The Elimination of Body Resonance Distortion from the Direct-Body Ballistocardiogram

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A simple method of obtaining a force ballistocardiogram has been presented. This type of tracing has been derived from the direct-body ballistocardiogram by electrically filtering out body resonance distortion. The resultant force tracings appear to be closely related to cardiovascular events.

The recorded ballistocardiogram is a distorted representation of cardiovascular forces.\(^1\)\(^2\)\(^3\) These forces, which are generated by the contracting heart and accelerated blood, are transformed in transmission to the surface of the body. The resultant body movement is determined by the amplitudes of the transmitted forces and the mechanical response of the body. It is the purpose of this paper to present a practical means of neutralizing the distorting effect of the body's resonance on the longitudinal ballistocardiogram of the supine subject lying on a rigid surface.

The longitudinal motion of the supine body may be described mathematically, if it is assumed that the body behaves as a simple mechanical system. The normalized displacement and velocity amplitude responses of such a simplified body to sinusoidal forces are given in equations (1) and (2),\(^4\)\(^5\)\(^6\)\(^7\)

\[
(1) \quad X = \frac{1}{\sqrt{(1 - S^2)^2 + (2rS)^2}}
\]

\[
(2) \quad V = \frac{(2rS)}{\sqrt{(1 - S^2)^2 + (2rS)^2}}
\]

where \(r\) is the ratio of actual damping to the critical damping of the body and \(S\) is the ratio of the frequency under consideration to the resonant frequency of the body.

The displacement and velocity of the body are derived in normalized form in order to effect optimum simplification and generalization of equations. Thus, the four parameters, mass, elastance, damping and frequency are replaced by two parameters, normalized damping and normalized frequency. The generalization effected by normalization makes equations (1) and (2) more readily applicable to all subjects.

The amplitude response curves shown in figure 1, plotted from equations (1) and (2), graphically demonstrate the variation of body motion with frequency. This variation of body response with frequency is the basic cause for distortion in the recorded ballistocardiogram.

One method of correcting this distortion consists of analyzing the recorded ballistocardiogram and resynthesizing a new tracing by the Fourier method.\(^2\) The corrected tracing is free of body resonance distortion. However, this method does not yield a continuous corrected record and is, therefore, unsuitable for clinical ballistocardiography.

A second method of correcting the distortion introduced by the body's resonant response consists of recording the ballistocardiogram by means of specially designed beds. Talbot and his coworkers\(^8\) approximate a tracing free of distortion due to the body, by recording the ballistocardiogram from a board floating in a mercury filled tank. von Wittern\(^4\) records the ballistocardiogram from a pendular bed adjusted so as to mechanically filter the distortions introduced by the body and the bed. Both techniques can approximate undistorted ballistocardiograms. However their application

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The acceleration $A = \frac{(S)^2}{\sqrt{(1 - S^2)^2 + (2rS)^2}}$

The resonant frequency and damping constant of a subject were measured by recording the damped oscillation subsequent to manual displacement of the supine body from its resting position. These constants were then substituted in equations (1) and (2) and the displacement and velocity responses of the body were determined. Finally, electric filters (fig. 3) were designed to correct these responses.

The equation representing these phase responses are as follows:

$$\theta_v = -\tan^{-1}\left(\frac{2\pi}{1 - s^2}\right)$$

$$\theta_e = \theta_v + \pi$$

$$\theta_a = \theta_e + \pi$$
Fig. 3. A schematic representation of the displacement and velocity filters used to eliminate body resonance distortions from the ballistocardiogram; and the placement of these filters in the recording systems.

Fig. 4. Responses of displacement and velocity filters used for a subject whose body resonant frequency is 4.5 cycles per second and whose normalized damping is 0.25. $A_{1(1)}$ and $B_{1(1)}$. Displacement and velocity filter diagrams. The coils (United Transformer Company—N 1181) have a $Q$ of approximately 5, at 5 cycles per second. $A_{2(3)}$ and $B_{2(3)}$. Displacement and velocity phase shifts of the body-filter systems. $A_{3(2)}$ and $B_{3(2)}$. Measured displacement and velocity filter input and output voltages as functions of frequency. The filter output voltages are amplified so as to yield 1 volt output at 4.5 cycles for a filter input of 1 volt. Note the linear phase shifts and the flat amplitude responses effected by the filters.
sponses. Variations in body resonant frequency from subject to subject were compensated for by varying the parameter C (or C'). The changes in the damping ratio were corrected by varying R (or R').

This method of correction was applied to five normal subjects. Simultaneous corrected and standard longitudinal direct-body displacement and velocity ballistocardiograms were recorded from the legs by means of the Sanborn photoelectric displacement transducer and the Dock electromagnetic transducer. Lead I of the electrocardiogram was recorded simultaneously with the ballistocardiograms. Heart sounds and respiration were also included in some tracings. All recordings were obtained with the subjects lying on a concrete floor.

The high impedance of the Sanborn photoelectric transducer (approximately 2 megohms) necessitated its isolation from the relatively low impedance displacement filter (6 to 7 kilohms). The electromagnetic transducer did not need to be isolated from its filter since the impedance of the former is approximately 1 kilohm, whereas the latter is approximately 7 kilohms. However, to assure uniformity of method the velocity transducer was similarly isolated from its filter. It was convenient to place the filters and isolating cathode followers between the preamplifier and power amplifier of the recorder (fig. 3).*

**Results**

The subject chosen for illustration here had a body resonant frequency of 4.5 cycles per second and a damping ratio of 0.25. The proper circuit values of the displacement and velocity filters to correct the body resonance distortions of the subject are given in figure 4. The measured response characteristics of the filters and their effect on the displacement and velocity responses of the body are also shown in this figure.

Equalized and standard direct-body longitudinal displacement and velocity ballistocardiograms of this subject are shown in figure 5. The corrected ballistocardiograms are similar to each other and show alteration of the characteristic wave form. The H wave is notched at its peak. The notch occurs at the time of the first heart sound. The J wave is bipedek. The JK stroke is shortened. The L wave is replaced by high frequency oscillations occurring at the time of the second heart sound. The di-

* Grass 8 Channel Electroencephalograph, Model IID.

![Fig. 5. Standard and corrected displacement and velocity ballistocardiograms recorded from the legs of a supine subject, whose body resonant frequency is 4.5 cycles per second, and whose body damping is 0.25. Simultaneous tracings are: 1. Electrocardiogram lead I. 2. Displacement recording using the Sanborn photoelectric transducer. 3. The displacement response (2) corrected by the displacement filter. 4. Velocity recording using the Dock electromagnetic transducer (without bypass capacitor). 5. The velocity response (4) corrected by the velocity filter.](http://circ.ahajournals.org/)

**Discussion**

The representation of the body as a simple mechanical oscillator is, of course, an oversimplification. The concept, however, is useful as a working hypothesis, and is supported by the following laboratory data:

1) The damped oscillation of the supine longitudinal body in response to a manual displacement mimics the oscillatory decay of the simple mechanical oscillator.

2) Nickerson and Mather find reasonable agreement between the motion of the supine body along the longitudinal axis, when forced by a mechanical generator, and the motion of a simple mechanical oscillator.

3) The correction of the displacement and velocity ballistocardiograms, by means of filters whose responses are inverse to the theoretical displacements and velocities of the
simple mechanical oscillator, yield recordings that are similar to each other.

The two corrected recordings can, therefore, be considered approximate tracings of the transmitted cardiovascular forces. Such a force ballistocardiogram could just as readily have been obtained by using an acceleration transducer in combination with a suitable filter. The particular transducer-filter system chosen to record the force ballistocardiogram is a matter of convenience.

