocardiograph with respect to the heartbeat is not more than about 0.1 mm.) By pressing a photoshutter the wire will suddenly spring out of the lightbeam, making the electrocardiograph record a deflection that corresponds with the swing's movement over a fixed distance, namely, the thickness of the wire. In this way, the sensitivity can be calibrated during the recording.

\*An electrocardiograph does not react on the constant input voltage caused by that part of the lightbeam which is not screened off at any moment by the movement of the swing.

## RESULTS OF THIS METHOD

Figures 7 and 8 give the curves of different, normal subjects holding their breaths; H is the headward direction of the swing-movement; B, C, D . . . are the names of the peaks. These curves represent the recording of the movement of the swing and not the movement of the subject; that is, in using the mirror method the thread causing the mirror to move is not attached to the subject itself, but to the swing. With the phototube method the screen is fixed also to the swing. Recording directly from the subject is preferable, in principle, to recording from the swing, because the swing does not follow accurately the movement of the subject lying on it. It appeared, however, that in general the patient cannot lie sufficiently still to permit obtaining a record directly

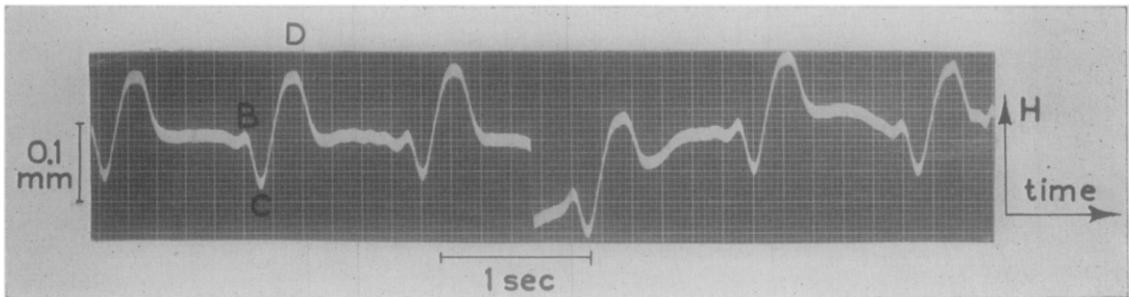


Fig. 7.—Ballistocardiogram with calibration of the sensitivity, recorded by an electrocardiograph.

from him. Hence records were obtained of the movement of the swing. So the error arising from the fact that the swing does not follow the body exactly is included in our curves. In order to determine how great this error is, synchronous records were taken of the movement of the swing with respect to the surroundings and of the swing with respect to the subject. In order

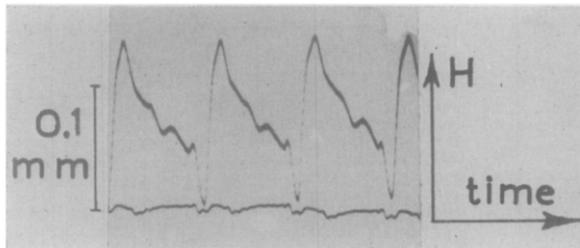


Fig. 8.—A ballistocardiogram synchronous with the movement of the swing, with respect to the patient, recorded by the mirror method.

to record both movements, a second mirror is fixed to the swing. During this recording the subject had a helmet on his head (the band round the chin as tight as possible). In this helmet a hook was soldered to which can be attached the thread transmitting the movement of the swing with respect to the subject to the brass plate of the mirror system. By the mirror method this movement is recorded on the same film as the common movement of the swing with respect to

the surroundings. With the original, rather heavy, swing (12 kg.) the relative movement (that is, swing with respect to subject) may be as much as 30 per cent of the movement of the swing. If the swing is made lighter, it will be able to follow the subject more accurately; therefore, the mass of the swing has been made as small as possible (5 kg.). By these means the relative movement could be expected to be  $\frac{5}{12} \times 30$  per cent = 12 per cent. If, moreover, the swing is

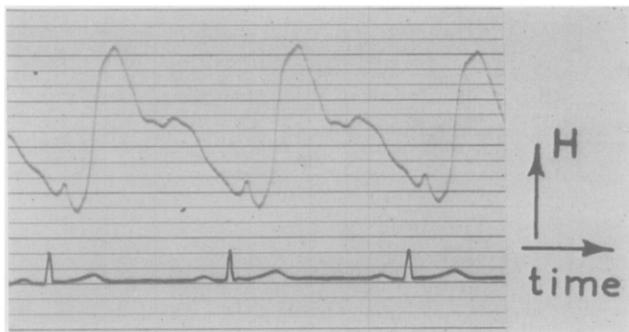


Fig. 9.—A ballistocardiogram synchronous with electrocardiogram.

better attached to the subject, then the relative movement for this reason will be less. The footboard mentioned earlier with which the patient's feet are in firm contact has been fixed for this purpose. Moreover, the damping has to be as weak as possible. The relative movement thus is reduced to about 6 per cent. Figure 8 shows a normal ballistocardiogram and the relative motion belonging to it, synchronously recorded by the mirror method.

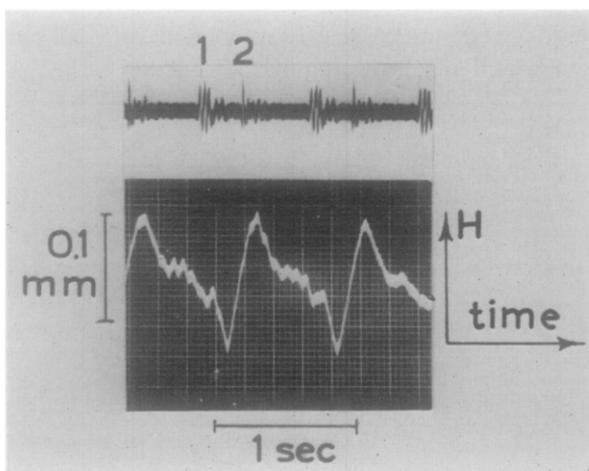


Fig. 10.—Synchronous curve of a ballistocardiogram and phonocardiogram.

Examples of synchronous records of ballistocardiogram with electrocardiogram or phonocardiogram are reproduced in Figs. 9 and 10. For instance these records can be made use of to settle the question whether the little peak (B) that is to be seen at the beginning of the heart beats in many ballistocardiograms (Figs. 7 and 8) appears at the beginning or at the end of a heart beat.

## SUMMARY

A ballistocardiograph has been constructed which is bound so weakly to the surroundings that the displacement of the center of gravity of the blood, caused by the action of the heart, can be measured.

Damping the ballistocardiograph appeared to be necessary. The influence of the binding to the surroundings and of the damping has been examined.

Records can be made by an electrocardiograph. During the recording the breath is held.

The obtained curve may be compared with others, generated by the heart action.

High-, middle-, and low-frequency ballistocardiographs have been compared theoretically.

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