Design of an Ultra Low Frequency Force Ballistocardiograph on the Principle of the Horizontal Pendulum

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A low frequency ballistocardiographic system based on the principle of the horizontal pendulum is described. By increasing the coupling of the body to the bed and by the use of an extended frequency range accelerometer, ballistocardiograms having clearly defined high frequency components were recorded. The physical principles of such a system are briefly reviewed.

The classic studies of Starr and associates,1 demonstrating that the displacement of a high frequency ballistocardiograph is related to the acceleration of cardiac ejection, opened a new and important field of physiology. The unique information so gained is perhaps more closely related to the functional status of the myocardium than any other accessible measurement. Recent analyses by von Rittern,2 Burger and co-workers,3 and Talbot and Harrison,4–6 have shown that the acceleration of ultra low frequency or aperiodic ballistocardiographs may yield the same information over a wider frequency range and with less distortion due to the resonant properties of the body. Using the basic concepts outlined in these studies, we have devised a system that records high frequency force components not visible in previously published tracings. These high frequency components have definite physiologic significance of fundamental importance as will be presented in a subsequent communication. The purpose of this paper is to describe the system used to obtain the extended frequency response necessary to record these components, and to present its physical validation. In addition, typical records are presented.

The factors to be considered in the design of a low-frequency ballistocardiograph include the following:

1. The natural frequency of the system, which must be significantly lower than the frequencies of the forces to be measured.
2. The damping of the system that can influence both the lower and the upper frequency ranges.
3. The relative motion between the body and the bed. This factor is of the utmost importance in determining the recording fidelity of the instrument in the upper range of frequencies.
4. The resonant characteristics of the ballistocardiograph. There should be no tendency of the ballistocardiograph or any of its components to resonate within the range of frequencies of the applied forces.
5. The motion should be sensed by an instrument that can give an undistorted record of acceleration throughout the entire spectrum of forcing frequencies.

Method

A seismographic suspension* (i.e., a horizontal pendulum) was adapted to ballistocardiography so that the above requirements were met (figs. 1 and 2). This ballistocardiograph consists of a light platform suspended from a wall by light cables but pushed away from the wall by an arm on a ball-socket joint. The suspension is such as to create a nearly horizontal pendulum having a very long period. The platform is an aluminum honeycomb panel trimmed to the general contour of the body for the sake of lightness. Its weight so trimmed is 8 pounds. The cables are \( \frac{3}{64} \) -inch stainless steel. The cables are attached below to the supporting V arm, which is

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† Available from the Honeycomb Corporation of America, Bridgeport, Conn.

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of 1-inch aluminum alloy tubing. These cables are suspended by a double ring hinge that projects 2 inches farther from the wall than the lower joint.

This forward displacement of the upper bearing is so designed in order to allow slow periodic motion of the bed. If the 2 bearings were exactly vertical the bed would be aperiodic. However, since such a state would be extremely difficult to maintain, the periodicity is desirable for the sake of stability.

The length of the supporting tubing, which is the pendulum arm, has 2 important effects. The period of a horizontal pendulum is determined by the angle between a vertical line and a line connecting the upper and the lower hinges and by the horizontal length of the pendulum arm. By adjusting either or both of these factors, the period of the pendulum may be controlled at will, including theoretic aperiodicity. The relationship of the factors is expressed by the formula:

\[ f = \frac{1}{2\pi} \sqrt{\frac{g}{l} \sin \theta} \]

where \( \theta \) is the angle from the vertical of a line between the 2 hinges, \( g \) is the acceleration due to gravity, and \( l \) is the length of the horizontal pendulum arm. The second major consideration in the length of the pendulum arm is the effect of the circular motion of the pendulum upon the transmission of the linear force. The actual motion imparted to the bed by the circulatory force is so small compared to the radius employed (30 inches) as to render the distortion negligible.

