Echocardiography for Teaching Cardiac Physiology in Practical Student Courses

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We have introduced echocardiography into the physiology courses for medical students to improve their understanding of cardiac physiology. Echocardiography allows a visualization of the events of the cardiac cycle and facilitates the correlation of anatomic structures with their physiological functions. The students record views on the human heart in the long and short axis, they follow wall and valve motions, and they interpret the obtained data in correlation with electrocardiography and phonocardiography. Echocardiography offers the opportunity to measure the interval of isovolumetric contraction and isovolumetric relaxation and permits the calculation of parameters assigned to left ventricular contractility. An evaluation showed that medical students consider echocardiography to be the most significant and interesting part of the physiology courses. In conclusion, echocardiography has been shown to be a valuable tool for teaching cardiac physiology.


Key words: physiology education; heart cycle; valve function

In teaching cardiovascular physiology, we have to deal with the major problem inherent to a successful transfer of information: although we are forced to present a great number of crucial data, we should avoid a simple cumulative presentation of theoretical details, because this often overstrains the students' ability to absorb substantial information. A valuable tool to encourage the students' interest in physiology, and thereby to improve their knowledge, is the presentation of physiological facts with the support of practical exercises. The topics of these practical exercises must be chosen carefully, because the time available for the discussion of the various physiological systems is limited. Because of scientific progress, medicine is subjected to continuous changes concerning both the methods of investigation and the concepts of therapeutic interventions. Medical education has to participate in scientific progress, not only to make sure that the students become familiar with new diagnostic tools but also to provide them with the substantial knowledge they need for a correct interpretation of the limits and possibilities inherent in a diagnostic technique. A method chosen for practical courses for students thus ought to achieve two goals: it should be suitable for the presentation of physiological processes, and it should be relevant for today's medical practice.

Faced with these preconditions, we integrated an introduction to echocardiography into the physiology courses for students. Today echocardiography is a widespread diagnostic aid for the clinician that is apt to further the students' interest in cardiovascular physiology. Echocardiography allows the correlation of anatomic structures with their physiological functions, thereby representing a powerful device to close the gap between theoretical knowledge and its practical application. Ultrasound can create pic-
tures of cardiac structures with a high resolution, and it records the motion of these structures over a certain period of time, thereby providing a facility to assess parameters assigned to the function of the heart. Echocardiography requires no preparation of the subject under investigation. It is a painless, noninvasive technique with no side effects known so far. Therefore echocardiographic measurements can be done repeatedly to investigate serial changes. Because no laboratory animals are needed, the problems associated with the use of animals for physiology education are avoided. The echocardiographic equipment for basic examinations is not too expensive, and the examination of a heart takes little time. Echocardiography can be combined with Doppler techniques to get more detailed information about blood flow velocities. These facts explain why echocardiography has become increasingly popular for medical purposes and make it attractive for teaching cardiac physiology in practical courses.

Nowadays, most physiology textbooks include echocardiographic recordings. But in contrast to the electrocardiogram (ECG), which is presented exhaustively in these textbooks, echocardiography is only discussed to a minor extent. It is strange that this should be so, because ultrasonic imaging is at present the technique used most widely for examining details of cardiovascular structure and function (e.g., 2, 6, 7).

The simultaneous recording of echocardiography, phonocardiography, and electrocardiography enables the student to follow physiological processes and their coordination over time. This definitely provides students with a better understanding of the events of the cardiac cycle.

Echocardiography encourages an integrative way of thinking, because it requires knowledge of several basic disciplines, such as physics, anatomy, and physiology, and can contribute to crossing the borders between basic and clinical sciences.

**ECHOCARDIOGRAPHIC APPARATUS**

A mechanical sector scanner providing B-mode sector image and M-mode image with a 3-MHz probe, middle focus type, and 80° scanning angle (model SSD-725, Aloka, Tokyo, Japan) was used. ECG signals can be displayed in B- and M-modes. Phonocardiography can be monitored in M-mode.

**GENERAL PROCEDURE**

Teaching students at preclinical levels in echocardiography requires an introduction into the physical and physiological basics with respect to their significance for the estimation of cardiophysiological parameters. Before the practical courses, these basics are taught in the lecture hall with a script being dealt out, which gives insight into the basics of echocardiography. The script also contains prefabricated worksheets on which to observe and calculate the changes of echocardiographic parameters during exercise. In addition, the students are to ascribe the terms of systole, diastole, isovolumetric contraction, and relaxation to M-mode echocardiographic recordings in conjunction with phonocardiograms (PCGs) and ECGs.

