Using two-dimensional ultrasound imaging to examine venous pressure

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INTRODUCTION

We have recently described simple observational procedures to investigate venous pressure (8). These have been successfully used for many years in our institution to emphasize the importance of the venous side of the circulation in terms of cardiovascular function in addition to the arterial side (8). This is crucial to understanding overall cardiovascular physiology and the role of venous return in maintaining cardiac output and systemic arterial blood pressure. In recent years, we and others have been developing the use of ultrasound imaging to aid the teaching of cardiovascular physiology (3, 5). Relatively cheap ultrasound equipment allows visualization of internal physiological processes as they occur. In our experience and others, ultrasound imaging is proving to be a useful additional teaching tool because of its perceived effectiveness and its popularity with students in Likert surveys (1, 5). Here we describe further procedures that demonstrate some of the same aspects of venous pressure to those described recently in our companion paper (8), but with the different visual insight facilitated by the use of imaging. Our previous paper provides an in-depth discussion of the concepts covered in these activities (8). Specifically, this paper will describe ways of imaging:

1. Venous valves and the muscle pump mechanism (crucial in ensuring adequate venous return and hence cardiac output).
2. The effects of hydrostatic pressure on venous pressure (causing varying degrees of venous distension, depending on the vein’s position above or below the heart and may contribute to raised capillary pressure and edema).
3. Central venous pressure (CVP), as indicated by the point of collapse of the internal jugular vein in the neck and how this may be affected by several maneuvers that can influence venous return to the heart.

We envisage that these imaging scenarios can be used as demonstrations in lectures or practical classes, either on their own or in combination with the observational approaches described previously in our companion paper (8). These classes will not focus on the operation of the ultrasound equipment or acquisition of the images. They aim to use the visualization to illustrate the fundamental physiology and bring it to life. We will describe these procedures in sufficient detail to allow procedures to be performed by an individual with a basic knowledge of sonography.

Learning Objectives

After completing this activity, the student should be able to:

1. Explain a clear understanding of structures and mechanisms that aid venous return.
2. Differentiate influences on venous pressure, including pressures generated by the right side of the heart, and variations in hydrostatic pressure and tissue pressure may vary.
3. Explain how venous pressure may be altered or manipulated to influence cardiac output and arterial blood pressure.

Activity Level

This activity is suitable for basic (years 1–2) undergraduate biomedical science, medical, and health science students who are studying control of the cardiovascular system.

Prerequisite Student Knowledge or Skills

Before completing this activity, students should have:

1. A basic understanding of how ultrasound imaging works, e.g., the ability of the soundwaves to penetrate the body tissues in a two-dimensional (2D) fan shape and show a cross section of the internal structures within that transmitted fan.
2. A basic understanding of differences between systemic arterial and venous blood pressures.
3. A knowledge of the Wiggers diagram (7), which links events occurring during the cardiac cycle with particular reference to the atrial pressure trace.

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Each individual procedure described will take 5–10 min, depending on the ease of imaging, so if all six activities are included in combination with the visual observations described previously (7), then 120 min should be allowed.

METHODS

Equipment and Supplies

We have previously (5) advocated the use of current ultrasound equipment that is portable, can easily produce high quality 2D images and is relatively cheap. (We currently use Sonoscape S2, Sonoscape Medical Corporation, Shenzhen, China, but there are many others available, particularly if the second-hand market is considered.) We have used this with a “vascular” probe that is suited to examining relatively superficial blood vessels (Sonoscape L741 10–5 MHz linear array transducer). This system has an output that can be readily distributed to student computers, or else displayed on an overhead projector.

It is most convenient to perform these procedures with the subject sitting upright and unsupported or lying flat on his/her back as necessary on a patient examination bed, but a bench top with a blanket to lie on will suffice.

Human Subjects and Approval

These noninvasive experiments do not require ethical approval at our institution. However, all students are invited to volunteer as a subject for practical classes, and informed, written consent is obtained. Students are made aware that there is no displeasure or disadvantage should they not want to volunteer. Adopters of these activities are responsible for obtaining permission for human research from their home institution. For a summary of Guiding Principles for Research Involving Animals and Human Beings, please see https://journals.physiology.org/author-info.animal-and-human-research.