The natural frequency of the bed should be significantly below the lowest frequencies of force encountered. At a degree of damping considerably higher than that present in this system, Burger found a natural frequency of 0.3 cycle per second entirely adequate. The frequency of this bed as described is 0.1 c.p.s., with a damping factor of 0.026. The lower end of the undistorted frequency response range of this physical system would then be less than 0.5 c.p.s. For further details on this aspect of the problem the analysis of Burger should be consulted.3

Relative Motion of Body and Bed. In 1953 von Wittern described his ballistocardiographic system, including a discussion of the factors affecting the frequency response range of any low frequency ballistocardiograph.2 He defined 2 frequencies, \( f_1 \) and \( f_2 \), between which acceleration recorded from the bed is proportional to the circulatory forces. Similarly, for ballistocardiographic frequencies between \( f_1 \) and \( f_2 \), velocity from the bed is proportional to the momentum of the circulatory mass, and displacement of the bed is proportional to the mass displacement of the circulatory mass. (These assertions ignore whatever distortion occurs in transmission through the internal body network.) Therefore, \( f_1 \) should be lower than the lowest forcing frequencies to be measured, and \( f_2 \) higher than the highest forcing frequencies to be measured. Otherwise, the record would be distorted in amplitude and time.

The \( f_1 \) frequency is very close to the natural frequency of the loaded bed. This frequency may be set at any desired level in a horizontal pendulum, and, therefore, is no problem at all. The present bed has a natural frequency of 0.1 c.p.s., loaded or unloaded.

The \( f_2 \) frequency is the frequency of relative motion between the body and the bed. The frequency of any vibratory system depends upon 2 factors—the mass that is oscillating and the strength of the spring involved, according to the relation:

\[ f = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \]  

(1)

where \( f \) = frequency, \( k \) = spring constant, \( m \) = mass involved. If the subject lies on a fixed platform:

\[ f_b = \frac{1}{2\pi} \sqrt{\frac{k_b}{m_b}} \]  

(2)

where \( f_b \) = natural frequency of body on a fixed platform, \( k_b \) = spring constant of body, \( m_b \) = mass of body.

The \( f_b \) frequency has been found to be about 4 or 5 c.p.s. on a fixed platform when no footboard or shoulder straps are used. If, however, both shoulder straps and footboard are used, \( k_b \) is quadrupled,
Fig. 2. A. Top view. B. Detail of bearing. C. Front view. D. Side view. The panel of honeycomb material is of Alclad aluminum plates, 0.012-inch with 3/8-inch hexagonal honeycomb, over-all thickness 1 inch. The support is 1-inch by .049-inch aluminum alloy tubing and the cable is 3/64-inch stainless steel. The ball is a 3/4-inch steel bearing welded to a steel V tip for insertion into the tubing. The socket is drilled bronze. The footboard brace is of 3/8-inch aluminum rod. The cables are attached above to a steel ring that is interlocked with an eyebolt attached to the wall. The total cost of the material is approximately $80.00.

approximately, so that \( f_0 \) is raised to about 9 c.p.s. If the body lies on a light freely movable platform instead of on a fixed platform, the physical situation exists in which a large mass (the subject) is connected to a small mass (the bed) by a spring (the body tissues). If the 2 masses vibrate relative to one another, as an approximation the large mass may be assumed to be fixed, with the small mass vibrating upon it through the connecting spring.

Mathematically:

\[
f_2 = \frac{1}{2\pi} \sqrt{\frac{k_b}{m_t}} \tag{3}
\]

where \( f_2 \) = frequency of relative motion between the 2 masses, \( k_b \) = spring constant of body, \( m_t \) = mass of bed.