The students become familiar with the principles underlying echocardiographic examinations when they repeat some aspects of medical physics, as for example the piezoelectric generation of ultrasound and the reflection between two media depending on the acoustic impedance. The principles by which ultrasound creates pictures is described with respect to A-, B-, and M-mode echocardiography. Resolution and degree of penetration as a function of the frequency used are discussed.

Because ultrasound cannot penetrate the air-containing lung or bony structures, echocardiographic monitoring is restricted to positions that avoid these strongly absorbing or reflecting tissues. These positions are found in the intercostal spaces along the left sternal border, subxyphoidal and suprasternal. The orthogonal planes for echocardiographic imaging are the long-axis plane, the short-axis plane, and the four-chamber plane. The latter can be obtained from the cardiac apex.

A two-dimensional image of the heart along the long axis is obtained with the transducer in the parasternal position. The anatomic structures that can be demonstrated are the right ventricle (RV), the interventricular septum (IVS), the left ventricle (LV) with the LV posterior wall (LVPW) and its posterior boundary made up by epicardial and pericardial echoes.
the aorta (Ao), the mitral valve (MV) with its anterior and posterior leaflet (AMVL and PMVL), and the left atrium (LA), as shown in Fig. 1. By rotating the transducer 90°, a parasternal short-axis view is obtained. Views on the heart in the parasternal long and short axes are shown and later practiced by the students.

The one-dimensional M-mode recording at the level of the chordae tendineae can be used to measure the wall thickness of the IVS, the LVPW, and the diameter of the LV at the end of systolic and diastolic. Their value for the diagnosis of LV hypertrophy and dilatation is discussed with the students. The end-diastolic diameter (EDD), the thickness of the LV wall, and the LV end-diastolic pressure (LVEDP) determine the “preload” of the heart. From the end-systolic diameter (ESD) and the EDD, the fractional shortening (FS) can be calculated according to the equation

\[ \text{FS(\%)} = \left( \frac{\text{EDD} - \text{ESD}}{\text{EDD}} \right) \times 100 \]

Normal values are found to be > 28% (5). Because the FS shows a linear correlation to angiographic LV ejection fraction, it is considered to be a measure of LV contractility. When the ESD decreases because of an increase of contractility, the FS rises, resulting in a higher ejection fraction. This can be demonstrated by echocardiographic recordings before and after physical exercise, as shown in Fig. 2.

The LV end-systolic and end-diastolic volumes (ESV and EDV, respectively) can be estimated from the ESD or EDD according to the formula of Pombo

\[ V(\text{ml}) = D^3 \]

which describes the LV as a prolate ellipse. Teichholz modified this “D^3 method” by changing the formula to

\[ V = \frac{7 \times D^3}{(2.4 + D)} \]

resulting in a better correlation between angiography and echocardiography for LV volumes > 200 ml. The difference between ESV and EDV is calcu-
FIG. 2
M-mode echocardiographic recording of LV before (left) and after (right) physical exercise. EDD, 41 mm; ESD, 27 mm before and 21 mm after exercise (15 knee bends in 30 s). Fractional shortening (FS) is calculated and found to rise from 34 to 49% during exercise.

lated as the stroke volume (SV). SV multiplied by heart rate gives the cardiac output (CO)

\[ \text{CO (l/min) = SV \times HR} \]

The ejection fraction is calculated by dividing SV by EDV

\[ \text{EF(%) = (SV/EDV) \times 100} \]

The estimation of LV volumes by M-mode echocardiography has to be considered critically, because several assumptions that are not always valid are required, for example, that the LV approximates a prolate ellipse and that the wall motion recorded by the measured ESD and EDD is representative of the entire ventricle. Moreover, the formulas do not take into account that the systolic shortening of the ventricle is associated with an anterior and rotational movement of the heart. Therefore, in today's clinical practice, M-mode echocardiography has lost its relevance for estimating LV volumes in favor of two-dimensional echocardiography.

