Ultrasound imaging in teaching cardiac physiology

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Ultrasound imaging offers a look inside the body in living human beings. The visualization of complicated structures, such as the heart as it beats, conveys so much more information than words can express in conventional lectures and practical laboratory sessions. This has been recognised and, to a degree, exploited successfully in anatomy teaching (4, 5, 10). However, there has been very little use in the teaching of basic physiology to either undergraduate scientists or medical students (1). In our experience, some areas of cardiovascular physiology, such as Frank-Starling’s law of the heart, are not totally appreciated by students. Ultrasound technology may be helpful in this area. In addition to seeing the aesthetic beauty of the inner workings of the valves and chambers of the heart during the cardiac cycle, subtleties of cardiac function that are of great significance physiologically, for example, the fact that the heart does not empty on each systolic contraction, is not so apparent when discussing cardiac function, even with the aid of pictures or illustrations. These become immediately obvious when viewing the beating heart with ultrasound.

Only a few reports have previously described the use of ultrasound in the practical laboratory to enhance teaching of principles of cardiac physiology and anatomy and have been both effective in the teaching of the subject matter and popular with students (2–4, 7, 9). The activities described offer excellent learning opportunities for students. Yet, some of the teaching processes were concerned with gaining hands-on experience of ultrasound as much as the interpretation of the images along with the acquisition of relatively large amounts of group data to make interpretations.

We hypothesized that our teaching of cardiovascular physiology may benefit from incorporating the use of an ultrasound imaging system. Here, we describe the methodology used to demonstrate these aspects of physiology and report the perceptions of the students of their understanding of the concepts both before and after the teaching.

METHODS

Ultrasound Imaging Procedures

In a practical class setting, we used a portable ultrasound machine that is simple to use (effective presets controls to optimize the image quality) and has the capacity for the output to be made visible to students via networked computers or overhead projector (Sonoscape S2 with 2P1 4-2 MHz Phased-Array Cardiac Transducer, Sonoscape Medical, Shenzhen, China). A suitable male subject (with good acoustic windows, that is, with clear views of the heart between the ribs) was identified, and his informed consent was taken to act as a subject. This activity was best performed with the subject sitting upright on a cycle ergometer to allow for relatively quick cardiac imaging. These noninvasive experiments do not require ethical approval at our institution. However, ethical approval to collect data from questionnaires from students participating in the class was granted by Queen’s University School of Medicine, Dentistry and Biomedical Sciences ethics committee.

The class lead conducted the ultrasound procedures, which were displayed on computers throughout the class. The following procedures were undertaken:

1. The session normally begins by obtaining the parasternal long-axis view (Fig. 1), in which a longitudinal section through the heart is obtained, where the left ventricle (LV), septal wall, and right ventricle (RV) are easily visible along with the left atrium and mitral and aortic valves. Although no measurements are taken from this view, it is excellent for orientating the students’ view of the ultrasound image and understanding the position of the transducer on the chest wall in relation to the position of the heart within the chest and the sequence of events in the left heart during the cardiac cycle.

2. The parasternal short-axis view (Fig. 2) was then obtained, in which the LV and RV are seen in cross section. What is most striking is the dominating nature of the LV with respect to the RV. The LV appears as a relatively thick-walled and definitely round structure, with the RV appearing almost as an add-on, having a less defined structure and reduced muscle mass. By tilting the probe toward the apex along the ventricle toward the atrium, structures including the papillary muscle, mitral valve, and aortic valve are visible. LV chamber diameter and wall thickness are easily measured at a mid-papillary muscle level (although these measurements are usually made from M-mode images clinically). By recording a loop over a few cardiac cycles, it is possible to make these measurements at end systole and end diastole (gauged by an ECG recording, if taken). Ventricular cross-sectional areas can then be calculated, either by using area calculator software by tracing around the endocardial
diameter border or calculated \( \pi r^2 \) (where \( r \) is the radius) after measuring diameter via calliper functions on the ultrasound image or may even be made physically with a ruler from a printed image. In this view of the apical four-chamber view (below), the significance of end-diastolic dimensions may be mentioned in terms of initial cardiac myofibril stretch and the subsequent force of contraction (Frank-Starling law) and the proportion of stroke volume (SV) can be expressed as a fraction of end-diastolic volume [ejection fraction (EF)].

3. The final view is the apical four-chamber view (Fig. 3), in which all four chambers are clearly visible, as are the mitral and tricuspid valves and the aortic outflow, depending on the angle of the probe. Again, by recording a loop of a few cardiac cycles, the ventricle lengths in systole and diastole can be measured. Although it is not recommended as normal sonographic measurement practice, LV diameters can be measured in this view as well. The systolic and diastolic cross-sectional areas and lengths may then be used in the “area length” equation to calculate ventricular volumes.