The spring constant, \( k_b \) which is difficult to determine directly, may be eliminated from the above equation by dividing equation 3 by equation 2 and simplifying:

\[
\frac{f_2}{f_0} = \frac{1}{2\pi} \sqrt{\frac{k_b}{m_t}} \text{ or } f_2 = f_0 \sqrt{\frac{k_b}{m_t}} \tag{4}
\]

The above derivation is essentially the same as that of von Witten, but arranged so as to show that \( f_2 \) is the frequency of relative motion between the body and the bed. The formula shows that for \( f_2 \) to be as high as possible: (a) \( f_0 \) should be as high as possible (i.e., footboards and shoulder straps should be used); and (b) the mass of the bed should be as small as possible. The horizontal pendulum bed being described is provided with a footboard and shoulder straps. The total weight of the bed is 12 pounds. The \( f_2 \) then, for a 192 pound man, could be calculated:

\[
f_2 = 9 \sqrt{\frac{192}{12}} = 36 \text{ c.p.s.}
\]

The upper limit of frequency fidelity on our system would range then from about 30 c.p.s. for a 120-pound subject to over 40 c.p.s. for a heavy subject.

It would, of course, be preferable to determine \( f_2 \) experientially, rather than to rely on mathematical calculations. We have attempted an experiment for determination of \( f_2 \) on several subjects, but have encountered difficulties such that the results cannot be presented with complete confidence. If the ballistocardiographic system loaded with a subject is oscillated with steadily increasing frequency, and velocity or force recorded as the frequency of the forcing oscillation approaches the \( f_1 \) point, a "node"
should appear—that is, the recorded amplitude should sharply increase, followed by a "roll-off" as the forcing frequency exceeds \( f_2 \). This procedure has been carried out with a variety of mechanical oscillators applied to the ballistocardiographic system in various ways. With the use of the mercury capillary accelerometer and a heavy subject with a calculated \( f_2 \) over 40 c.p.s., no node and no roll-off were found at forcing frequencies rising from 5 to 40 c.p.s. With lighter subjects a node was invariably found quite close to the calculated \( f_2 \), but other nodes were also present at lower frequencies, so that no one node could be singled out as indubitably the \( f_2 \) point. It was found that the node thought to represent the \( f_2 \) point behaved as predicted with varying body weights, bed weights, and presence and absence of shoulder blocks or footboards. It was therefore considered that \( f_2 \) had been experimentally determined and found to agree with the calculated \( f_2 \), but the presence of one or more unexpected nodes at lower frequencies made certainty impossible. The presence of these nodes (which were actually of small magnitude) is important in itself. These nodes may well represent resonant frequencies of various parts of the body, such as the head or arms, vibrating independently of the body as a whole. Such a phenomenon has been considered by Talbot and Harrison\(^4\) previously. These nodes demonstrate that at certain forcing frequencies the recorded ballistocardiographic waves will be subject to a certain amount of distortion, which is at present unavoidable. No one has been able to devise a method to force the body to vibrate as a unit at all frequencies of ballistocardiographic interest.

The vast differences in the contour of the ballistocardiographic waves with varying \( f_2 \) points is demonstrated by figure 3. The \( f_2 \) frequency may be gradually lowered on the same subject by removing shoulder blocks, footboards, and then by progressively increasing the mass of the bed. The progressive distortion of the force patterns results from loss of high frequency components and resonance of certain waves at various \( f_2 \) points. Thus we are able to duplicate the tracings of other force ballistocardiographs by deliberately reducing the frequency fidelity of this system.

**Resonance of System.** Distortion of the acceleration tracings in the above system can be produced by resonances of the ballistocardiographic table or of its supports, if these resonance points are within the ballistocardiographic frequency spectrum. That is, frequency response at 17 c.p.s. The top tracing was from the mercury capillary accelerometer. Note especially the G-H amplitude, the clear separation of 2 J peaks, and the notching of the H-I downstroke in the top tracing. None of these details are present in the lower record. Preliminary observations have indicated physiologic significance of such high frequency forces.

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**Fig. 3 Top.** A series of force ballistocardiograms made on a patient with mitral stenosis. The \( f_2 \) point (the frequency of relative motion between the body and bed) has been progressively lowered to demonstrate the distortions in amplitude, time, and contour that result when the \( f_2 \) point is low enough to be within the frequency range of ballistocardiographic interest. (The \( f_2 \) point may be lowered by omitting shoulder straps, or footboard, or both, and by adding sandbags to the ballistocardiographic bed.) In A, the calculated \( f_2 \) was 30 c.p.s. In B through H, the calculated \( f_2 \) points are approximately 22, 17, 13, 10, 8, 7, and 6 c.p.s, respectively. Note the progressive disappearance or distortion of some of the distinctive high frequency features of A. The arrows represent the onset of the QRS complexes.