The appearance of high frequency oscillations in the corrected ballistocardiograms is due to the equalization of the overall responses effected by the filters. The high frequency oscillations which are normally masked by the accentuated body oscillations at the resonant frequency are presented in more correct proportion by the method of equalization.

Some of the high frequency oscillations are related to cardiovascular events (figs. 5 and 6). Those oscillations in time with the first and second heart sounds are related to the closing of the heart valves. The bipeaking of the J wave is similar to that seen in thoracic ballistocardiograms, and has been attributed to the separate recoils of blood in the pulmonary artery and in the arch of the aorta. The various high frequency oscillations are more prominent in some of the corrected tracings (fig. 6).

The typical force ballistocardiogram presented by Talbot and his associates has a configuration comparable to those shown in figures 5 and 6. In their tracing the H wave is discernibly notched, the J wave shows evidence of a second peak, the JK stroke is shortened, and the L wave and the diastolic waves are replaced by high frequency oscillations.

The force ballistocardiogram presented by von Witten3 shows evidence of notching on the H wave, and has a shortened JK stroke. However this ballistocardiogram does not show some of the high frequency markings evident in our tracings and in those presented by Talbot and his colleagues.

Basically our tracings and those presented by Talbot and coworkers and von Witten are quite similar despite the differences in recording methods.

The floating bed used by Talbot and associates is conceptually simple. The only constraints on the bed are those due to the viscous damping and surface tension of the mercury. As a result the body and bed move almost synchronously and the recorded ballistocardiogram is relatively free of body resonance distortion.

The pendular bed used by von Witten is more complex. The subject must be clamped to the platform and external damping must be added to mechanically filter the distortion due to the motion of the body with respect to the bed.

The development of a force ballistocardiogram by electric filtering technics is readily applicable to the direct-body ballistocardiograph, but cannot be practically applied to...
table ballistocardiographs (such as the Starr 1 or the Nickerson 19 table). The table ballistocardiogram is a function of the body-table system response to cardiovascular forces. The responses of the body and the table cannot be analyzed separately (as proposed by Nickerson and Mather 6) since the table impedance loads and modifies body activity. The calculation of this loading effect and the design of variable electrical filters to effect an overall correction of table ballistocardiograms suitable for a wide range of subjects is difficult.

The method of obtaining a force ballistocardiogram by electrically filtering the direct-body tracing is simple. This method does not require any special ballistic bed; and the tracing can be recorded with either a displacement, a velocity, or an acceleration transducer. The distortion introduced by the body is easily defined and can be readily corrected by a suitable electric filter.

**SUMMARY AND CONCLUSIONS**

A mathematic analysis of body displacement and velocity in response to cardiovascular forces was presented on the assumption that the body behaves as a simple mechanic system.

Guided by this analysis, electric filters were developed to eliminate body resonance distortions from the direct-body displacement and velocity recordings.

The corrected tracings were similar to each other, and it was concluded that they both approximated the force ballistocardiogram.

The corrected ballistocardiograms showed evidence of physiological events, such as heart valve closure, not seen in the standard ballistocardiograms.

**SUMMARIO IN INTERLINGUA**

Es presentate un analyse mathematic del displaciamiento e del velocitate corporee in responsa a fortias vascular, basate super le postulato que le corpore se comporta como un simple systema mechanic.

De acordo con le datos assi establite, nos ha disveloppate filtros electric pro eliminar dis- torsiones, resultante del resonantia corporee, ab le direcute registrationes de displaciamiento e velocitate.

Post le correction del duo registrationes per iste metodo, illos esseva simile le un al altere, e nos concludeva que ambes se approximava al ballistocardiogramma de fortia.

Le corrige ballistocardiograms refleche certe eventus physiologic—per exemplo le clausion del valvula cardiac—que non es visibile in ballistocardiograms standard.

**REFERENCES**


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Circulation. 1955;12:108-113
doi: 10.1161/01.CIR.12.1.108

Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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