4. LV volume measurements were then repeated after the subject performed a brief period of exercise on the cycle ergometer (2 min at relatively high intensity), and the measurements to calculate volume (LV diameters and lengths in systole and diastole) were repeated. It is more likely that an increase in end-diastolic volume will be measureable in subjects in the upright position compared with when supine (8).

Calculations of Ventricular Volumes, SV, and EF

LV end-systolic and end-diastolic volumes. LV end-systolic volume (LVESV) and LV end-diastolic volume (LVEDV) were calculated as follows:

\[
LV\,\text{volume} = \left(5 \times LV\,\text{cross-sectional area} \times \text{ventricular length}\right)/6
\]

Fig. 1. Parasternal long-axis view of the heart (end diastole). The left ventricular (LV) and left atrial (LA) chambers are readily visible, as is the movement of mitral valve (MV) and aortic valve (AV) leaflets. The right ventricle (RV) and root of the aorta (Ao) are also clear. The transducer is placed just to the left of the sternum around the third or fourth intercostal space. The “marker” on the transducer head is orientated in line with the right shoulder.

Fig. 2. Parasternal short-axis view just below the MV, from which the internal and epicardial diameters of the LV chamber can be measured in systole and diastole (arrows). The transducer is placed as in the parasternal long-axis view except that the “marker” on the transducer head is orientated in line with the left shoulder.
LV cross-sectional area = \pi r^2 \text{(where } r = \text{diameter of } \text{LV}/2)\)

\(LV\ SV\). LV SV represents the volume of blood in the LV that is ejected in one cardiac cycle. LV SV was calculated as follows:

\[
SV = \frac{LVEDV}{LVESV}
\]

\(EF\). EF represents the amount of blood ejected from the LV as a fraction of the volume of blood in the ventricle before contraction (end-diastolic volume). EF was calculated as follows:

\[
EF = \frac{SV}{LVEDV} \times 100\%
\]

As part of the class, students witnessed these images being captured and the measurements being made. They are required to enter the measurements that are called out as they are made into the relevant table (for example, Table 1) and then perform the calculations to derive ventricular volumes and EFs. End-diastolic diameter gives an indication of ventricular stretch (preload). EF gives an indication of ventricular work and function.

**Evaluation of Student Perceptions of Teaching Effectiveness**

Students were asked to rate their understanding of the Frank-Starling law before and after the ultrasound class. Questions were also asked on the usefulness of the class. All questions are shown in Table 2. A five-point Likert scale was used to evaluate the response to the questions (where 5 = strongly agree and 1 = strongly disagree). Data are presented as means \pm SE. A paired Student’s t-test was used to discern whether students perceived their understanding to be better after the teaching with ultrasound compared with before. There was also an open-ended question to which the students could give a written response, asking to comment about the use of ultrasound in teaching physiological concepts.

**RESULTS**

**Expected Imaging Results and Evaluation of Student Work**

Sample measurements taken from the resting images of the LV in a single subject are shown in Table 1, which also contains normal ranges for most common measurements and the results of the calculations provided above. From the basic LV dimension measurements in systole and diastole, the ventricular areas and then volumes can be simply calculated and, hence, ventricular EF. After exercise (Table 1), a moderate increase in end-diastolic diameter and length and, therefore, volume was seen, as was an increase in EF.

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**Table 1. Results at rest and after exercise from a single representative subject**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Subject Value (Normal Range for a Male Subject) (6)</th>
<th>After Exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV diameter at end diastole, cm</td>
<td>5.0 (4.2–5.9)</td>
<td>5.2</td>
</tr>
<tr>
<td>LV diameter at end systole cm</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Posterior wall at end diastole, cm</td>
<td>0.9 (0.6–1.0)</td>
<td>—</td>
</tr>
<tr>
<td>LV length at end diastole, cm</td>
<td>7.8</td>
<td>8.5</td>
</tr>
<tr>
<td>LV length at end systole, cm</td>
<td>7.2</td>
<td>6.8</td>
</tr>
<tr>
<td>Calculated end-diastolic LV area, cm²</td>
<td>19.6</td>
<td>21.2</td>
</tr>
<tr>
<td>Calculated end-systolic LV area, cm²</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>Calculated LV volume at end diastole, ml</td>
<td>127.4 (67–155)</td>
<td>150.0</td>
</tr>
<tr>
<td>Calculated LV volume at end systole, ml</td>
<td>45.0 (22–58)</td>
<td>42.5</td>
</tr>
<tr>
<td>Calculated LV stroke volume, ml</td>
<td>82.4 (75–100)</td>
<td>107.5</td>
</tr>
<tr>
<td>Calculated LV ejection fraction, %</td>
<td>64.8 (&gt;54 %)</td>
<td>71.7</td>
</tr>
</tbody>
</table>

