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Prabasaj Paul and Laurel B. Symes

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Ballistocardiography in the Physics Classroom

Prabasaj Paul and Laurel B. Symes, Denison University, Granville, OH

Ballistocardiograms (BCGs) are graphical representations of the recoil from the pumping action of the heart. Introductory mechanics and a basic knowledge of the circulatory system are sufficient to understand the key features of a BCG. BCGs with adequate detail for instructional purposes may be produced easily and rapidly using hardware (a force plate) and software common to introductory physics labs. The interdisciplinary nature of this exercise is a particularly attractive feature. We have used it as a demonstration in a course on mechanics for non-physics majors as well as for visiting high school students, and indicate here possible ways to incorporate it into upper-level physics or biomechanics courses.

The human circulatory system is driven by periodic contractions of the chambers of the heart. The periodic variation in the flow of blood and the motion of the heart itself manifest themselves through recoil of the rest of the body. This small but measurable motion may be recorded as a BCG. Ballistocardiography, as a clinically significant noninvasive technique to study the heart, was pioneered in the 1950s.\(^1\) Traditionally, BCG readings have been collected by placing the subject on a horizontal airbed such that the longitudinal force on the bed + body is negligible. We neglect the mass of the airbed and define the system as the body of the subject in the following analysis. The preponderance of circulatory movement occurs in the longitudinal (head-to-toe) direction. As a result, the human body may be considered as a one-dimensional system for the purpose of this analysis. We assume that in all three arrangements the relative motions of the different parts of the body are identical. Choose the origin at the center of mass of the system (so that its coordinate \(x_{\text{CM}} = 0\)), and let the (longitudinal) coordinate of the center of mass of the circulatory system (blood + heart of mass \(m\)) be \(x\) and that of the rest of the body (of mass \(M\)) be \(X\). Then, the momentum of the system remains constant and

\[
m\ddot{x} + M\ddot{X} = (m + M) \ddot{x}_{\text{CM}} = 0,
\]

where \(\ddot{x}_{\text{CM}}\) is the acceleration of the center of mass.
where \( \ddot{x} = \frac{d^2x}{dt^2} \), etc. Typically, the BCG consists of a record of \( \dot{X} \) (expressed in terms of \( g \), the acceleration due to gravity, with toe-to-head considered the positive direction) versus time.

In an alternative arrangement, the supporting airbed and the body (excluding the circulatory system) are held stationary and the horizontal force \( F_B \) needed to do so is measured. The center of mass is no longer stationary, but the relative acceleration of the body (excluding the circulatory system) with respect to it still remains \( \dot{X} \). Thus, in an inertial frame, the acceleration of the center of mass of the system becomes what was \(-\dot{X}\) in the previous case. Since \( F_B \) results in the acceleration of the center of mass of the system (of mass \( m + M \)), we have

\[
F_B = -(m + M) \dot{X}.
\]

In our implementation, where the subject stands upright on a force platform that records the vertical force \( F \), we have \( F = F_B + (m + M) g \), so that

\[
F = (m + M)(g - \dot{X} \dot{X}).
\]

Note that, in this case, \( W = (m + M) g \) is simply the total weight of the subject, and

\[
\frac{\ddot{X}}{g} = \frac{W - F}{W} = 1 - \frac{F}{W}.
\]

This allows the translation of the force platform output \( F \) to a traditional BCG, which is a record of \( \dot{X}/g \).

The quantities of interest, i.e. those that contain information about the heart and the circulatory system, are \( m \) and \( \dot{x} \), which are related to the ballistocardiographic record (\( \dot{X}/g \)) through Eq. (1). The quantity \( m \) is usually estimated; \( \dot{x} \) is the acceleration of the center of mass of the heart and blood (with respect to the center of mass of the entire body). Clearly, it is not possible to obtain detailed quantitative information regarding the cardiac cycle from a BCG alone. On the other hand, some of the more prominent events of this cycle do show up on a BCG, as discussed below.

