Ultrasound imaging in teaching cardiac physiology.

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ABBREVIATED TITLE: Echocardiography in teaching cardiac function

ABSTRACT

This laboratory session provides hands-on experience for students to visualize the beating human heart with ultrasound imaging. Simple views are obtained from which the students can directly measure important cardiac dimensions in systole and diastole. This allows students to derive, from first principles, important measures of cardiac function, such as stroke volume, ejection fraction and cardiac output. By repeating the measurements from a subject after a brief exercise period, an increase in stroke volume and ejection fraction are easily demonstrable, potentially with or without an increase in left ventricular end diastolic volume (which indicates preload). Thus, factors that affect cardiac performance can readily be discussed. This activity may be performed as a practical demonstration and visualised using an over-head projector or networked computers, concentrating on using the ultrasound images to teach basic physiological principles. This has proved to be highly popular with students, who report a significant improvement in their understanding of Frank-Starling's law of the heart with ultrasound imaging.

INTRODUCTION

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). But 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, 3, 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 acquisition of relatively large amounts of group data in order to make interpretations.

We hypothesise that out teaching of cardiovascular physiology may benefit from incorporating the use of an ultrasound imaging system. Here we describe the methodology employed 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 pre-sets controls to optimise the image quality) and has the capacity for output to be made visible to students via networked computers or overhead projector (Sonoscape S2 with 2P1 4-2MHz Phased Array Cardiac Transducer, Sonoscape Medical Corporation, 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 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 non-invasive experiments do not require ethical approval at our institution. However, ethical approval to collect data from questionnaires from the students participating in the class was granted by the 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 (PLAX) view (Figure 1) in which a longitudinal section through the heart is obtained, where the left ventricle, septal wall and right ventricle are easily visible, along with the left atrium, 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 (PSAX, Figure 2) was then obtained in which the left and right ventricles are seen in cross section. What is most striking is the dominating nature of the left ventricle with respect to the right. The left ventricle appears as a relatively thick-walled and definitely round structure, with the right ventricle appearing almost as an add-on, having a less defined structure and reduced muscle mass. By tilting the probe towards the apex then along the ventricle towards the atrium, structures including the papillary muscle, mitral valve and aortic valve are visible. Left ventricular 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 ECG recording if taken). Ventricular cross-sectional areas can then be calculated, either by using the area calculator software by tracing around the

endocardial diameter border, or calculated (πr^2) 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 subsequent force of contraction (Frank-Starling law) and the proportion of stroke volume expressed as a fraction of end-diastolic volume (ejection fraction).

3.   The final view is the apical four chamber (A4C, Figure 3) view 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, left ventricular 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.   The left ventricular volume measurements were then repeated after the subject performed a brief period of exercise on the cycle ergometer (2 minutes at relatively high intensity) and the measurements to calculate volume (left ventricular 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 sat upright as compared to when supine (8).

Calculations of ventricular volumes, stroke volume and ejection fraction:

LV end systolic and end diastolic volumes (LVESV and LVEDV):

LV volume = (5 x LV cross-sectional area x ventricular length)/6

LV cross-sectional area = πr^2 (where r = diameter of LV/2)

LV stroke volume (SV) - Represents the volume of blood in the left ventricle that is ejected in one cardiac cycle:

SV = LVEDV – LVESV

Ejection fraction (EF) - Represents the amount of blood ejected from the left ventricle as a fraction of the volume of blood in the ventricle before contraction (end-diastolic volume)

EF = SV/LVEDV x 100 %

As part of the class, the 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 ejection fractions. End-diastolic diameter gives an indication of ventricular stretch (preload). Ejection fraction gives an indication of ventricular work and function.

Evaluation of student perceptions of the 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 (5 = strongly agree to 1 = strongly disagree). Mean data are presented ± SEM. A paired Student's t-test was used to discern whether students perceived their understanding to be better after the teaching with ultrasound as 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 left ventricle in a single subject are noted down in the Table 1, which also contains normal ranges for most common measurements and the results of the calculations that are provided above. From the basic left ventricular dimension measurements in systole and diastole, the ventricular areas and then volumes can be simply calculated, and hence ventricular ejection fraction. After exercise (Table 1), a moderate increase in end diastolic diameter, length and therefore, volume was seen, as was an increase in ejection fraction.

Evaluation of student perceptions of the teaching effectiveness

There was a significant increase in understanding of the Frank-Starling law reported by the students (Table 3), with scores increasing from 2.77 ± 0.10 before, to 3.82 ± 0.07 after the class (Student's t-test, $P<0.001$, n=114). 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. The students scored a statement on how ultrasound enabled better visualisation of the Frank-Starling law with a mean of 3.91 ± 0.08, with 79 % of students agreeing /strongly agreeing with this statement. Students reported particularly 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 amongst 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 have 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 ejection fraction, 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 screen or to networked computers, students can observe simple measurements of basic cardiac dimensions being made, and then calculate indications of left ventricular function from those measurements. This allows derivation of meaningful values of cardiac function from basic principles. It can lead to 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 the students the techniques of ultrasound, but rather to use the ultrasound as a teaching tool to image the beating heart.

It is envisaged that the students are asked to elaborate on their findings. This could involve comment on 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, of due to some form of experimental error. Along the lines of the latter, it is useful for the 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 discussion of factors that may influence cardiac output during/after exercise. This requires a basic knowledge of intrinsic and extrinsic mechanisms that coordinate control of cardiac output, and specifically the factors which contribute to the increased stoke volume and ejection fraction during and after exercise. These include:

i.   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 stroke volume and ejection fraction.

ii.   Frank-Starling mechanism: there can be an increase in the ventricular stretch (end-diastolic volume) prior to 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 towards the heart.

iii.   Sympathetic control of blood vessels: differentiated control of sympathetic outflow can increase to 'non-essential' organs such as the splanchnic circulation, skin (unless exercise is prolonged and core temperature increases) and renal circulation, whilst 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 wide-spread vasoconstriction and skeletal muscle vasodilatation

iv.   Local control of blood flow: skeletal muscle is responsive to the metabolic conditions in the surrounding muscle. Hypoxia due to increased oxygen 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 off-sets 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 left ventricle 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 stroke volume and ejection fraction, as well as heart rate. This variability in the cardiac responses can be used to trigger discussion 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 adaptions, similar contents can be delivered in different teaching environments. We have used this approach extensively in teaching of smaller groups (five 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.

<u>Safety Considerations</u>

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 minutes 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 prior to 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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Figure Legends

Figure 1

Parasternal long axis (PLAX) view of the heart (end diastole). The left ventricular and atrial chambers (LV and LA) are readily visible, as is the movement of mitral and aortic valve (MV and AV) leaflets. The right ventricle (RV) and root of the aorta (Ao) is also clear.

The transducer is placed just to the left of the sternum around 3rd or 4th intercostal space. The 'marker' on the transducer head is orientated in line with the right shoulder.

Figure 2

Parasternal short axis (PSAX) view just below the mitral valve, from which the internal and epicardial diameters of the left ventricular chamber can be measured in systole and diastole (arrows).

The transducer is placed as in PLAX except that the 'marker' on the transducer head is orientated in line with the left shoulder.

Figure 3

Apical 4 chamber view (A4C) which show the 4 main chambers of the heart, and from which ventricular length (and diameter if not taken form PSAX) can be measured.

The apical beat of the heart can often be found around 5th intercostal space, roughly in line with a line dropped from the ventral surface of the axilla. Once found, the transducer is placed with the 'marker' orientated to 2 – 3 o'clock.