LV, left ventricular.
Table 2. Student feedback from 114 subjects

<table>
<thead>
<tr>
<th>Question</th>
<th>Strongly Disagree/Disagree, %</th>
<th>Neutral, %</th>
<th>Agree, %</th>
<th>Strongly Agree, %</th>
<th>Mean ± SE Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>I understood Starling’s law of the heart well before the ultrasound class</td>
<td>52</td>
<td>17</td>
<td>18</td>
<td>3</td>
<td>2.77 ± 0.10</td>
</tr>
<tr>
<td>I understood Starling’s law of the heart well after the ultrasound class</td>
<td>7</td>
<td>20</td>
<td>56</td>
<td>17</td>
<td>3.82 ± 0.07*</td>
</tr>
<tr>
<td>Ultrasound enabled me to visualize the Frank-Starling processes better</td>
<td>8</td>
<td>13</td>
<td>54</td>
<td>25</td>
<td>3.91 ± 0.08</td>
</tr>
<tr>
<td>Using ultrasound to calculate cardiac parameters is useful</td>
<td>0</td>
<td>6</td>
<td>52</td>
<td>42</td>
<td>4.36 ± 0.06</td>
</tr>
<tr>
<td>I enjoyed the teaching sessions that incorporated ultrasound</td>
<td>1</td>
<td>10</td>
<td>48</td>
<td>41</td>
<td>4.29 ± 0.06</td>
</tr>
<tr>
<td>The use of ultrasound in teaching is more effective than conventional methods</td>
<td>5</td>
<td>19</td>
<td>41</td>
<td>35</td>
<td>4.03 ± 0.08</td>
</tr>
<tr>
<td>Calculating physiological parameters using ultrasound is useful</td>
<td>1</td>
<td>10</td>
<td>47</td>
<td>48</td>
<td>4.29 ± 0.06</td>
</tr>
</tbody>
</table>

Scores were as follows: strongly disagree = 0, disagree = 1, neutral = 3, agree = 4, and strongly agree = 5. *P < 0.001 by paired Student’s t-test.

**Evaluation of Student Perceptions of Teaching Effectiveness**

There was a significant increase in understanding of the Frank-Starling law reported by the students (Table 2), with scores increasing from 2.77 ± 0.10 before the class to 3.82 ± 0.07 after the class (n = 114, P < 0.001 by paired Student’s t-test). This equated to only 21% agreeing/strongly agreeing that they understood Starling’s law of the heart before the ultrasound class, improving to 73% after. Students scored a statement on how ultrasound enabled better visualization of the Frank-Starling law with a mean of 3.91 ± 0.08, with 79% of students agreeing/strongly agreeing with this statement. Students particularly reported on the usefulness of performing calculations (4.36 ± 0.06), with 94% agreeing/strongly agreeing that this was useful. The ultrasound proved to be extremely popular among these students, with 89% agreeing/strongly agreeing that they enjoyed the teaching session (4.29 ± 0.06).

Students were also asked to respond with free text comments, and, commonly, students reported that they could visualize and understand the concepts better, appreciated the clinical application of the physiological concepts, and had a better understanding of the application of the calculations for cardiac output. There were also many comments on how much they enjoyed the session.

**DISCUSSION**

We examined the use of ultrasound imaging in the teaching of factors surrounding increased cardiac output and, in particular, the Frank-Starling law of the heart. By witnessing the images of the beating heart, seeing ventricular measurements being made, and then calculating ventricular volumes and EF, students felt that their understanding of these concepts was greatly improved.

We have developed simple and quick procedures that offer students an opportunity to see the heart working at rest and responding to exercise, without emphasis on the process of acquiring images. From images projected on a screen or to networked computers, students can observe simple measurements of basic cardiac dimensions being made and then calculate indications of LV function from those measurements. This allows derivation of meaningful values of cardiac function from basic principles. This can lead to an exploration of the interplay of cardiac and vascular changes that occur in response to exercise and factors that affect cardiac output (such as Frank-Starling’s law) and arterial blood pressure. It must be emphasised that the intention of the session is not to teach students the techniques of ultrasound but rather to use ultrasound as a teaching tool to image the beating heart.

