A SIMPLE BALLISTOCARDIOGRAPHIC SYSTEM
FOR A MEDICAL CARDIOVASCULAR PHYSIOLOGY COURSE

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Ballistocardiography is an old, noninvasive technique used to record the movements of the body synchronous with the heartbeat due to left ventricular pump activity. Despite the fact that this technique to measure cardiac output has been superseded by more advanced and precise techniques, it is useful for teaching cardiac cycle physiology in an undergraduate practical course because of its noninvasive application in humans, clear physiological and physiopathological analysis, and practical approach to considering cardiac output issues. In the present report, a simple, low cost, easy-to-build ballistocardiography system is implemented together with a theoretical and practical session that includes Newton’s laws, cardiac output, cardiac pump activity, anatomy and physiology of the vessel circulation, vectorial composition, and signal transduction, which makes cardiovascular physiology easy to understand and focuses on the study of cardiac output otherwise seen only with the help of computer simulation or echocardiography. The proposed system is able to record body displacement or force as ballistocardiography traces and its changes caused by different physiological factors. The ballistocardiography session was included in our medical physiology course six years ago with very high acceptance and approval rates from the students.

Key words: cardiac output; physiology teaching; left ventricle; ballistocardiography

The record of heart-induced body movements known as ballistocardiography (BCG) is an old, noninvasive technique used to measure left-ventricular blood ejection. Despite the fact that this technique has been superseded by more advanced and precise techniques, it is still very useful for teaching cardiovascular physiology in an undergraduate course because it is an illustrative, inexpensive, and simple model for cardiac output measurement otherwise performed only by more complicated, expensive, or invasive techniques such as echocardiography or cardiac catheterization (4, 8, 9, 19), which are normally not available for the undergraduate physiology laboratory. The name of the technique is composed of three linguistic roots: ballist-, meaning launching, cardi-, meaning heart, and graph-, meaning recording.

With its hydraulic pump activity, the heart is capable of impelling a volume of ~70–80 ml of blood per beat at considerable speed into the aorta (4). From the physical point of view and following Newton’s Third Law of Motion, every action force is opposed by a reaction force of equal magnitude and opposite direction (10). The anatomic arrangement of the exit from the left ventricle as well as the ascending arch, carotid branches, and descending segments of the aorta (5)
must be taken into account to understand the form in which the cardiac activity generates this action-reaction process. When ventricular ejection occurs and the blood moves through the different segments of the aorta (Fig. 1), a sequence of two main action force vectors is produced (16, 19). The first of them, generated in the ascending aortic segment and carotid branches, has a caudocephalic direction. The second is a cephalocaudal-oriented vector generated when the blood circulates into the descending aortic segment. These action force vectors induce in the body a sequence of reaction force vectors with opposite direction to the blood flow, and these reaction vectors move the body first in the cephalocaudal and after in the caudocephalic orientations (16). The fact that these main force vectors are only two of several generated during the blood’s trajectory through the aortic arch actually induces a three-dimensional displacement of the body (14, 17), but from these displacements, the cephalocaudal and caudocephalic orientation express by and large, the main amplitudes (14, 16, 17). The body displacements are proportional in amplitude to the volume, speed, and acceleration of ventricular left ejection and inversely proportional to the subject body mass. For these reasons, the more body mass has the subject the greater resistance to its movement (16).

The technique is performed by placing a subject on a bed or table with great mobility and very low movement resistance. A pneumatic mattress or a table suspended by cords is generally used for this purpose (16). Body movements are transmitted to the table, which is connected to displacement or force transducers, allowing its recording and indirect estimation of the left-ventricular ejection volume, which is the most important index of left ventricle function (2, 3, 7, 11). A clinically useful BCG system must comply with a series of expensive technical requirements to achieve the needed precision; however, it is possible, for academic purposes, to build a BCG system at low cost with enough sensitivity to visualize, with the naked eye but better with a simple recording device, the BCG body movements.