M-mode recordings with simultaneous recording of ECG and PCG enable the student to follow the events of the heart cycle over time. With the beginning of ventricular relaxation, the intraventricular pressure falls below the aortic diastolic pressure and the semilunar valves close, giving rise to the second heart sound, which can be displayed phonocardiographically during an M-mode recording of the MV. The MV remains closed, and the ventricular muscle continues to relax for another 30–60 ms until the LV pressure has dropped below the blood pressure in the LA. Thereafter the MV opens, and the students can see the characteristic biphasic opening motion of the leaflets as shown in Fig. 3. The period, measured as the interval between the second heart sound and the beginning of the MV opening movement, is called isovolumetric relaxation. The maximum excursion of the leaflets during early diastole is called "E." It is a consequence of the rapid filling of the ventricle due to myocardial relaxation and upward movement of the ventricular base. A third heart sound would occur during the E-F or closing slope of the MV (1, 3). In adults a distinct third heart sound is usually heard under pathological circumstances, as for example heart failure with ventricular diastolic gallop rhythm. During the middle third of diastole blood flow is diminished. This corresponds to the mid-diastolic closing wave F and reflects the phase of slow ventricular filling or diastasis. During the latter third of diastole, atria contract and the MV leaflets reopen again, giving rise to the A wave. The end-diastolic MV motion after LA contraction reflects the diastolic function of the heart. The amplitude of the A wave is normally lower than the D-E wave.
amplitude. With decreasing LV compliance, the F wave decreases as a consequence of diminished passive ventricular filling in the early diastole, and the A wave increases because of a vigorous atrial contraction. This phenomenon is commonly associated with diastolic heart failure. The relaxation of the myocardium during early diastole has been described by the term lusitropy. A fourth heart sound occurs during the A-C period, is preceded by the P wave in the ECG, and follows immediately the LA contraction. This heart sound is associated with a high blood volume in the atria during late diastole and an increased atrial contraction, which can be indicative of diminished filling of the ventricle during early diastole due to an alteration of ventricular compliance.

The systolic part of the heart cycle can be observed in an M-mode recording of the aortic valve. After the QRS complex the first heart sound is heard, and the MV closes. It takes another 10–50 ms until the aortic valve opens, as soon as the LV pressure exceeds the diastolic pressure in the aorta. Ventricular myocardium contracts during this period, but there is no ejection of blood. This period is called isovolumetric contraction. The period of LV ejection time (LVET: 280 ± 20 ms) is measured as the interval of systolic separation of the aortic valve leaflets.

The FS as described above is widely applied to assess LV contractility. Another M-mode echocardiographic technique for assessing LV performance is the quotient of FS and ejection time. This quotient provides the mean velocity of circumferential fiber shortening or mean circumferential shortening

\[ \text{VCF mean} (\text{circ/s}) = \frac{(\text{EDD} - \text{ESD})}{(\text{EDD} \times \text{ET})} \]

Normal values are found to be > 1 circ/s. VCF shows a good correlation to ejection fraction as long as the ventricle contracts uniformly to reflect global function of the LV, but it depends also on heart rate and ventricle size.

An M-mode recording of aortic valve leaflet motions allows the visualization of a physiological process that has been a matter of long-lasting controversy in the course of medical history. The reduced blood flow in the coronary arteries during ventricular systole has been considered to result from the movement of the aortic valve leaflets toward the ostia of the coronary arteries until the ostia are occluded and the blood flow declines. This was postulated by Thebesius and later propagated by Bruecke (see Tigerstedt, Ref. 9). The decrease of coronary blood flow during systole due to the suprasystolic intramyocardial pressure of the ventricle, and not to an occlusion of coronary ostia, was claimed by the anatomist Hyrtl in 1855 ("Über die Selbststeuerung des Herzens") and led to a conflict with contemporary physiologists. An M-mode recording of the aortic valve leaflets (Fig. 4) supports Hyrtl’s assumption, because it clearly shows that, indeed, the aortic valve leaflets do not touch the aortic wall during their systolic separation, which disables them to obstruct the coronary ostia. The pressure within an area of increasing flow has to fall as a consequence of the Bernoulli equation. The resulting “suction” and the configuration of the aortic sinus prevent the aortic valve leaflets from completely occluding the coronary ostia.

