Medical student misconceptions in cardiovascular physiology

Stephen J. Bordes,1,2* Roni Manyevitch,2* John D. Huntley,3 Yun Li,4 and Ian V. J. Murray5
1Tulane University School of Medicine, New Orleans, Louisiana; 2Medical Student Research Institute, St. George’s University School of Medicine, St. George’s, Grenada; 3University of Texas, Austin, Texas; 4Education Psychology, Texas A&M University, Houston, Texas; and 5Department of Medical Physiology, Engineering Medicine Program (EnMed), Texas A&M University, Houston, Texas

Abstract

Students find cardiovascular physiology challenging. Misunderstandings can be due to the nature of the subject, the way it is taught, and prior knowledge, which impede learning of new concepts. Some misunderstood concepts can be corrected with teaching (i.e., preconceptions), whereas others are resistant to instruction (i.e., misconceptions). A set of questions, specifically created by a panel of physiology experts to probe difficult cardiovascular concepts, was used to identify preconceptions, misconceptions, and the effect of education level on question performance. The introductory cardiovascular lecture used in this study was created based on these questions. In-class poll of medical students’ (n = 736) performance was performed using the Turning-Point clicker response system during lecture instruction. Results were compared with published data from undergraduates (n = 1,076) who completed the same questions but without prior instruction. To our knowledge, there have been no studies directly comparing performance using the same instrument and large numbers of undergraduate and medical students. A higher education level was associated with increased performance (preconceptions), whereas several concepts resistant to instruction (misconceptions) were identified. Findings suggest that prior knowledge interfered with the acquisition of medical knowledge. Based on these results, potential causes for these misconceptions and remedial teaching suggestions are discussed.

cardiovascular physiology; conceptual difficulties; difficult concepts; medical education; pedagogy

INTRODUCTION

Cardiovascular physiology is a challenging course for medical students. This may, in part, be due to the nature of the subject, the way it is taught, and baseline erroneous student knowledge (1). The latter may be a result of inaccurate prior knowledge and misconceptions interfering with the understanding of the cardiovascular system (2–5). Several publications have identified specific cardiovascular concepts that students find difficult, which include the path of blood flow through the circulation and equations such as Ohm’s law of fluid flow (F = ΔP/R) and cardiac output (CO = HR × SV, where HR is heart rate and SV is stroke volume) (4, 6–13). This study aimed to identify preconceptions, misconceptions, and the effect of education level on performance on a set of previously published questions. Of note, these questions were created by a panel of physiology experts, the Physiology Educational Research Consortium (PERC), to probe difficult cardiovascular concepts (4).

Erroneous concepts resistant to change or accommodation are referred to as misconceptions, whereas those that can be removed through instruction or teaching are termed preconceptions (2). When teachers provide instruction in lectures, students reconstruct this knowledge and incorporate it with preexisting knowledge and concepts (schemata) (14–16). Misconceptions form when the association of new knowledge with incorrect schemata results in a flawed understanding of concepts (17, 18). Indeed, misconceptions are due not to a lack of knowledge but the misunderstanding of concepts during the knowledge construction process (13). Overcoming misconceptions tends to require ontological shifts or a radical change in students’ knowledge. Incorrectly learned concepts must first be unlearned and then relearned correctly before taking the subject to a more advanced conceptual level (9). It is therefore crucial to identify misconceptions and adjust methods of instruction. Ordinary forms of instruction, such as lectures, laboratories, discovery learning, or merely reading texts, are often not very successful in helping students to overcome misconceptions (17, 18).

Questions developed by the PERC were used in this study to compare the performance of two student groups on difficult cardiovascular concepts (4). The first group consisted of undergraduate students who were presented the questions before learning the concepts in lectures; this data came from a previously published report (4). The second group
METHODS

The authors aimed to identify medical students’ conceptual errors in cardiovascular physiology comprehension and compare them with published data from undergraduate students.

Institutional Review Board

This study was determined to be exempt from the St. George’s University’s Institutional Review Board.

Undergraduate Students (Previously Published Data)

Undergraduate student data came from the previously published report, Michael et al. (4), which studied 1,067 students across 12 courses at 8 different institutions (see Fig. 2). For direct comparison to our data, the data in Michael et al. was converted from percentage incorrect to percentage correct. For the original data, see Table 5 in Michael et al. (4).

Medical Students

In the present study, in-class questions were administered to first-year medical students (n = 736) in their first medical school term. Specific demographic data for this class, such as student age, gender, ethnicity, and overall academic performance, were not collected. However, an undergraduate degree and competency in the MCAT exam are requirements for entry into medical school. Reported demographics for the 4-yr medical degree are 49% female, 51% male. The majority of students are US citizens (75%), and the remainder consisting of non-US citizens (25%; of which 11% are from Canada) (19).

Curriculum

St. George’s University recently changed its curriculum from a discipline-based system to an organ-based integrated system. The present study was performed under the organ-based curriculum. The first-year, first-term organ-based curriculum integrates anatomy, physiology, and biochemistry. It includes lectures, mandatory problem-based learning (PBL) activities, anatomy laboratories, and independent study. Before the introductory cardiovascular lecture used in the study, the students were only taught foundational biological concepts (e.g., osmosis, homeostasis, and membrane potential). The cardiovascular system is the first organ system covered; thus the students had not covered other organ systems, such as the renal and pulmonary systems, at the time of this study. Additionally, students would not have had any clinical training in cardiovascular techniques, such as measuring blood pressure, heart rate, etc., at this point. As a result, the respiratory question used for survey validity by Michael et al. (4) could not be used in the present study.