Instructions

1. Imaging a venous valve. In subjects with prominent forearm veins, it is possible to see valves as small raised areas along the course of the large veins draining the arm (e.g., median antebrachial vein, basilic vein). Even when the valves are not prominent, they may still be viewed once located by following the vein longitudinally with the probe. With the arm below the heart supported so as to keep steady, these can be imaged with delicate placement of the transducer so as not to crush the vein or impede valve function. These structures are relatively close to the surface, so the depth of the image can be optimized to capture these more superficial depths. Thus it is possible to see the valve opening and closing during each cardiac cycle, with the valve cusps bowing back to prevent back flow during diastole (Fig. 1).

2. Muscle pump. With the subject standing upright and a calf region of the lower leg exposed, deep veins such as the tibial veins can be visualized in transverse (Fig. 2) or longitudinal section. These are surrounded on all sides by muscle and are well distended due to the relatively high hydrostatic pressure in this region below the heart. The subject is then asked to tense the muscles in the calf region (e.g., by raising the heels), which can be seen to press on the sides of the vessel, forcing blood back toward the heart due to the presence of venous valves (which are more difficult to visualize than in peripheral vessels). When the contraction stops, the vessels refill relatively quickly, usually within 1 s.

Venous valves are not as easily visible in leg vessels, but their presence and their role in ensuring flow back to the heart, however, can be reinforced by the imaging of the venous valves in the forearm as described, but also by asking the students to replicate William Harvey’s demonstration of venous flow and valves on the surface of the forearm (4), and also as we have recently described (8). Briefly, a subject selects a relatively long and “filled” vein in the forearm. A finger is placed toward the distal end, and another finger swipes upwards, toward the heart, along the vessel. This squeezes blood out of the vessel, and the vessel will remain empty if there is a valve present, up to the point of the valve. When the distal finger releases the vessel, flow returns, and the vessels distends from the distal region toward the heart.

3. Veins on hand/position. Carpal veins just under the skin on the back of the hand can be easily visualized with the settings for the least depth on ultrasound (Fig. 3A). This imaging can also allow veins to be visualized in subjects where the veins are not prominent on the skin surface. These vessels are particularly vulnerable to collapse from external pressure by application of the probe, and it is possible to “brace” the probe on the hand of the subject, with a small gap filled with ultrasound gel to avoid this. With the subject standing upright and holding the hand at waist height, the veins will appear distended and round. The subject then has his arm and hand slowly and passively raised by the sonographer, still visualizing the veins with the ultrasound probe (Fig. 3B). Around shoulder height, at approximately the level of the right atrium, the veins begin to collapse and disappear, and this becomes complete as the hand is raised farther beyond this point (Fig. 3C). Students should note the approximate height of the hand above the sternal angle (which is an anatomical landmark that approximates the center of the right atrium when upright) where the veins collapse.

In addition to the ultrasound imaging, the students can make their own observations of venous pressure in different regions of the body.
For example, veins on the top of the foot in the standing subject will normally appear distended, and palpation will give a sense of the relatively high intravenous pressure in this region, compared with the veins in the back of the hand and as the hand is raised up to and above the level of the right atrium.

4. Imaging internal jugular vein. With the subject sat upright, the transducer can be placed on the neck ~2 cm below the angle of the jaw, under which is the bifurcation of the carotid artery, to obtain a transverse section of the neck containing both the common carotid artery and internal jugular vein. In this view, the carotid artery is easily visible as a round anechoic (dark), pulsatile vessel (Fig. 4B). The internal jugular vein is much less visible as it is normally deflated and flattened in this position, appearing as a crescent in transverse section (Fig. 4B). The subject is then requested to perform a Valsalva maneuver for a few seconds (increasing intrathoracic, and therefore venous pressure, by straining/exhaling against a closed glottis). The internal jugular vein gradually inflates, somewhat like a balloon, to assume a roughly round diameter that may be two to three times that of the carotid artery (Fig. 4C). The internal jugular vein may also inflate and deflate as intrathoracic pressure varies with both inspiration (less likely to be visible) and expiration (more likely to be visible), and also speech.