EVALUATION

To evaluate the acceptance of echocardiography, students (n = 62) were asked whether they considered each topic of their practical exercises significant or interesting, respectively, and they demonstrated their degree of agreement by giving a value between 0 and 10. Among the various topics of medical physiology, echocardiography achieved the best acceptance as shown in Fig. 5.

DISCUSSION

The correct interpretation of an echocardiographic examination demands knowledge of several medical disciplines such as physics, anatomy, and physiology. Thereby echocardiography necessitates an integrative way of understanding preclinical basic sciences and favors an interdisciplinary approach to medical education. Integrative learning prepares students to deal with complex medical situations and forces them to retrieve and rearrange the knowledge that they acquire from several disciplines.
We should be aware of the problems that arise in introducing echocardiography for student practice during the physiology courses. As a prerequisite, members of the department need to be advised of the skills necessary for basic echocardiographic examinations. This point should be considered clearly, because the quality of an echocardiographic examination depends most of all on the routine of the examiner.

The student's acceptance of echocardiographic practice in the physiology courses promises that echocardiography will be an opportunity to make basic medical education more interesting. Why do students consider echocardiography to be such a valuable tool for teaching physiology? Obviously echocardiography connects basic to clinical sciences. Any effort linking theoretical knowledge of basic sciences to clinically relevant methods evokes the interest of medical students. Echocardiography shows clearly the necessity of basic physiological knowledge for clinical applications. The "insight" into the living heart makes their education far less abstract and clearly illustrates the morphological changes underlying cardiophysiological events. Echocardiography provides a fascinating way to scrutinize the coordination of heart sounds and valve motions over time. Isovolumetric relaxation, isovolumetric contraction, and the filling of the left ventricle in early and late diastole can be presented clearly.

An introduction to echocardiography provides students with insights into a relatively new diagnostic method that was established in the 1960s. Echocardiography is routinely performed by specialists.
TABLE 1
Formulas to calculate LV mass and wall stress from simple echocardiographic and cardiophysiological measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula</th>
<th>Reference No.</th>
</tr>
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<tbody>
<tr>
<td>SWS</td>
<td>$0.334 \times \frac{SAP \times LVESD}{LVPWs} \times (1 + \frac{LVESD}{LVPWs})$</td>
<td>8</td>
</tr>
<tr>
<td>LVM</td>
<td>$1.05 \times [\frac{(LVPWd + IVSd + LVEDD)^3}{LVESD} - 14 g$</td>
<td>3a</td>
</tr>
</tbody>
</table>

SWS, systolic wall stress ($10^5$ dyn/cm$^2$); SAP, systolic arterial pressure (mmHg); LVESD, left ventricular end-systolic diameter; LVPWs, LV posterior wall (end-systolic), LVM, LV mass (g), LVPWd, LV posterior wall (end-diastolic); IVSd, inter-ventricular septum (end-systolic); LVEDD, LV end-diastolic diameter.

However, the physician who decides about diagnostic efforts and treatment for the patient also has to know about the limits and the value of echocardiography to assure the suitability and the correct interpretation of the examination. Physicians who are not familiar with echocardiography find this technique extremely confusing. For example, many physicians are not aware of the fact that the mitral valve closes in middiastole because the blood flow diminishes between passive and active filling of the ventricle (4).

Physicians should be aware of the problems inherent in a determination of cardiac volumes by means of echocardiography. Any technique that attempts to calculate volumes from an examination that is less than truly three-dimensional permits only an approximate estimation of the volume, and its relevance should not be overrated. The integration of echocardiography into the physiology courses improves students' ability to evaluate the suitability of an echocardiographic examination and has certainly contributed to progress in medical education.

APPENDIX

Table 1 shows formulas to calculate left ventricular mass and wall stress, which is a quantitative index of myocardial afterload, from simple echocardiographic and cardiophysiological measurements that seem to be useful for educational purposes although they are not routinely applied for clinical purposes because the inter- and intraobserver variability is high. Further measurements of left ventricular function are the mitral E point-septal separation, which is an indicator of global left ventricular performance and correlates inversely with ejection fraction, and the difference between electrocardiographic PR interval (beginning of P wave to beginning of R wave) and echocardiographic A-C interval, which should give a value of < 0.06 s and correlates with left ventricular end-diastolic pressure (5).

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References
Teachers and their students may find the following articles from *News in Physiological Sciences* useful when exploring cardiac physiology:

