Some Observations on the Relation of the High-Frequency Bed Ballistocardiogram to that Obtained from an Aperiodic Bed

By Dennis C. Deuchar, M.D., M.R.C.P., Samuel A. Talbot, Ph.D., and W. R. Scarborough, M.D.

A previous analysis of the mechanical behavior of current ballistocardiographic systems allowed the prediction of certain relationships between records from the Starr high-frequency bed and those representing undistorted forces applied to the body by the cardiovascular "generator." The latter were obtained by recording the acceleration of an "aperiodic mercury bed" platform. A relationship between the form of these two types of records from 80 subjects was sought. In varying types of normal and abnormal records the predicted relationship between the two different kinds of ballistocardiograms was consistently observed. It is concluded that records from the high-frequency bed generally reflect the slower forces applied to the body, but are distorted with respect to phase, amplitude and frequency content, this being due in part to the elastic properties of the dorsal surface of the body and in part to the weight and stiffness of the platform support.

AN analysis of the current methods of ballistocardiography has shown that they are all subject to significant limitations and distortions.¹ ² The most important factor involved relates to the manner in which the human body is supported. With both the high-frequency bed and the direct body methods the body is coupled to and loaded by heavy, relatively rigid platforms or tables. When the body moves in response to internally generated cardiovascular forces, such supporting structures are unable to follow these motions since their weight and rigidity render them relatively immobile. This causes the body to oscillate back and forth on its own soft springs which are formed by the dorsal tissues connecting the body to its supporting surface. As a consequence, the behavior of high frequency bed and direct body systems becomes largely dominated by the elastic properties of the dorsal tissues. This inevitably produces a seriously distorted frequency response in an important part of the ballistocardiographic frequency range. One of the errors introduced is in amplitude response. Those forces applied at frequencies comparable to the body's own natural frequency (4 to 5 cycles per second) are greatly exaggerated in amplitude while those applied at higher frequencies are considerably attenuated. Furthermore, since the human body is underdamped, a single impact applied to it is followed by a series of diminishing oscillations. That this behavior causes distortion of the ballistocardiogram is a fact well recognized by Starr at a very early stage in his work.³ Another error produced by the dominance of the body's dorsal springs is in phase (or timing) characteristics. Beginning with frequencies well below the body's own natural frequency, the motions of the body (and the high-frequency bed platform) tend to lag behind forces driving the body. This phase lag, which progressively increases as the driving frequency is increased, leads to errors in timing.

We have already published a brief report ⁴ concerning our attempts to approach the ideal system, as described by Nickerson ⁵ and Burger and co-workers ⁶ in which the body would be free of all restoring and damping forces, as if floating in space. With such a system the body's...
acceleration would measure directly the force transmitted to it from the cardiovascular system, assuming a unified body mass. Briefly, our aperiodic ballistocardiography consists of a light platform (weight about 11 pounds) floating on a shallow pool of mercury; such a system has no restoring force, so can be called aperiodic, and has minimal damping. These properties minimize excitation of the dorsal tissues; coupling of the body to platform is further improved by use of a footboard. The relative motion between the body and platform on the high-frequency (Starr) ballistocardiograph is compared with that on the aperiodic (mercury) bed in figure 1. This figure shows the ballistocardiogram as recorded from these systems together with simultaneous “direct body” ballistocardiograms taken from the shins (and referred to the platform) by means of a calibrated ballistocardiographic pickup.\footnote{D.V.A. ballistocardiograph, manufactured by the Industrial Development Laboratories, Inc., Jersey City, N. J. Displacement is recorded with a differential transformer; although the core is spring-mounted, the spring constant is so small as to be negligible in this application. Acceleration is obtained by differentiating the output of an electromagnetic pickup.}

Fig. 1. Four sets of simultaneous recordings of platform motion and relative motion between subject (shins) and platform; in each case the platform record is the upper tracing. The same subject was used for all the tests. The records in A and C relate to the high-frequency bed while those in B and D refer to the aperiodic bed. In C and D the subject's feet were against a footboard; in A and B they were not.

In A and C the upper tracing is the usual high-frequency bed record, representing the displacement of the platform. The lower tracing is a direct-body record from the shins of the subject lying on the high-frequency bed and represents displacement of the body with respect to the platform. The calibration marked “C” corresponds to a displacement of 3.5 microns for the Starr bed record and of 25.0 microns for the direct-body record.

In B and D the upper tracing is the acceleration record from the aperiodic bed platform and the lower tracing is the acceleration record from the shins referred to the platform. Calibration is the same for both records (1 cm = approx. 1 cm per second²).

With the high-frequency bed the displacement of the body is about seven times as great as that of the platform; although the use of a footboard reduces the discrepancy, relative motion remains large. On the other hand, motion of the body with respect to the aperiodic bed platform is so small as to be almost unmeasurable, and this is made even smaller when a footboard is used. For practical purposes, the aperiodic bed platform and the subject on it can be considered to move in unison in response to cardiovascular forces.
CURRENT METHODS OF BALLISTOCARDIOGRAPHY

This demonstrates the very small motion between body and platform on the aperiodic bed, even more reduced by the use of the footboard, as compared with the similar motion on the high-frequency bed.

Burger and associates\(^6\) in their analysis of the physical basis of ballistocardiographic systems suggested that the magnitude of the displacement of a high-frequency bed platform represents the force acting on the body. In reaching this conclusion, however, they did not take into account all the complexities of the system. The analysis from this department\(^3\) has shown that this suggested relationship is true only for a limited frequency range. This range, however, seems to include the largest forces acting on the body, which are those responsible for the main features of the Starr-type record. We might expect, then, that the gross features of this type of record would give an indication of the major forces applied to the body by the cardiovascular generator.

The analysis previously mentioned\(^6\) enables us to predict certain relationships between the records from the high-frequency bed and those from the aperiodic ballistocardiograph. Taking the latter as the reference record depicting force acting on the body, it is possible to predict that the record from the high-frequency bed will show the following properties: (1) it will show the main forces in the lower frequency range while those of higher frequency will be more or less attenuated and those about the body’s natural frequency will be exaggerated; (2) in sections of the record following deflections at the natural frequency of the body it will show waves compounded of freshly impressed forces and after-oscillations excited by the earlier deflection, and (3) it will represent all but the slowest oscillations later in time, a result of the phase shift referred to above.

The work being reported here was undertaken to investigate whether this theoretically predicted relationship could be confirmed in practice.

**Methods and Materials**

Head-foot records were obtained on both a high-frequency bed and the aperiodic ballistocardiograph. The high-frequency bed was the instrument used in previously reported studies,\(^4,11\) but for this study the records were made using a Sanborn strain gage amplifier and two-channel direct-writing recorder; the second channel was used to record the lead II electrocardiogram. The aperiodic ballistocardiograms were obtained as previously reported,\(^4\) using a 2g Statham accelerometer on the platform with a cathode-follower and the Sanborn amplifier: additional amplification with a direct current amplifier was used to obtain adequate sensitivity and a high-cut filter was incorporated to obtain a response from transducer to pen flat to 40 cycles per second but with attenuation above this level. Sensitivity was adjusted to 5 mm. deflection for one thousandth of g (acceleration due to gravity), roughly 1 cm. per second\(^2\). On both systems records were taken with the subject’s feet against the footboard and with the subject breathing normally except for a short period during which the breath was held in midinspiration. The records so obtained were compared to determine the relationship between those from the two systems. It should be kept in mind that the comparison was between the usual displacement record from the high frequency bed and the acceleration record from the aperiodic bed.

Records from 80 subjects have been used for this study; 55 of these had no evidence of cardiovascular disease, 16 had coronary artery disease and nine had other forms of cardiovascular disease. A breakdown of the subjects and records is given in table 1. In this table the term “normal” applied to the character of the aperiodic ballistocardiogram means that the complexes had a form similar to that consistently observed in all young normal subjects. Our experience, previously reported\(^4\) on the basis of 20 subjects, that such a consistent, easily recognizable pattern is obtained from the aperiodic ballistocardiograph has been confirmed in the larger series now under discussion. “Abnormal” records are those which depart from the normal pattern in some clear qualitative fashion; “borderline” is used to described records intermediate between clearly normal or abnormal, for which, at present, our criteria are insufficiently precise to permit certain classification. It should be noted that no statis-

<table>
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<th>Diagnostic classification of subjects</th>
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Fig. 2. Typical acceleration records obtained from four young normal subjects on the aperiodic bed, together with the simultaneously recorded electrocardiogram. Note the general resemblance of the form of the records. The calibration, marked “C” on the records, represents the deflection produced by an acceleration of 0.002 g, which would result from the action of a 136 Gm. force on a 150 pound body. (This figure is reproduced here by permission of the Bulletin of the Johns Hopkins Hospital.)

Typical action of a tonic muscle in a young normal subject, taken on both systems, superimposed upon each other to illustrate their mutual relationship. By the nature of things it is not possible to record these two types of ballistocardiogram simultaneously, but in the preparation of this and similar figures care has been taken to match complexes with respect to phase of respiration.

Normal Records

Figure 2 shows some typical normal records from the aperiodic ballistocardiograph. The main features of these records are a small headward wave with its tip occurring at a mean interval of 0.09 second after the Q wave in the lead II electrocardiogram, a prominent footward wave with its tip 0.14 second (mean) after the Q wave followed by the main headward deflection with a tip 0.21 second (mean) after the Q*. After this deflection the record is more variable in form, with a slower return to the base line and usually a footward segment of small amplitude but longer duration, often culminating in a sharper footward deflection just before a more uniform headward wave of small amplitude at 0.52 second after the Q wave. Sometimes the last footward deflection referred to is preceded by a well-defined wave approaching the base line but rarely crossing it. (See also figure 12 for a diagrammatic representation of this.)

* These intervals may be compared with previously reported mean values from normal high-frequency bed records: Q-H = 0.10, Q-I = 0.18 and Q-J = 0.25 second.
FIG. 3. Four examples of single complexes from normal records taken on the aperiodic and high-frequency beds, traced and superimposed to demonstrate their mutual relationship. The aperiodic bed records in this and all other similar figures in this paper are represented by the continuous line, the high-frequency bed records by the broken line; the lead II electrocardiogram is reproduced in each case to provide a reference for timing. For full discussion of this figure see the text.
Fig. 4. High-frequency bed (HFB, above) and aperiodic bed records (AB, below) together with the simultaneous lead II electrocardiogram in each case, as in all similar figures in this paper, from a 67 year old, clinically normal man. Both records are abnormal because of very large initial headward deflections (H waves); note the similarity of the abnormality in the two records. (See figure 5)

Fig. 5. Superimposed single complexes from the two records of the subject shown in figure 4, to demonstrate their relationship more clearly. (The aperiodic bed record is shown with a continuous line.)

Fig. 6. Ballistocardiograms (high-frequency bed above and aperiodic below) from J. T., a 26 year old man, with coarctation of the aorta and aortic regurgitation. The amplitude of the high-frequency bed record is large, probably related to the aortic incompetence, but the K wave is clearly shortened as compared with the I and M waves. Every complex of the aperiodic bed record contains a large, abnormal, long-acting headward deflection (marked with arrows) corresponding in time to the K wave of the other record. (See figure 7)
and to correct for any parallax error in relating them to the electrocardiogram. It can be seen that in the early part of the systolic complex the waves in the two records roughly correspond but that those from the high-frequency bed occur slightly later than those from the other. Thus the aperiodic ballistocardiogram contains waves which resemble the H, I and J waves of the record from the high-frequency bed, and we may justifiably assume that the forces thus represented are those which give rise to the corresponding named waves in the record from the high-frequency bed. Inspection immediately reveals that there is, in the normal records, no wave in the aperiodic bed complex corresponding to the K wave. Starr originally believed that the K wave was largely an artefact due to after-oscillation, and this observation would suggest that it is. The L wave also is not represented, but the last two waves in the aperiodic bed records correspond well to the M and N waves; this may be significant but could be fortuitous. Even if the M and N waves do not actually result from the forces occurring at the same time in the aperiodic bed record, the manner in which their amplitude differs from simple damped vibrations after the J wave can be explained on the basis

Fig. 7. Superimposed single complexes from the two records of the subject with coarctation of the aorta shown in figure 6. Note how the abnormal headward-acting force, shown by the deflection marked with the arrow, in the aperiodic bed record is so timed as to act against the K wave deflection in the high frequency bed record.

Fig. 8. The two records (high-frequency bed above, aperiodic below) from a 44 year old man with coronary artery disease. The high-frequency bed record shows shortening or absence of the K wave varying with respiration. In the aperiodic bed record there appears an abnormal, headward wave (marked by arrows) in each complex, corresponding in time to the K wave in the other record, which shows similar respiratory variation.
of impressed forces occurring at that time. Brown and his co-workers and others have pointed out that the features just referred to indicate that new forces were acting there, for if these waves were due to simple underdamped after-oscillations alone they would fall equally astride the baseline with a decline in amplitude instead of, as is usually seen, the L wave being close to the baseline with the M and N being of larger amplitude below and above it. The portion of the record from the high-frequency bed following the J wave would thus seem to exemplify compounded effects of after-oscillation and freshly impressed forces.

