Realizing the actual magnitudes of aortic diameter and cardiac output: a multisensory learning approach

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Abstract

The conventional physiology courses consist of theoretical lectures, clinical application seminars, numerical exercises, simulations, and laboratory practices. However, in subjects that involve relevant physical quantities, even students who successfully pass exams may be unable to realize the actual quantities involved. For example, students may know what the values of the aortic diameter and cardiac output are, and they may be skilled at calculating changes in variables without being able to realize the actual physical magnitudes of the variables, resulting in limited understanding. To address this problem, here we describe and discuss simple practical exercises specifically designed to allow students to multisensory experience (touch, see, hear) the actual physical magnitudes of aortic diameter and cardiac output in adult humans at rest and exercise. The results obtained and the feedback from a student survey both clearly show that the described approach is a simple and interesting tool for motivating students and providing them with more realistic learning.

cardiocirculatory variables; multisensory learning; practical teaching

INTRODUCTION

Regardless of the specific didactic approach followed (1, 2), there is currently unanimous agreement on the importance of combining theoretical and practical training to achieve optimal learning. This is particularly relevant in topics related to biomedical disciplines such as physiology, as most students will become professionals who will have to apply the acquired knowledge to real life activities, for instance, physicians, nurses, physiotherapists, and biomedical engineers. Optimal learning requires that the students not only understand the underlying theoretical principles but also master their application to solve problems applied to specific scenarios (1, 2). To this end, it is common practice for teaching programs, either face-to-face or e-learning (3), to include a combination of lectures and practical sessions including simulations, case discussions, and laboratory exercises. However, given the benefits of multisensory inputs in optimizing learning (4), it is also important for the student to realize, and ideally touch and see, the physical magnitude of the variables he/she is working with on any specific problem.

Experiencing the real-life physical meaning of the variables involved in learning is easy in some cases. For example, when it comes to the physiology of metabolism and the student focuses on the possible loss/gain of body weight. Specifically, when balancing the energy intake and expenditure corresponding to ingesting 100 g of carbohydrates and running for 30 min. In this case, the student will apply his/her theoretical knowledge and practical skills to answer what is the energy balance and will be able to calculate a rough estimate of the corresponding body weight change. In this example, the student will solve the problem, give numerical results, and, more importantly, will also realize the problem because the variables involved (eating a certain amount of carbohydrates, running for 30 min, and body weight change by a certain number of grams) provide a clear physical picture in his/her mind due to his/her personal experience of these variables. However, understanding the magnitudes involved in the question under study may not be so easy when learning many other topics in physiology. For example, by studying basic cardiocirculatory physiology, students learn that the different blood vessels in the vascular tree exhibit enormous diameter variation ranging from ~3 cm in the aorta to ~6 μm in the capillaries. Students also learn that a healthy adult increases cardiac output by fourfold from rest (~5 L/min) to maximum exercise (~20 L/min). However, unless specifically instructed, a student who is able to calculate how vessel resistances, flows, and pressures vary along the circulatory circuit could nevertheless finish his/her training without a clear idea of what the physical reality of the managed variables are. The reason is that, contrary to the previous example on energy balance, students do not have an
intuitive experience of the physical variables in the cardiocirculatory system.

To address the relevance of realizing the physical meaning of physiological variables, we carried out a new teaching experience. As a proof of concept, we used the cardiocirculatory example above. Specifically, we tested whether students who had just completed a conventional theoretical and practical introductory program in cardiovascular physiology were able to identify the physical magnitudes of aortic diameter and cardiac output at rest and exercise. In the following sections, we describe the teaching experience, the results and the feedback from a student survey, and we conclude by reinforcing the concept that practical sessions to “see and touch” are crucial to improve learning in physiology topics involving physical variables.

### PRACTICAL EXERCISES

The two new exercises described herein were carried out in the teaching laboratory by the group of 40 students in the second year of a 4-yr degree on Biomedical Engineering at the School of Medicine and Health Sciences of the University of Barcelona, Spain (no written consent required). At the time of these practical exercises, the students had recently finished the topic on cardiocirculation and were ready to take the corresponding exam 1 wk after the practical exercises were completed. The students had attended 8h of teacher lecturing on cardiocirculatory structure and function, mainly focused on biomechanics. These classroom activities were devoted to theory, seminars on clinical applications, and solving 50 exercises on application of equations to compute cardiocirculatory variables.

The practical exercises were carried out in individual sessions involving the teacher and each student. The student’s answers were recorded anonymously, and none of the students were aware of how the exercises of the other students had developed.

**Exercise 1**

The learning aim was that the student physically realized the width of the human aorta.

The practical session is described below.

