Design of a Clinical Ultra-Low Frequency Ballistocardiograph

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The potential advantages of an ultra-low frequency ballistocardiograph are presented.

WHILE the first record of body movement was made over 75 years ago,1 nearly all of the advances in the field of ballistocardiography have taken place since the entrance of Starr and associates in 1939.2 During the latter period, several recording techniques have been developed and numerous papers published. However, only within the past 5 years have basic theoretical investigations been made of the dynamic properties of the various ballistic systems by Von Wittern, Burger, Talbot, and Harrison.3-5 These investigations indicate that the more widely used high frequency and direct body techniques introduce a large degree of distortion into the wave forms and that the more rarely used ultra-low frequency system is the most acceptable of the presently existent methods from this viewpoint. Since comparatively little work has been done with this type of instrument and since it is potentially the most informative, it would seem desirable to acquire more clinical data with the ultra-low frequency instrument. It is the purpose of this paper to describe an ultra-low frequency ballistocardiograph designed for clinical use.

METHOD

The final device shown in figure 1 evolved from an earlier research instrument shown in figure 2. This conical pendulum suspension of the earlier research instrument can be seen to be that first used by Henderson, and later by Rappaport,6 employing horizontal rods to offset the support-

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ing wires from the vertical. This arrangement performs a dual function, limiting motion to the longitudinal axis of the body, and permitting attainment of ultra-low natural frequencies without the use of excessively long wires.

The suspension of the clinical instrument is shown schematically in figure 3, and is an inversion of the above suspension. The platform is supported by 7 rods, pivoted at both ends, and the angular displacement of the rods from the vertical is maintained by short sections of woven cable. The rods are made from aluminum tubing, with conical hardened steel tips (fig. 5). The tips have been ground and lapped into their individual sockets and are lubricated with a light grease to which a small percentage of stearic acid has been added to reduce friction and wear. The original woven cables have been replaced with strips of steel shim stock, 0.03 inch wide and 0.003 inch thick, to reduce the bending stiffness that tends to raise the natural frequency of the platform when the subject is of low weight.

In principle, the operation of this suspension, in either normal or inverted configuration, is analogous to that of an ordinary door swung on frictionless hinges (fig. 4). If the upper door hinge is moved outward slightly, the door will have a definite resting position about which it will oscillate if displaced. The natural frequency of oscillation is a function of the angle θ between the hinge axis and the vertical. Since the natural frequency goes to zero θ (i.e., the tendency toward oscillation disappears when the hinges are vertically aligned), it follows that the natural frequency can be adjusted to a suitably low value by correct choice of the relative hinge positions. The addition of several wires and rods in the suspension of the instruments shown does not invalidate the analogy, providing all are respectively parallel. The only added complication is several separate but parallel hinge axes, necessitating pivots at the platform, since all points no longer rotate about the same center. Reeves and associates7 designed a suspension that uses single upper and lower hinge points, removing the necessity for pivots at the platform. (Readers familiar with the concept of virtual dis-
Fig. 1 Top. Clinical ballistocardiograph. Headrest and footboard are adjustable; footboard can be clamped to platform to permit application of foot pressure. Honeycomb panel platform is shown locked in position by taggle clamps at each end.

Fig. 2 Bottom. Research ballistocardiograph. Suspension similar to that of Rappaport; total weight approximately 8½ pounds. Loud-speaker motor for application of external force to body can be seen at left-hand side of photograph.
placements may notice that these suspension systems cause any point on the platform to trace a portion of a rim of a cone during platform motion and that a vertical cone axis will therefore result in no change of potential energy of the platform upon a virtual displacement, which is the criterion for aperiodicity.)

The natural frequency of this type of suspension is independent of platform load, except for the slight effect of the lateral resistance to deflection of the thin steel strips used to maintain the offset platform position. The natural frequency of platform oscillation is 0.16 c.p.s. with a 75-pound load; increasing the load to 200 pounds reduces the natural frequency to 0.11 c.p.s. This characteristic provides adequate reduction of respiratory interference and convenience of instrument use for a large range of patient weights. Platform friction damping also varies somewhat with load; values fall in the range of 5 to 10 per cent of critical equilibrium viscous damping for loads between 75 to 200 pounds.

In order to raise the natural frequency of relative motion between body and platform (von Wittern's $F_2$ frequency$^a$), platform weight should be minimized. Practical experience also indicates that a platform providing rigid vertical support for the body is desirable, although this has never been conclusively demonstrated. To provide both low weight and rigidity, a "sandwich" structure was chosen for the platform, because of an inherently high ratio of stiffness to weight. The outer supporting sheets are of high strength aluminum alloy, 0.012 inch thick, and are bonded to a "honeycomb" cellular aluminum core. The core is 1 inch thick and the hexagonal cells are of $\frac{1}{4}$ inch width, with 0.001-inch wall thickness.$^a$

Cones spun from 0.020-inch aluminum sheet are bonded to the underside with an epoxy resin, to permit attachment of the horizontal strips and pointed support rods (fig. 5). As seen in figure 1, an irregular platform shape was utilized to reduce weight further, while providing adequate support for a range of body sizes. The total weight of the platform, including headrest, footboard, and transducers, is 6.86 pounds. Removable elbow rests (not shown) are necessary for some patients, and increase the weight to 7.0 pounds.

The frame of the instrument is of welded steel construction with a total weight of approximately 500 pounds. A plywood panel is located beneath the platform, containing circular holes to permit passage of the support rods. Quick-acting clamps are located at either end to lock the platform in position, and a handwheel, connected to a nut-and-screw assembly, permits adjustment of the null position of the platform by causing slight lateral movement of the fixed ends of the horizontal steel strips. Leveling screws are located at the four corners, and the frame is supported

*Available from the Dumont Corporation, San Rafael, Calif.
on four ½-inch thick, hard rubber pads to reduce background vibration. Building vibration was still found to be a problem, and it was necessary to locate the instrument in a basement room.

The clinical instrument is equipped to measure displacement, velocity, and acceleration (plus the electrocardiogram), since it is conceivable that any of these might yield significant clinical information; however, since the displacement curve is simple and invariant, and since it has been found to be quite difficult to obtain without extreme baseline weave, recording of displacement has been discontinued.

Acceleration is measured with 2 Schaevitz Model HG5 accelerometers,6 which are connected to carrier preamplifier units of a Sanborn 150-100A 4-channel recorder. These accelerometers are a seismic type, and operate on a differential transformer principle. They have a natural frequency of 42 c.p.s. when damped 71 per cent of critical, and a weight of 4 ounces. The over-all amplitude frequency response for the accelerometer-recorder system is shown in figure 6. (No accurate phase shift curves have been obtained.)

One of these accelerometers is mounted on the platform, and the other is securely strapped between the ankles of the patient. The two provide very similar, but not identical, records (fig. 7), thereby providing a check on one another, which is useful in detecting transducer difficulties. Both accelerometers are calibrated to produce a 1 cm. pen deflection for an input of 2 cm. per second.2 Since the accelerometers respond to a static input, and since a rotation from horizontal to vertical corresponds to an input of one g, or 980 cm. per second,2 calibration is accomplished with a device which rotates the accelerometers through an angle having a sine of 2/980.

Fig. 6. Frequency response curves. Curves are for entire recording systems, from transducer input to recorder pen output.

The velocity of the platform is measured with a bar-magnet and coils,9 of the type used by Rappaport.9 The signal is fed into a Sanborn AC-DC preamplifier, which is operated on alternating current to produce attenuation below 1 c.p.s., thereby reducing baseline weave from respiration. The frequency response curve is also shown in figure 6. The velocity measuring system is calibrated to produce a 1-cm. pen deflection for an input of 0.1 cm. per second calibration being accomplished with a shaking table. Displacement can be obtained by use of a resistance-capacitance integrator circuit placed between the coil output and the AC-DC preamplifier input.

RESULTS

Two sample records taken with the clinical instrument are shown in figure 7. Both records were taken during respiration under basal conditions. The record on the left was taken on a clinically normal young woman; that on the right was taken on a young man suffering from an atrial septal defect. Both records are consistent from cycle to cycle and resemble those of other workers; comparatively larger amplitude of the high frequency detail appears in the record taken directly from the body. Further discussion of clinical data will be given in a subsequent communication.

DISCUSSION

The inverted suspension has resulted in several improvements, compared to the formerly used configuration. It has been possible to enclose the instrument in a rigid, compact, and semi-portable unit. The overhead wires are eliminated, removing a hindrance to the patient using the instrument, and in addition, a possible source of spurious vibration. From a structural viewpoint, suspension from below permits optimum placement of the points of support without interference with the body of the patient. Further, a slight psychologic advantage is gained from the more innocuous appearance of the instrument with the suspension concealed beneath the platform. The suspension system requires initial adjustment, but once adjusted it provides trouble-free operation over a long period of time.


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*Available from Schaevitz Engineering, Camden, N.J.
The omission of body restraints, to increase coupling between body and platform, is a design decision based on several factors. First, restraints are self-defeating to some extent in that they increase the weight, which must move in unison with the body. Secondly, although the increased coupling may raise the calculated "F₂" frequency, all of the theoretical analyses thus far presented are based on the simplifying assumption that the body behaves as a rigid mass over the entire ballistocardiographic frequency spectrum. Deviation of the actual behavior from the ideal behavior, due to the segmental motion of various parts of the body, may introduce a degree of distortion larger than that caused by body-platform interaction. Unpublished studies have been made in this laboratory (with use of the instrument of figure 2, which has a weight of 8½ pounds) in which a known external sinusoidal force of variable frequency was applied to the body, and the acceleration of the platform and of various body points was measured. If the body behaved as a rigid unit, a graph of the product of mass and acceleration divided by force, versus frequency of excitation as an argument, would yield curves similar to those presented by Burger et al. The experimental curves indicate an amplification of about 2 to 4 in the upper half of the frequency spectrum, varying considerably from subject to subject. A variety of restraints were devised and tested in an attempt to reduce the distortion, and it was found that the degree of restraint (i.e., from footboard only to footboard with shoulder clamps, wrist, hip, knee, and ankle straps, plus girdle and cervical brace) had a rather small effect on the higher frequency distortion. The tentative conclusions are (a) that the body-platform interaction causes a comparatively small part of this distortion.

Fig. 7. From top to bottom, platform velocity, body acceleration (at ankles), and platform acceleration. Left side, clinically normal 18-year-old female; right side, 19-year-old male with atrial septal defect. Arrows, S waves of electrocardiogram. Both records were taken during normal respiration and under basal conditions.
due to the small effect of large variations in body-platform coupling; and (b) that the body tissues are so compliant as to make body restraints ineffective, the tissues simply moving within the restraints, like jello in a rigid bowl. There is need for further investigation in this area in order to determine what phenomena occur within the body at the higher ballistocardiographic frequencies, with a view toward counteraction of the effects (perhaps by electronic means, similar to the method of Schwarzschild⁹).

The last reason for omission of additional restraints is related to the psychological effect on the patient. It is desirable that the patient be fully relaxed during the recording period, in order to obtain a basal heart rate and to eliminate artifacts in the record due to tremor of tensed muscles. For the uninitiated clinical patient, restraints may cause mental apprehension and physical discomfort to the extent of preventing complete relaxation.

In view of the amplification caused by the body, the high-frequency attenuation of the accelerometers may be desirable, although it was not found to be sufficient to compensate fully for the body amplification. It is considered that, for the present, the high-frequency components of the ballistocardiogram should be treated with reserve until more information is available regarding the body dynamics in this frequency range. Some interesting and encouraging progress has been made by Reeves and associates in the correlation of high-frequency detail in ultra-low frequency records with physiologic events,¹⁰ but it still cannot be determined whether an abnormality in high-frequency detail is a reflection of cardiovascular irregularity, or whether it is due to a variation in the physical properties of the body of the subject.

**Summary**

The design and construction of an ultra-low frequency ballistocardiogram for clinical use has been presented. Technical data regarding the suspension, platform, and transducers are included, following the recommendations of the "Committee on Ballistocardiographic Terminology." Some discussion of factors influencing particular design choices have been given. Sample records of a normal and an abnormal subject are contained in the illustrations.

**Acknowledgment**

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**Summario in Interlingua**

Le plano e le construction de un ballistocardiographo a frequentia ultra-basse pro uso clinic es descritt. Es includite datos technic relative al suspension, platteforma, e transductores, secundo le recommendaciones del "Committee pro le Terminologia Ballistocardiographic." Ee presente un breve analise de certe factores que determina le selection del un o del altere typo de construction pro ballistocardiographos. Specimens de registraiones obtenite ab subjectos normal e anormal es contintite in le illustrationes.

**References**

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It has been demonstrated that carbon dioxide gas can be safely used to visualize the right side of the heart with little or no disturbances in hemodynamics. The gas has also been used with no untoward effects on the left side in normal dogs. The present study was to determine the usefulness of carbon dioxide gas in demonstrating interatrial septal defect in the dog. A cinefluorographic technic gave a permanent record of the course of injected carbon dioxide gas and physiologic measurements were made at the same time. Gas injected into the right heart was detected shortly afterward in the left atrium and then as a residual bubble in the left ventricle for 10 to 15 seconds. Gas passed rapidly from the right to the left atrium, despite the fact that the shunts were mainly from left to right. Pressures recordings in the right atrium indicated that values above 100 mm. Hg could be record for 1 to 5 seconds after introduction of gas, but little change in pressure readings was noted in the left atrium. At the time the gas passed through the defect the systemic pressure rose; if no defect was present the systemic pressure fell. Radiologic detection of gas in the left atrium and then in the left ventricle and motion picture recordings suggest that it will be possible to estimate both the size and position of the defect by duration, shape, and position of the gas bubble. The dissolution of the residual bubble is an important problem.
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