It is envisaged that students are asked to elaborate on their findings. This could involve comments on the dimensions and function of the subject’s heart. It is of value to go through a process of evaluation and make a rough assessment as to whether the values obtained are normal. Most measurements and calculated values are usually normal, but if not, students can discuss whether this might be due to a genuine abnormality in the subject or due to some form of experimental error. Along the lines of the latter, it is useful for students to speculate as to what those sources of error might be, such as imaging issues and measurement inaccuracies.

This investigation is particularly useful for discussions of factors that may influence cardiac output during/after exercise. This requires a basic knowledge of the intrinsic and extrinsic mechanisms that coordinate control of cardiac output and, specifically, the factors that contribute to the increased SV and EF during and after exercise. These include the following:

1. Autonomic control of the heart. The concurrent increase in sympathetic drive to the heart from sympathetic innervation and circulating catecholamines along with parasympathetic withdrawal results in an immediate increase in heart rate. Their effects are also seen in the increased contractility of cardiac muscle that increases SV and EF.

2. Frank-Starling mechanism. There can be an increase in the ventricular stretch (end-diastolic volume) before contraction that increases the force of contraction and is partly due to the skeletal muscle pump, which increases venous return due to the action of the working muscles compressing muscular veins and venous valves combining to push blood toward the heart.

3. Sympathetic control of blood vessels. Differentiated control of sympathetic outflow can increase to “nonessential” organs such as the splanchnic circulation, skin (unless exercise is prolonged and core temperature increases), and renal circulation while reduce sympathetic discharge in muscle vasoconstrictor nerves can increase flow to skeletal muscle. At the same time, sympathetic venoconstriction can increase venous
return and contribute to the increased ventricular contractility resulting from the Frank-Starling mechanism. Depending on the severity of exercise, sympathetic activation of the adrenal medulla may cause epinephrine to be released into the systemic circulation to produce more widespread vasoconstriction and skeletal muscle vasodilatation.

4. Local control of blood flow. Skeletal muscle is responsive to metabolic conditions in the surrounding muscle. Hypoxia due to increased O₂ uptake/usage and the associated metabolic products of working muscle (such as adenosine and K⁺) causes local vasodilatation. This allows increased blood flow in active muscles but also offsets the increase in peripheral resistance in other circulations, thus reducing afterload, or the pressure against which the ventricle must work to push blood into the aorta.

The response of the LV can vary considerably, depending on the individual, the intensity of the exercise, and the position of the subject during cardiac imaging. For example, an increase in end-diastolic volume may or may not be seen after exercise, but there should always be an increase in SV and EF as well as heart rate. This variability in the cardiac responses can be used to trigger discussions as to what is affecting cardiac output.

The level of inquiry can be increased in the laboratory report by asking students to find out about forms of hypertrophy and cardiac disease and the changes in these dimensions and calculated values that might be expected. By including a couple of further ventricular dimension measurements, calculations of ventricular muscle mass can be made and incorporated into this discussion.

The activities described have been used as a demonstration in a practical class. With minor adaptations, similar contents can be delivered in different teaching environments. We have used this approach extensively in teaching of smaller groups (5 students at a time) in which it is possible to oversee the students individually applying the ultrasound probe and provided another dimension to the session with students experiencing the acquisition of ultrasound images. The location may also be moved to a lecture theatre where the activity can be delivered in a similar way.

Safety Considerations

There are no known side effects of cardiac ultrasound, but many students will not know this, including the subject, so reassurance that this is the case is necessary. The subject should be fit enough to complete 2–3 min of moderate exercise, and so subjects that are unwell or have cardiovascular or respiratory problems should be avoided. Nevertheless, it is not unknown to discover in the screening process before the demonstration that a “normal” subject has an abnormality. It is thus prudent to have a referral procedure in place should this occur.

We conclude that the use of ultrasound imaging provides a valid addition to the potential methods at the educator’s disposal to teach basic physiological principles. Teaching sessions incorporating cardiac ultrasound imaging are popular with students due to their ability to visualize physiological process, in this case, Frank-Starling’s law of the heart, and from conducting calculations from first principles based on the measurements taken from these images. It also allows trainee medics an early opportunity to appreciate the increasing role of ultrasound in all aspects of diagnostic medicine yet have an appreciation of the information it provides from fundamental scientific principles, which might not be the case if the values derived from the analysis software were to be used alone. Further studies will quantify learning improvements as well as establish other areas of basic physiology that may benefit from this technology.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS


REFERENCES