When viewing the internal jugular vein in the longitudinal section, and particularly during the Valsalva maneuver, described above, the “swirl” of blood flow is often visible as it sweeps through the widened

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**Fig. 2.** A deep tibial vein (TV) is imaged in the transverse section with the subject seated upright (with the margins of the vessel outlined to emphasize the vessel shape).  
**A:** the TV is well rounded, reflecting the relatively high hydrostatic pressure in the lower limb.  
**B:** when the subject contracts his calf muscles, the surrounding muscles immediately press on the vein walls to obliterate the lumen (thus the margins flatten to a single line).  
**C:** on relaxing the muscles, the vein begins to refill as flow is restored from the distal regions, and not from back flow from caudal regions due to the presence valves in the veins (not visualized).  
**D:** after 1 s or so, the fully rounded appearance is restored within the vein. P, probe.

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**Fig. 3.**  
**A:** with the ultrasound probe (P) held onto the back of the hand in such a way that no pressure is transmitted to the vessels underneath, superficial carpal veins are distended and readily visible at the level of the hip in the upright subject. The image also shows borders and shadows of metacarpal bones. The top dashed line in the inset shows the approximate position of the sternal angle, which denotes the position of the right atrium within the chest. The bottom dashed line represents the level below the heart at which the distension in the veins is being observed.  
**B:** as the hand is raised to just below shoulder level, the hand is at approximately the same level as the right atrium (denoted now by the bottom dashed line), and the veins will be significantly less distended and may disappear.  
**C:** as the hand is raised farther, the vessels completely disappear. This height above the sternal angle gives an approximation of central venous pressure. The veins will reinflate as the hand is lowered again.
that drain into it. By observing the internal jugular vein at this point, the top of the column of fluid is visualized and is the site of the external JVP in the neck. Two oscillations may be seen in short succession, representing the “a” wave, which is the rise in pressure as the right atrium contracts, and the “c” wave, which is the rise in pressure as the tricuspid valve bulges into the right atrium during ventricular systole. The observation of the “c” wave is less reliable than the “a” wave. After a noticeable delay, the “v” wave oscillation is visible, occurring due to a rise in pressure during the atrial diastolic filling phase of the ventricular systole and associated retrograde bowing of the tricuspid valve into the right atrium (8). These positive pressure waves are seen as outward movements, or “fluttering” of the venous walls, the most prominent being the “a” and “v” waves. These are most obvious if the 2D image (Fig. 5A) is taken simultaneously with M-mode imaging (Fig. 5B), which highlights the vessel wall excursions. M-mode is an imaging method that looks at a single beam of ultrasound passing through the tissue in one plane (as indicated by the dotted line in the top trace in Fig. 5B) and follows the excursions of the structures in that beam over time. The interpretation can also be enhanced by taking timings from a simultaneously recorded ECG. The “a” wave begins after atrial depolarization (the P wave of the ECG) and before the ventricular depolarization (QRS complex), with the “c” wave, if visible, just after. The “v” wave occurs some time after ventricular repolarization (T wave) and the beginning of the next cardiac cycle (P wave).

6. Estimating CVP by observing internal jugular vein. We have previously provided a description of making visual observations to estimate CVP (8), and the ultrasound imaging may be carried out alongside these observations, or as an activity on its own. It is often difficult to see either the internal or external jugular pulse with the naked eye in many individuals due to subcutaneous fat, etc., so ultrasound imaging can facilitate this observation by looking under the skin. Briefly, in the upright position, normal CVP (0–10 cmH2O) inflates the internal jugular vein to a point below the level of the clavicle, and the vessel is usually not visible. With the subject reclining at an angle of 60° or less, there comes a point where the column of pressure emanating from the right atrium is sufficient to inflate the internal jugular vein above the level of the clavicle, at which point the internal jugular vein will inflate, and the external jugular vein may become visible. Ultrasound can be used to scan in a transverse section up and down the neck, superior to the clavicle (Fig. 5A). By finding the approximate point at which the internal jugular vein is no longer inflated, CVP may then be measured by marking the neck under the transducer with a pen and measuring the vertical height above the sternal angle (which represents a position 5 cm higher than center of the right atrium while reclining at any angle from supine to 60°). Here, CVP = 5 cm + vertical height of mark (cmH2O).

This procedure can yield an estimate of CVP in almost all subjects, including those (the majority) in which the JVP is not visible externally by visual inspection of the neck above the clavicle.