The relation of the normal record from the high-frequency bed to the tracing from the aperiodic bed can thus be readily understood in terms of the analysis outlined above.

**Abnormal Records**

Further confirmation of this relationship has been sought and obtained in a variety of abnormal records. Thus we have found that patients with large H waves in the high-frequency record also have increased amplitude of the initial headward waves in the aperiodic ballistocardiogram. Figure 4 is from a clinically normal man, aged 67 years, and shows a quite abnormal record from the high-frequency bed with very large H waves dominating most of the complexes; the aperiodic bed record in this man shows similar very large initial headward waves. The timing of the waves in the remainder of the complexes is somewhat disturbed by this large deflection, as is often the case; in addition, there is an abnormal head-
Fig. 11. The high-frequency bed (above) and aperiodic bed ballistoeardiograms from a 55 year old man with syphilitic aortic incompetence and multiple aortic aneurysms. All the waves in the high-frequency bed record, as judged by their timing in relation to the lead II electrocardiogram, are abnormal. Note that the aperiodic bed record has a similar abnormal form except that here the largest systolic components are two large, fast headward waves occurring at about the same time as the single large wave in the high-frequency bed record. (See text)

ward deflection in the record from the aperiodic bed occurring about 0.4 second after the Q wave in the lead II electrocardiogram which corresponds in the record from the high-frequency bed to a very large L wave, often exceeding the J in amplitude. These relations are more clearly seen in figure 5.

More interest attaches to changes in the K wave in the records from the high-frequency bed. As already mentioned, Starr originally thought this wave was an artefact due to after-oscillation but Hamilton and his colleagues postulated that it was produced by a footward acting force. This force was supposed to be generated when the normal, rapid footward flow of blood along the descending aorta was abruptly slowed by the peripheral resistance of the smaller vessels in the lower extremities. It is generally recognized that in coarctation of the aorta the K wave is shortened or even absent; this change has been explained as resulting from the diminution, by the coarctation, of the normal blood flow in the descending aorta with consequent impairment of the mechanism producing the K wave. This observed change in coarctation could be regarded as supporting Hamilton's hypothesis, it being argued that if the K wave arose simply as an after-oscillation it ought always to follow a J wave of adequate amplitude, and that shortening as in coarctation must indicate reduction of some force which normally acts to produce it. This is not a valid argument, however, for a deflection normally occurring as an after-oscillation could be more or less canceled by a contrarily acting abnormal force.

In figure 6 are shown the two records from a young man (26 years) with coarctation of the
aorta and some degree of aortic regurgitation; the over-all amplitude of the high-frequency bed complexes is large, probably due to the valvular incompetence, but the K wave is greatly shortened relative to the I and M waves. In the aperiodic bed record there is an abnormal, moderately large, headward-acting force timed just so as to coincide with the K wave. This relationship is shown more clearly in figure 7. Another patient, a 44 year old man with coronary artery disease, showed slurring of the J-K segment and shortening of the K, varying with respiration, in his high-frequency bed record (fig. 8). Again the aperiodic bed complexes show abnormal, headward forces, similarly varying with respiration, and so timed as to act against the K wave.

Another well-known abnormal form of the high-frequency bed complex involving the K wave is that called by Starr20 the “late downstroke pattern” and commonly associated with hypertension. In this pattern the amplitude of the early part of the systolic complex is reduced while the K wave is unaltered or increased. We have not so far obtained a clear-cut example of this form change in this small series, but the records in figure 9 and 10 illustrate features suggesting the development of this abnormality in a man aged 57 years with mild hypertensive disease. The aperiodic ballistocardiogram in this patient shows a generally similar form with a large abnormal footward wave representing a new force occurring at such a time as would be expected to augment the K wave in the record from the high-frequency bed. This suggests that the K wave in the late downstroke pattern is at least largely due to an abnormal force.

Of considerable interest also were the records shown in figure 11 from a patient with syphilitic aortic incompetence and multiple aortic aneurysms. The complexes in the record from the high-frequency bed were composed entirely of abnormal waves as judged by their timing; the record from the aperiodic ballistocardiograph showed a very similar form with one major exception. In the latter record the largest systolic components are two large, fast, headward waves occurring between 0.10 and 0.20 second after the Q wave of the lead II electrocardiogram. The high-frequency record in this region shows only one large headward wave with a knee on its downstroke; we interpret this difference as an indication of the failure of the high-frequency bed to follow faithfully the faster phenomena shown in the other record.