**Step 1.**

The student was asked to identify the diameter of the ascending aorta of an average adult (data previously provided in a lecture, specifically Figs. 1 and 2 in Ref. 5). The student was asked to observe three-dimensional printed models of real tubes of different internal diameters (0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, and 5 cm) (Fig. 1A), and he/she was asked: “Which of these tubes do you think represent the diameter of the aorta at the outlet of the heart in an average adult?”

**Step 2.**

Regardless of the student answer in step 1, he/she was reminded that, as explained in lectures, the ascending aorta diameter in a typical adult is 3 cm. Then, he/she was asked: “Knowing this value would you now change your previous answer and indicate which of these tubes do you think is 3 cm in diameter?”

**Results.**

When recording the answers in steps 1 and 2, if the student hesitated between two consecutive diameters, the mean value was assigned. Figure 1B shows the values that the students identified as the diameter of the ascending aorta of an average adult (3 cm). The answer of the students was 2.24 ± 0.88 cm (means ± SD). When the answers of the students were compared with the actual value (3 cm), No significant difference was observed between answers provided in steps 1 and 2.

After steps 1 and 2, the teacher showed what was a tube having the diameter of 3 cm representing the typical ascending aorta in an adult.
Conclusions.
First, the students poorly identified the diameter of a healthy adult ascending aorta, which they should know from lectures and exercises. In some cases, the error in physical estimation was considerable (answers of 1-1.5 cm in diameter). Second, on average the students poorly identified the physical magnitude of a tube of 3 cm in diameter. In some cases, there were remarkable errors (answers of 1-1.5 cm).

Exercise 2
The learning aim was that the student physically realized the magnitude of the cardiac output of a healthy adult at rest and in exercise.

The practical session is described below.

Step 1.
The student was asked to identify the magnitude of the average cardiac output at rest (5 L/min). To this end, he/she observed the minute volume of water generated by a pump controlled by the teacher. The experimental setting, placed inside a (60 × 30 × 30 cm) domestic aquarium glass box, consisted on a domestic fountain pump (3,600 L/h; 20 W, Yaobluesea, Amazon), a stopcock, a minute volume sensor (NPT 9-100 L, Cicony, Amazon) that was calibrated after the setting was mounted and placed with the reading not visible by the student, and an outlet tubing 3 cm in diameter to roughly mimic the aorta (Fig. 2A). The flow of water was manually varied by the teacher following the instructions of the student until he/she estimated that the observed flow corresponded to the mean cardiac output at rest of an average adult, which, as explained in previous lectures and exercises, was reminded to be 5 L/min. The teacher recorded the minute volume selected by the student.

Step 2.
The previous step was repeated but asking the student to identify the cardiac output corresponding to a typical normal subject at maximum exercise. To this end, the student was reminded that, as previously explained in lectures, this value is typically 20 L/min (4-fold the resting value).

After performing steps 1 and 2, the teacher showed the students what were the actual magnitudes of 5 L/min and 20 L/min and allowed him/her to put his/her hand in front of the water flow outlet to sensorially experience the actual magnitude of a cardiac flow of 20 L/min. The teacher also mentioned that this magnitude is the average cardiac output over the heart cycle but that, given that blood ejection occurs only during systole (~1/3 of the cycle period), the ejection peak flow is approximately three times higher than the average.

Results.
Figure 2B shows the values that 40 students identified as a cardiac output of 5 L/min. On average, the identified value was 13.0 ± 2.74 L/min (white column), 2.6-fold higher than the expected value. All the students dramatically overestimated the actual value (with their answers ranging 8–18 L/min). By contrast, when the flow was increased to 20 L/min, the value estimated by the students was slightly higher (21.61 ± 4.47 L/min, P < 0.05) than the actual value.

Figure 2. Student estimation of the cardiac output. A: experimental setting to generate a controlled water flow to simulate the cardiac output: fountain pump (1), stopcock (2), flow sensor (3), and 3-cm in diameter outlet tube (4). B: detail of the flows simulating the cardiac output of a human adult at rest (5 L/min) and during exercise (20 L/min). C: values that the students (n=40) identified as the cardiac output of 5 L/min (white column) and 20 L/min (gray column) (exercise 2; steps 1 and 2, respectively). Data are means ± SD. Dashed black lines indicate 5 and 20 L/min. *P < 0.05 and ***P < 0.001, respectively, when the answers of the students were compared with the corresponding actual value.

Conclusions.
Whereas on average the students estimated the exercise cardiac output reasonably well, they considerably overestimated the cardiac output at rest. In fact, students were unable to realize the actual fourfold increase in cardiac output form rest to exercise.

Students’ Survey
After finishing exercises 1 (aorta diameter) and 2 (cardiac output), a detailed summary of the group results was provided to the students, and they were asked to voluntary and
anonymously answer an online survey. The survey was answered by 82.5% (33/40) of the students. The questions posed and the corresponding answers were the following:

Do you think that the practical demonstration of the typical diameter of the aorta has been useful for you to realize its actual size?
YES: 33 (100%); NO: 0; N/A: 0

Do you think that this demonstration is useful for all students and therefore would you suggest including it in future laboratory sessions?
YES: 32 (97%); NO: 1; N/A: 0

Do you think that the practical demonstration of the typical cardiac output at rest and during exercise has been useful for you to realize their magnitude?
YES: 33 (100%); NO: 0; N/A: 0

Do you think that this demonstration is useful for all students and therefore would you suggest including it in future laboratory sessions?
YES: 33 (100%); NO: 0; N/A: 0

Would you suggest any changes in its realization? Please explain.

Few students answered this open question, most of them restating that the practical exercises were very useful and saying that they were surprised by how far from the actual values were their own and their colleague’s identification.

**DISCUSSION**

The main result obtained in this practical teaching experience is that biomedical students in a second-year university degree course on cardiovascular structure and function failed to realize the physical magnitude of basic variables such as aortic diameter and cardiac output. Interestingly, as reflected by the almost unanimous survey results, the students found the new practical exercises very useful and recommended incorporating it in the future practical program.

Interestingly, the students’ poor results in physically identifying the actual magnitudes of aortic diameter and cardiac output were not assessed in naive students (for example, just before starting the cardiocirculatory topic) but in students who had already followed the conventional course and who were ready to take the exam in a week. In fact, the average score they got on that exam was 7.1/10 (with only 3 students below score of 5 which was the minimum to pass). However, to exclude any potential lack of background, during the practical session the students were explicitly reminded of the value of aortic diameter (exercise 1, step 2) and of the cardiac output at rest and exercise (exercise 2, steps 1 and 2). We believe that the observed misidentification of actual magnitudes was caused by lack of physical references in conventional courses. In fact, if only exposed to the relatively abstract learning provided by theoretical lectures and numerical exercises, the student might have difficulty in realizing the physical values of the variables under consideration. In fact, the only previous physical experience of students on cardiocirculation was feeling the weak pulse of a small vessel on the wrist or sensing the rapid beat of the heart during intense exercise. Therefore, it is not surprising that these simple previous perceptive experiences did not help students to realize the actual size of the aorta and the magnitude of cardiac output. Furthermore, it is noteworthy that in exercise 1, step 2, the students made erroneous identifications that do not correspond to a lack of knowledge of the aortic diameter. It should be noted that 40% of the students enrolled in the second year of a Biomedical Engineering degree failed to correctly identify a width of 3 cm, confusing it with 1, 1.5, 2, or 4 cm. This inability should be attributed to a deficit of previous basic training in identifying length magnitudes.

The practical exercises described herein (together with the students’ survey) were designed with two aims. The most important one was to physically confront the students’ idea they had on aorta diameter and cardiac outputs with the actual values. The second aim was to assess the need, and thus the interest, of these practical exercises. In our opinion, and that of students, the employed format was suitable. However, implementing the practical exercises could be simplified. First, in exercise 1, the three-dimensional printed piece (Fig. 1A) could be simply replaced by a series of different diameter tubes from any hardware store, or alternatively asking the students to roll up a sheet of paper to form a tube of the desired diameter. Second, although the setting we used to generate water flows to mimic cardiac output was simple, it could be further simplified by replacing the flow sensor by a precalibrated set of obstructions providing known flow values. If necessary, the laboratory practice could be also moved to a e-learning session including video-recorded demonstrations of the exercises. However, it is important to stress that in this case the session should be carefully recorded allowing the student to realize the actual size of the tube representing the aorta. Moreover, the student should clearly perceive the actual magnitude of cardiac outputs by a video recording clearly allowing him/her to hear the sound, feel the force, and see and hear the splashing when the water jet representing cardiac output hits the demonstrator hand. In that way, the multisensory perception (touch, see and hear), which is the key of these exercises for improving learning (4), could be minimally preserved online. However, we did not test these possible simplified approaches.

To conclude, we modestly dare to add some words (in parentheses and italic type) to the famous sentence by Sir William Thomson, Lord Kelvin, regarding the importance of measuring variables for improving knowledge (6): “I often say that when you can measure what you are speaking about, and express it in numbers (you can realize), you know something about it; but when you cannot (understandably) measure it, when you cannot express it in numbers (meaningful for you), your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be.”

**DISCLOSURES**

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

N.F. and R.F. conceived and designed research; I.A., J.O. and R.F. performed experiments; N.F., I.A., J.O., and D.N. analyzed data; N.F., I.A., J.O., D.N., and R.F. interpreted results of experiments; I.A., J.O., and D.N. prepared figures; N.F. and R.F. drafted manuscript; N.F., J.O., D.N., and R.F. edited and revised manuscript; N.F., I.A., J.O., and R.F. approved final version of manuscript.

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