**Fig. 4 Bottom.** Ballistocardiograms from a young woman 2 weeks after mitral commissurotomy. The simultaneously recorded ballistocardiograms above exhibit marked difference in relative amplitude of some of the deflections, as well as significant phase shift. The lower record was made by a commercially available accelerometer having a sharp roll-off of the
If a force of varying frequency is applied to the bed, nodes are produced at the frequencies of natural resonances within the system. These resonances will amplify and distort in time any force having a similar frequency. Since any metal surface and any supporting wire has a resonant frequency, there will invariably be ballistocardiographic distortions at these frequencies. In the proposed system, this difficulty available accelerometer having a sharp roll-off of the has been minimized by using a plate of aluminum sandwich construction that has a natural frequency of about 50 c.p.s., which is above the frequency of relative motion, as is the natural frequency of the supporting wires with the tension of the body on the table. This has been demonstrated experimentally by placing a variable frequency resonator on the ballistocardiographic bed and recording at rates up to 50 c.p.s. Below this point the amplitude varies directly with force, illustrating the absence of significant distortion due to resonance of the system.

**Transducer.** For adequate registration of the acceleration ballistocardiograph a pickup is needed that is quantitatively accurate through the frequencies of the ballistocardiographic spectrum, without distortion of either high frequency or low frequency impulses. A satisfactory accelerometer for this system is the electrokinetic device described by Elliott and co-workers. It consists of a capillary tube with alternate cells of mercury and sulfuric acid generating an electric current proportional to acceleration by the changing shape of the interfaces. This unit has been found to be easy to construct, sensitive beyond requirement, and free from distortion. Various commercial accelerometers tested in this laboratory have been found to be less satisfactory. One should bear in mind that the upper limit of frequency response of a commercial accelerometer as given by the manufacturers applies only to sinusoidal forces, and not necessarily to the transient forces encountered in ballistocardiography. The desirable properties of the mercury accelerometer include a flat frequency response far beyond ballistocardiographic requirements, absence of phase shift, a satisfactory output, adequate stability, and simplicity. The importance of an adequate accelerometer can be seen in figure 4, in which tracings on the same subject are compared, showing a tracing using the mercury accelerometer and another accelerometer with an upper frequency response of 17 c.p.s. As can be seen, high frequency components are not registered by the commercial accelerometer, which rolls off at 17 c.p.s. There is also an appreciable phase shift.

In construction of the accelerometer, it has been found that if the output amplitude is sufficiently synchronous with the delayed closure of the pulmonary valve. In tracing H, aortic closure (AC) and pulmonic closure (PC) have been marked. These times were obtained from simultaneously recorded carotid pulses and heart sounds.
high, distortion from electric interference is minimized.*

Results

The force ballistocardiograms obtained by this system have the general configuration of records published from other ultra low frequency systems except for the presence of additional high frequency forces. The records have demonstrated a very consistent pattern in young normal subjects. An example of such a ballistocardiogram is shown in figure 5. The labeled points have been present in all normal subjects thus far studied.

Many of these points are of relatively high frequency and will not be seen in clarity if the frequency response of the system is appreciably less than the one described. The importance of this factor is clearly illustrated in figure 3.

The ballistocardiograms of various subjects with cardiovascular abnormality have been of great interest. In general it would appear that many aberrations in cardiovascular physiology are manifested by forces of high frequency. Although experience to date is too limited for any conclusion as to the significance of such high frequency phenomena, it would appear obvious that in the present state of ballistocardiography it is desirable to record all forces in their true proportion. A few examples of abnormal contrasted to normal ballistocardiograms are shown in figure 6.