**Discussion**

We have described and illustrated above various individual examples to show the relation between the two records in a variety of patterns. It should be emphasized that these records were selected as illustrations only and that the same type of relationship was found in all the other records we examined.

From this study we conclude that the relationship between the records from the high-frequency bed and the aperiodic bed is in keeping with our predictions based on an analysis of their respective behaviors. This finding provides observational support for the validity of this analysis. Records from aperiodic or closely related types of beds with similar mechanical behavior6, 21, 22 can be regarded as representing more faithfully the motions of the body, considered as a unified mass, resulting from cardiovascular activity. Acceleration records will reflect the acceleration of the body and, hence, taking into account its mass, the forces acting on it; displacement records will reflect displacement of the body and, hence, shifts in its center of gravity internally due to changes of the position of blood and the heart during each cardiac cycle (as described by Burger and co-workers6). Displacement records from the high-frequency bed, and also of the direct-body type, reflect predominantly the slower forces acting on the body but with the distortions described above.

The fact that both the aperiodic bed acceleration records and the displacement records from the high-frequency bed show to a greater or lesser extent the forces acting on the body as a result of cardiovascular activity has important implications. The close correspondence between many of the waves in the two records, demonstrated here, suggests that the corresponding waves in the aperiodic bed acceleration records represent more or less the same events which give rise to the H, I, J, M, and N waves of the
high-frequency bed displacement records. These letters, as applied to the appropriate waves in the records from the high-frequency bed, have now many years of generally accepted usage to their credit so that their retention would seem best suited to promote understanding of the newer type of records. For this reason these letters have been used to name the appropriate waves in the aperiodic bed records as shown in figure 12. The interval between the J and M waves may be referred to as the J-M segment and, in view of its variable form, suitable descriptive terms may be applied to it as seem necessary.*

**Summary**

On the basis of a theoretic and experimental analysis of its behavior it is believed that displacement records from the high-frequency bed ballistocardiograph reflect grossly, but subject to significant distortions, the forces impressed on the body by the cardiovascular "generator." A light platform floating on mercury has been used to obtain ballistocardiograms; this apparatus, because of its lack of restoring force, has been termed the "aperiodic ballistocardiograph." Acceleration records from this system are thought to represent more faithfully the forces acting on the body.

A relationship between the form of these two types of records has been predicted and confirmation of it sought in records obtained from 80 subjects. In both normal and abnormal records of varying types the expected relationship has been consistently observed; this finding provides factual support for our views on the behavior of these ballistocardiographic systems. It also provides a sounder basis for analyzing the wave form of records from Starr-type beds. The following generalizations regarding ballistocardiograms from these high-frequency instruments may be made:

1. The records reflect, in a general way, the forces acting on the human body, the slowest forces being the most faithfully represented.

2. Errors in phase, amplitude and frequency content are introduced because of the soft, elastic coupling between the body mass and its supporting surface and because of the weight and rigidity of the latter.

3. The H, I, J, M and N waves of normal records do, in fact, represent true forces applied to the body but are delayed in time. Since no forces corresponding to the normal K and L waves were consistently observed, it must be assumed that these represent the passive after-oscillations characteristic of underdamped, vibratory systems. However, unusually deep K waves may result from the addition of a new and abnormal footward force to the normal passive K wave afteroscillation. Conversely, short or absent K waves may be produced when an abnormal headward force occurs at such a time as to partially or completely cancel the normal K afterfling.

4. In general, our studies tend to support Starr's contention that ballistocardiograms from high-frequency bed systems are related to the forces produced by cardiovascular activity.

**Summario in Interlingua**

Un analyse previamente publicate del reacciones mechanic del systemas ballistocardiographic currentemente in uso permitteva le prediction de certe relationes inter registroes ab le lecto typo Starr a alte frequentia e le registraziones que representa non-distorquite fortias applicate al corpore per le "generator" cardiovascular. Iste secunde grupo esseva registraziones del acceleration de un platte-forma typo "lecto aperiodic a mercurio." Nos ha investigate le relationes inter le formas de iste duo typos de registraziones in 80 subjectos. In varie typos de registraziones normal e anormal le predicte relationes inter le duo typos de ballistocardiogramma esseva observate. Nos conclude que registraziones ab le lecto a alte frequentia reflecte grossiermente le plus lente fortias applicate al corpore. Sed quanto a phase, amplitude, e frequentia iste registraziones es distorquite, in parte a causa
del qualitates elastic del superficie dorsal del
corpore e in parte a causa del peso e rigiditate
del platteforma.

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