METHODS

A BCG suspension table for displacement or force recording was designed and built in our Department of Physiological Sciences. A rigid, rectangular, metallic framework taken from an old clinical examination bed was used (Fig. 2A). Four nylon cords (80-kg load capacity each) were affixed to the upper framework at its four corners by means of four adjustable screws for a final suspension distance of 60 cm. A wood table (200 × 40 × 2 cm) was hung by the four nylon cords and perfectly balanced and leveled in the horizontal plane by the adjustable screws. All four nylon suspension cords were placed strictly perpendicular to the table. To reduce the bulk that will be impelled by the force vectors (16) the wood table must be light enough, ≥10 times less than body weight; in the present case, the table was 3.8 kg. The surface of the BCG table must also be rough enough to ensure that the body impulse generated by the cardiac force vectors will be totally transmitted to the table without the body sliding. The surface of the table can be made rough enough by sandpapering.

No electrodes are needed to be connected to the subject. The body impulse transmitted to the table can be evaluated by recording displacement, force, or acceleration by the use of adequate transducers.
connected to the table. This record is presented in a displacement (mm) or force (dyn) vs. time (s) graph. It should be pointed out that the magnitude of the BCG wave (displacement, force, or acceleration) is proportional to the cardiac output (2, 7–9, 11, 15, 19).

PROCEDURES

In a previous theory lecture, the students received background knowledge about the cardiac cycle and cardiac output. During the demonstration, one non-obese male student is chosen from the group, who is then dressed only in light shorts and with shoes off. The subject is instructed to lie still on the BCG table in the dorsal decubitus position with the arms extended alongside the body. After resetting for any initial movement artifact of the table, the BCG effect is easily observed as a longitudinal oscillation of the body.

Recording systems. To record the body oscillations, two types of recording systems can be used: 1) an “L”-type pen acting as a mechanical amplifier with inscription over a classical chemographic drum (Fig. 2B) and 2) electronic transducers whose signal is recorded on an oscilloscope, paper recorder, or computer (the last by means of an analog-to-digital converter). A piezoelectric crystal taken from a kitchen lighter can be used as a practical force transducer. It must be fixed rigidly to the BCG frame and in contact with the table (Fig. 2C). With this setup, no movements will be seen on the table, but the force vectors will be recorded by the piezo device when its two pole wires are connected directly to the input of an oscilloscope for visual monitoring or to an electrocardiograph (right foot and one precordial lead) to obtain a paper trace. In both setups, the record can be quantified by measuring either the wave amplitude or the area under the curve. The BCG waves can be recorded continuously over 5–20 heart beats or as an average curve according to the recording system available. The data presented here use real basetime, i.e., not normalized to an ECG. An additional improvement of the session could be the use of a two-channel recording system, one for the BCG and another for an ECG for a simultaneous recording; this setup demonstrates the time relation between both signals.

The BCG is able to record not only cardiovascular function but also respiratory and body movement-related motion (8, 13, 14); thus instructions to the test subject must be given to carefully avoid muscular movements and perform a relaxed respiratory rhythm, thus reducing recording artifacts. Changes in the BCG amplitude waves reflect changes in intrathoracic pressure variation (13). Another way to reduce respiratory artifacts during the recording is to hold the breath for 15–30 s (13).

Teaching session. The demonstration is easy enough to allow the hands-on participation of the students during the subject preparation, recording,
and analysis of BCG waves. The teaching session implemented in our physiology course consists of three parts of 30 min each. 1) The first part of the session includes recordings of the BCG waves during the following experimental situations: a) normal respiration, b) maximum sustained inspiration, c) maximum sustained expiration, d) increase of body weight (simulated by addition of weights to the BCG table), e) application of tourniquets to the arms and legs, and f) elevation of feet and knees. These BCG recordings induce curiosity in the students and expectation about the origin or causes of recorded waves. 2) The second part of the session is designed to explain and discuss interactively the anatomic and physiological bases of cardiac output and BCG, focusing on left-ventricular ejection and involved factors. For this part, useful hemodynamic values of cardiac output (1) are discussed, such as the cardiac index, e.g., the blood volume ejected by the heart per minute per body surface area unit, being $3.5 \pm 0.7 \text{ l m}^{-1} \text{min}^{-1} \text{m}^{-2}$ (mean $\pm$ SD), and the stroke index, e.g., the blood volume ejected per heartbeat related to body surface area unit, being $46 \pm 8.1 \text{ ml beat}^{-1} \text{m}^{-2} \text{m}^{-2}$ (mean $\pm$ SD); all values are related to the body surface to make them adaptable to any person. These parameters enrich the discussion about the intense pump activity of the heart and how it is able to induce the BCG body movements. Finally, 3) there is discussion about the clinical relevance of the cardiac output recording as well as other, more used and more precise, noninvasive or invasive, measurement methods, such as echocardiography and cardiac catheterization, respectively.