Troubleshooting

In our institution, the lead academic staff member is familiar with the use of ultrasound for cardiovascular investigations. Staff leading this practical should have at least a basic understanding of how to use ultrasound equipment.

It is essential to preselect the subject and run through procedures with a volunteer before the class, for three main reasons:

1. Not all subjects have the same acoustic properties or anatomy, and the ease of imaging can vary immensely between subjects.
2. It aids in time management if the subject is prepared and is aware of the procedures.
3. It is essential to rule out any visually obvious abnormality of the thyroid gland, which is usually visible, at least in part, when imaging the internal jugular vein. Thyroid cysts are relatively common and are usually clinically insignificant.
Safety Considerations

Subjects may need to be reassured that the ultrasound procedure is safe. If the Valsalva maneuver is too vigorous, fainting may occur, which must be guarded against.

RESULTS

Expected Results and Evaluation of Student Work

There is little in the way of hard data to collect in this set of demonstrations beyond the estimation of CVP. However, by taking note of the phenomena being visualized and answering questions that explore explanations for the observations, along with consideration of the applications to normal physiology and clinical situations, students should gain a deeper understanding of venous physiology.

Inquiry Applications

We have recently published an account of conventional procedures to evaluate venous pressures that have addressed several inquiry applications relevant to the study of this subject. Here we have provided some further inquiry applications that are more specifically addressed with these ultrasound images of veins.

1. Describe the appearance of the internal jugular vein on the ultrasound when the subject is sitting upright in comparison to lying down. Explain your observations.

This requires an appreciation that the JVP at this height in the neck in this position is not usually influenced by pressure generated in the right atrium, as the vessel is too far above it. Hence the pressure is negative, and this deflates the venous walls, collapsing the vessel.

2. At what height above the sternal angle/right atrium was the JVP observed? At what height above the sternal angle/right atrium did the veins on the back of the subject’s hand disappear? What was CVP estimated to be? Did your two estimates match?

The estimate of JVP is the height above the sternal angle that the JVP pulse is observable, or the height above the sternal angle at which the veins on the back of the hand deflate completely. If this is 10 cm, CVP = 10 cmH₂O.

3. What is the effect on CVP of the subject lying flat and then raising his/her legs? How might this result be useful in a clinical situation?

This question brings out the fact that a change in body position can alter CVP, via hydrostatic pressure. Since increased CVP can increase diastolic filling of right ventricle and ventricular preload, this can then increase cardiac output via Frank-Starling’s law of the heart. Thus the students see directly the beneficial effect of raising a subject’s or patient’s feet when his/her cardiac output/blood pressure is reduced.

4. When William Harvey first described the presence of valves in forearm veins in 1628, how did this provide evidence of the existence of the circulatory system?

Here the students must appreciate the function of venous valves in ensuring the unidirectional flow of blood, often at low intravenous pressure or in the face of high hydrostatic pressure, back to the right atrium.

5. Why, do you think, is it advisable for soldiers standing still on guard duty on a hot day to wiggle their toes/flex their calf muscles?

Fig. 5. A: when the subject is reclining at ~45°, jugular vein (JV) pressure is usually sufficient to inflate JV so that it is visible above the clavicle, with darker anechoic blood visible between the anterior and posterior JV walls (Ant. and Post JV, respectively). By tracking the vessel in the transverse or longitudinal (shown) section, it is possible to find the transitional region of JV where internal pressure gradually becomes greater than the external pressure (bracket). This is the area of the neck where it is most likely to see the JV pulse externally. Whether the pulse is visible externally or not, it may be imaged internally with ultrasound, and it appears as fluttering of the vessel wall diameter. The top of the head lies to the right-hand side of this ECG. B: slightly more challenging to obtain, but often easily managed, is to see the components of JV pulse in wave form by imaging this region in M-mode. This mode of visualization captures images along a single line into the neck over time (indicated in top section). The motion of the anterior and posterior JV walls may trace the “a,” “c,” and “v” wave components with the pressure variation in the vessel transmitted from the right atrium, and timings may be checked if ECG is recorded simultaneously on the ultrasound recording. The top of the head lies to the left-hand side of this ECG. C: a central venous pressure (CVP) wave and ECG are shown for one cardiac cycle for comparison. CA, carotid artery; SCM, sternocleidomastoid muscle; P, probe.
It is hoped that the students can combine their observation of contracting calf muscles squeezing veins in the lower leg musculature with their observation of venous valves preventing back flow in the veins and ensuring blood flow in the veins in the direction of the right atrium, to conclude that this engagement of the muscle pump in the lower limb will prevent venous pooling and ensure sufficient venous return to the heart to maintain cardiac output so that arterial blood pressure does not drop and reduce cerebral perfusion.