Discussion

The upper range of linear response of any ballistocardiographic system is limited by the frequency of relative motion between the body and the bed. As previously mentioned, this frequency is a function of the elastic coupling of the body to the bed, the mass of the body, and the mass of the bed. This frequency can be raised by either lowering the mass of the bed or increasing the effective elastic springs of the body. The latter can be accomplished by footboards and by shoulder blocks or shoulder straps. The latter approach has been emphasized in this ballistocardiograph because of the engineering difficulties, especially resonances, encountered with the ultra light platforms. Published tracings from ultra light systems having a theoretically wide frequency response have failed to show the high frequency components that have been present with the system here reported. Some reasons for these differences may be the increased coupling obtained by the application of tight shoulder straps and the accelerometer with a satisfactory frequency response used in this study.

The significance of the increased frequency response range of this instrument depends upon the importance of cardiovascular forces of the higher frequency range. Data thus far obtained by such a technic have led to a conviction that highly significant forces in certain abnormal states will be found in the frequency range of 20 to 35 c.p.s. When the frequency response of the ballistocardiograph is deliberately lowered to 20 c.p.s., marked "normalization" of grossly abnormal patterns has been repeatedly observed (fig. 3). It is evident that exaggeration of any force by resonance within the ballistocardiographic spectrum will lead inevitably to inaccuracy of interpretation of such a force. The various possibilities considered here, including the relative frequency of the body and bed, the suspension, and the bed itself, have all been shown experimentally to be capable of marked distortion of the ballistocardiogram. Two factors inherent in this and other ballistocardiographic systems that may be responsible for distortion of amplitude or phase should be borne in mind. The first is the possible accentuation of recorded ballistocardiographic forces due to resonance near the frequency of relative motion between the body and the bed (the $f_2$ point). The second factor is the possible distortion of recorded ballistocardiographic forces due to the effects of the internal elastic suspension of the heart and blood vessels. The authors are aware of the possibility that some high frequency forces may have been exaggerated by

* The addition of a capacitor across the leads from the accelerometer has been found necessary to correct for the relatively short time constant of the instrument. The amount of capacitance varies slightly with each accelerometer but has been found to average 0.2 mfd. With the use of the proper capacitor, the accelerometer has been demonstrated to remain 180° out of phase with displacement through the frequencies tested, 1 to 35 c.p.s. Each accelerometer must be checked for phase and amplitude prior to use.
the presently described system because of the high $f_2$ point, but consider this unlikely on the basis of the oscillation experiment in which the amplitude of the node at the $f_2$ point was small. This indicates that there is little amplitude distortion at this point. Further, even granting a certain exaggeration of the high frequency ballistocardiographic components, it seems better to have these forces visible than almost completely absent, since they are believed to have physiologic and pathologic significance.\(^8\) The other factor, the effect of the internal body elastic network, remains unknown.

SUMMARY

Some of the considerations involved in the design of a low frequency undamped ballistocardiographic system have been discussed. A practical ballistocardiographic system based on the principle of the horizontal pendulum is described. By increasing the coupling of the body to the bed and using an accelerometer of extended frequency range, ballistocardiograms having force components of high frequency have been recorded. These forces have not been clearly shown in any previously published study, but appear to have physiologic significance.

SUMMARIO IN INTERLINGUA

Es discutite certe considerationes que interessa le construction de un non-tamponate ballistocardiographo a basse frequentia. Un practic systema ballistocardiographic, basate super le principio del pendulo horizontal, es describite. Per augmentar le accopulamento del corpore al lecto e per usar un accelerometro de un plus extense gamma de frequentias, ballistocardiogrammas esseva registrate que ha componentes de fortia de alte frequentia non clarmente monstrate in ulle previemente publicate studio sed nonobstante de apparente signification physiologic.

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To fight out a war, you must believe something and want something with all your might. So must you do to carry anything else to an end worth reaching. More than that, you must be willing to commit yourself to a course, perhaps a long and hard one, without being able to foresee exactly where you will come out.—O. W. Holmes, Jr., 1884.
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