The human heart has four chambers: a left and right atrium above the left and right ventricle, respectively. During an individual heartbeat, both atria contract simultaneously, followed by ventricular contraction.\(^2\) Deoxygenated blood enters the right atrium of the heart through the vena cava and is then pumped through the tricuspid valve into the right ventricle. From the right ventricle, blood is pumped through the pulmonary artery to the lungs where it is oxygenated and returned to the left atrium through the pulmonary veins. The blood then passes through the mitral valve into the left ventricle. The contraction of this heavily muscled chamber propels blood into the aorta (toward the head, in the conventional positive direction) and is responsible for the distribution of blood to extremities. Although the entire motion of the heart is represented in the BCG, the contraction of the left ventricle is one obvious feature and is responsible for the large acceleration peak in the negative direction (labeled I in Fig. 2). (Recall that the BCG records the recoil of the body, which will be toward the feet—the negative direction—for this event.) The subsequent positive acceleration peak (labeled J) is due to the impact of blood against the wall of the aorta as this artery curves downward to deliver blood to the lower portion of the body. Calculating the period between beats provides a measurement of pulse rate, while the height of J, the largest peak, can be used to estimate the volume of blood expelled from the heart (for details see Brown et al.\(^3\)). Low volume and other abnormalities can be used for assessment and diagnosis in a clinical setting. This system of measurement is sensitive enough to pick up other physiological movements such as respiration, swallowing, etc.

Typical total variation in \( \dot{X}/g \) is about 0.01 with a time period of about 1 s. A relatively crude BCG would require \( F \) measured to an accuracy of 0.0005 \( \times W \) with a time resolution of about 0.05 s. Data were collected from a PASCO CI-6461 force platform using a computer running Data Studio at the maximum possible sampling rate of 1000 Hz, at a resolution of about 2.8 N \( \approx 0.005 \times W \). Preliminary data-smoothing—a moving average over 50 readings (representing 0.05 s) using Data Studio’s built-in smoothing function—produced BCGs adequate for introductory level lecture-demonstrations (Fig. 1).

A more interesting and feature-rich BCG requires the application of a band-pass filter to reduce noise. The filter was implemented as follows.\(^3\) First, the prominent J-peak was used to identify individual cardiac cycles or frames. Frames that were free of obvious irregularities (as would be caused by sudden...
movement of the subject, for example) were selected for further processing. The Fourier series representation of each selected frame was determined; the zeroth (constant) term and terms beyond the 20th were dropped. Each retained coefficient was averaged across the selected frames, and the truncated series of averaged coefficients was inverse Fourier transformed to yield a single typical or average frame. Figure 2 shows an example.

We have used the ballistocardiography demonstration in two different settings. The first was in an introductory mechanics class predominantly composed of biology majors. The in-class demonstration was introduced by an exercise in predicting and analyzing the force plate output when a student stood on the plate with a vertically oscillating spring-mass system held in her hand—a convenient opening for a discussion of an oscillating system within the body. Smoothed force plate output with the student standing still (see Fig. 1) was of sufficient resolution to read off the pulse rate and display the prominent features within each cycle.

A workshop for visiting high school students provided the second setting. After the same introductory exercise, BCGs were recorded for each student in this small group. The filtered BCGs served to demonstrate variations both between students, as well as for the same student under different conditions (rested versus just after a short run, for example).

It is certainly possible to extend the pedagogical possibilities of this exercise. A quantitative analysis of the peaks and troughs (especially I and J) may be used to estimate heart volume. In a computationally intensive course, filtering of the force plate data can be used as an example of the application of Fourier analysis. Use of BCG in a physiology classroom has been described elsewhere.

In conclusion, we reiterate that combining simplicity with relevance, ballistocardiography is an exercise in introductory physics that will appeal to a broad range of students.

References
3. A Mathematica notebook that implements this filter may be obtained by contacting the authors.

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**Prabasaj Paul** is an assistant professor at the Department of Physics and Astronomy, Denison University. His main research interest is in the analytical and numerical modeling of photonic crystals. paulp@denison.edu

**Laurel B. Symes** graduated with a BS in biology from Denison University and is currently a graduate student in ecology and evolution at Dartmouth College. Her wide-ranging research interests include coloration in damselflies and ballistocardiography. She can be identified by her BCG (Figs. 1 and 2).