6. Relate the “a” and “v” waves seen in the internal jugular vein back to the cardiac events that produce them.

As the right atrium contracts, the pressure generated is easily transferred to the vessels entering the right atrium, including the short distance of the superior vena cava and then the internal jugular vein. Thus the “a” wave occurs during atrial systole (and the ECG P wave). The “v” wave represents rapid atrial filling during atrial diastole, concurrent with ventricular systole (hence “v”-wave).

Wider Educational Applications

A thorough appreciation of venous circulatory physiology is essential to fully understanding the mechanisms maintaining cardiac output and arterial blood pressure. For any health professional working in intensive care/high-dependency units, it should be obvious why CVP is frequently monitored to track the status of the cardiovascular system. Yet, particularly in early stages of learning, if a medical student is asked why CVP is such a useful physiological parameter to measure, his/her answer is often flawed. By examining venous pressure in the ways described here, and, in particular, by raising the legs so that improved venous pressure/venous return may be actually observed, then the value of monitoring CVP can be discussed in the context of Frank-Starling’s law of the heart. The consequences of increased venous return can be followed through to the consequent increased performance of ventricular contraction, increased stoke volume, and consequent cardiac output. Further discussion may then ensue concerning other factors that alter venous return, such as renal function, diuretic therapy, vasodilator drugs, etc., and how the balance of these influences is crucial to the treatment of cardiovascular scenarios such as heart failure (8).

Although the procedures described here are not intended to provide technical expertise in performing and interpreting ultrasound images, currently a recognition is emerging that familiarity with imaging techniques, including ultrasound (2), is often sparse in early medical training. As such, these activities will help to familiarize health professionals with such images while supporting their basic physiology education.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

C.D.J. conceived and designed research; C.D.J. performed experiments; C.D.J. analyzed data; C.D.J. interpreted results of experiments; C.D.J. prepared figures; C.D.J. drafted manuscript; C.D.J., S.M.R., and E.A.T. edited and revised manuscript; C.D.J., S.M.R., and E.A.T. approved final version of manuscript.

REFERENCES

1. Bell FE III, Wilson LB, Hoppmann RA. Using ultrasound to teach medical students cardiac physiology. Adv Physiol Educ 39: 392–396, 2015. doi:10.1152/advan.00123.2015.
2. Grikaitis MJ, Scott MP, Finn GM. Twelve tips for teaching with ultrasound in the undergraduate curriculum. Med Teach 36: 19–24, 2014. doi:10.3109/0142159X.2013.847909.
3. Hammoudi N, Arangalage D, Boubrit L, Renaud MC, Isnard R, Collet J-P, Cohen A, Duguet A. Ultrasound-based teaching of cardiac anatomy and physiology to undergraduate medical students. Arch Cardiovasc Dis 106: 487–491, 2013. doi:10.1016/j.acvd.2013.06.002.
4. Harvey W. On the Motion of the Heart and Blood in Animals. New York: Prometheus, 1993.
5. Johnson CD, Montgomery LEA, Quinn JG, Roe SM, Stewart MT, Tansey EA. Ultrasound imaging in teaching cardiac physiology. Adv Physiol Educ 40: 354–358, 2016. doi:10.1152/advan.00011.2016.
6. Levick JR. An Introduction to Cardiovascular Physiology. London: Arnold, 2010.
7. Mitchell JR, Wang JJ. Expanding application of the Wiggers diagram to teach cardiovascular physiology. Adv Physiol Educ 38: 170–175, 2014. doi:10.1152/advan.00123.2013.
8. Tansey EA, Montgomery LEA, Quinn JG, Roe SM, Johnson CD. Understanding basic vein physiology and venous blood pressure through simple physical assessments. Adv Physiol Educ 43: 423–429, 2019. doi:10.1152/advan.00182.2018.