During the session, the students can gradually answer the following questions. 1) What is the morphology of the BCG wave? 2) Explain the origin of the BCG movement vectors. 3) Indicate the key elements of the BCG recording system. 4) Explain the relationship between left-ventricular ejection volume and BCG body movement. 5) Explain the effect of deep inspiration on cardiac output. 6) Explain the effect of deep expiration on cardiac output. 7) Explain the effect of body weight on the BCG waves. 8) Explain the effect of the vascular tourniquets on cardiac output. 9) Explain the effect of foot or knee elevation on cardiac output. 10) Indicate the clinical methods used at present to measure cardiac output and their relevance.

RESULTS AND CONCLUSIONS

An example of a mechanically recorded BCG with an L-type pen on a chemographic drum is presented in Fig. 3, where the displacement (nm) of the BCG table is presented on the ordinate and the recording time (s) on the abscissa. The left-ventricular systolic and diastolic events are time-related to the BCG waves. The predominance of the caudocephalic displacement vector (outline upward) in the recording indicates that the major force vector of the cardiac activity induced in the body is generated when blood circulates through the descending aorta during late systole. By use of the piezoelectrical transducer and the electrocardiograph, the BCG paper record displays more waves per heartbeat (Fig. 4, A–D) due to the natural frequency of the suspension bed used. The high sensitivity of the transducer is able to record the major force vectors and the passive damping of the bed until the next heartbeat.

Changes in the blood returning to the heart also induce changes in the BCG wave amplitude. Deep inspiration increases, whereas deep expiration or application of tourniquets in arms and legs decreases, BCG amplitude (Fig. 4B) due to the increase or decrease, respectively, of the preload (3, 9, 13, 14, 17). If feet and/or knees are raised, the blood flow to the legs decreases the cephalocaudal force vector, thus reducing the BCG amplitude (Fig. 4C) and increasing...
the head blood flow (Trendelenburg maneuver). One of the characteristics of the BCG recording is its inverse dependence on body mass (16). This fact is demonstrated by increasing the body mass, simulated by adding weights to the BCG table, which consequently reduces the wave amplitude (Fig. 4D).

The recording of the BCG allows the direct hands-on participation of at least four or five students; wave analysis allows whole-group participation. In this way, the BCG demonstration is equivalent to other practical sessions, such as with an ECG. The system described here is easy to build and use, which makes it possible to have two recording setups to increase the direct participation of more students in the session group. The BCG system and the session described in the present report have been successfully implemented in the undergraduate medical physiology course, and its take-home messages are the strength of the heart as a hydraulic pump, the BCG waves as a consequence of left-ventricular ejection, and their changes in different situations. Yearly evaluations of the session were made to assess student satisfaction at the end of the course. This evaluation was made during the past six years with a total of 1,260 students (210 per year) using a five-question survey with a 0 (bad)-to-5 (very good) rate scale obtaining the following values [mean (SD) [Mode]]:

1) How do you rate the overall BCG session? 4.82 (0.31) [5]

2) How do you rate the simplicity and clarity of the BCG session? 4.91 (0.48) [5]
3) Is the information from the BCG session useful and/or relevant to medical practice? 4.68 (0.54) [5]
4) Did the BCG session help you better understand heart pump activity and cardiac output? 4.85 (0.27) [5]
5) How do you rate the planning and duration of the BCG session? 4.92 (0.43) [5]
6) How do you rate the support material (guidelines)? 4.75 (0.62) [5]

Similar Likert rate scales have been used in the evaluations of other physiology courses (6), and the present results strongly suggest the students’ high satisfaction, with the BCG session described here as one of the most interesting physiology sessions. An intense teacher-student interaction, clear laboratory activity guidelines, and a demonstration technique divided into three parts (30 min per part for a total duration of 90 min) could have contributed to the high student ratings for the session (18). Student judgements were associated with a significantly high percentage of correct answers (96.2%) to cardiac output and cardiac pump activity multiple-choice questions and/or descriptive exams; this contrasts with the lower percentage of correct answers from the students (72.1%, P = 0.034) before implementation of this activity.

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