Lecture Materials

The 50-min introductory didactic lecture on cardiovascular physiology was created as part of the St. George’s University (SGU) physiology curriculum. The lecture’s content was specially created around the pre-existing, published questions designed by the PERC to probe difficult concepts (4). Relevant content was taught before each question that was presented to the class. The sequence of concepts that was taught is listed in Table 1. Specific learning objectives are listed in appendix 1. Content was based on the textbooks, Rhodes and Bell’s Medical Physiology: Principles for Clinical Medicine (20) as well as Klabunde’s Cardiovascular Physiology Concepts (21).

The rationale for selecting cardiovascular physiology content for this study was because the topic represents complex phenomena, requires learning several different concepts in different categories [i.e., concrete concepts (matter) and abstract processes], and involves understanding of separate facts as a representation of a whole system (3, 6). The lecture is copyrighted by SGU and thus cannot be added to this publication.

Presentation of Questions during the Lecture

Questions were delivered at ∼10-min intervals over the course of a single PowerPoint lecture. Students were given 60 s to answer and discuss the questions among each other. Correct answer choices were revealed and discussed by the professor after the allotted time for each question expired. Table 1 relates the question content to specific concepts, and lists the questions in the sequence they were presented during the lecture.

In-Class Polling during the Lecture

The in-class polling Turning-Point system was used to record and collect students’ responses to lecture questions. The questions are numbered herein the sequence in which they were presented in the lecture. Questions were delivered to the medical students only after the respective content was covered in the lecture, with the exception of question 1 (Q1), which was given at the very start of the lecture, before instruction.

Creation of the Preexisting, Previously Published Questions Used in This Study

The 50-min lecture allowed the incorporation of seven previously published questions that assessed common misconceptions in cardiovascular physiology (4). These
questions were created by members of the PERC; they identified difficult concepts based on PERC members’ teaching experience and were selected for relevance to their course content (4). In brief, PERC members submitted lists of difficult cardiovascular physiology concepts, which were then used to create multiple choice questions to probe for conceptual or reasoning difficulties. The questions were later circulated to the PERC members for their course content were selected for use in their courses (4). Thus the content validity of these questions has been determined by several experts.

**Question Content Validity and Reliability**

As described above, content validity of the questions administered to students as a part of this study has been determined by several experts in the PERC. True the reliability statistics could not be performed in the present study due to the lack of individual student data. However, these questions were previously evaluated in a population of 1,076 undergraduate students from 12 different courses at 8 institutions (4). Michael et al. (4) demonstrated relatively low standard deviations when questions were repeated across diverse student populations and courses at several undergraduate institutions. While this is not an accurate measure of reliability, it does demonstrate consistency in answers across a large sample size of students from different institutions.

**Differences and Similarities between the Medical Students and Published Undergraduate Data of Michael et al. (4)**

Since the same questions were used in the present study with medical students and the published study with undergraduates, we outline some methodological similarities and differences between the two studies’ procedures:

1) **Medical student population**: Our questions were administered only once to a single group of medical students (n = 736) at a single institution, whereas Michael et al. (4) studied undergraduate students (n = 1,076) across eight different institutions.

2) **Questions administered after learning content**: Our medical students were taught the relevant content before each question was administered, with the exception of Q1. Conversely, in the previously published study, the undergraduates were asked all of the questions either at the beginning of each course or just before the class began learning the topic of cardiovascular physiology (4).

3) **A subset of published questions used (similarity)**: Like in the undergraduate study, only questions relevant to the course content were selected for use in the present study. Some questions (CVDQ2-5, 8, and 9, covering the topics of hemorrhage, metabolism, cardiac cycle, heart innervation, and timing) were not used in the present study because these concepts were not taught in our introductory cardiovascular lecture.

4) **Order of question presentation**: Our questions are numbered in their order of presentation in the lecture and are in a different order from those in Michael et al. (4). This difference in ordering was due to the organization of the lecture content.

5) **Internal control question**: Michael et al. (4) used an additional respiratory question for validation. At the point of this study, the medical students had not covered any respiratory content. Q1 (CVDQ10) was instead administered at the very start of the lecture, before instruction. This allowed for a more direct comparison of our data to those of Michael et al. (4).

6) **Conversion of undergraduate data to percent correct**: For direct comparison to our data, the data in Michael et al. were converted from percentage incorrect to percentage correct. For the original data, see Table 5 in Michael et al. (4).

7) **Only multiple-choice questions were used**: Only multiple-choice questions were used in the present study, and the short answer written responses from Michael et al. (4) were not included. Of note, the short answer responses were administered only for a small subset of the questions from Michael et al. (4), and only one corresponded to a question selected for this study.

**Statistical Analysis**

Averages and standard deviations for the data from our study could not be calculated as the study was only performed once, with all students in the same lecture at the same time. Thus standard t tests are not applicable. The proportions of students identifying correct answers from two
Table 2. Performance of medical vs. undergraduate students on cardiovascular questions probing difficult concepts

| Question | CVDQ [Michael et al. (4)] | Content | Correct/ Total Responses | Correct, % | Correct, % [Michael et al. (4)] | Distractor |
|----------|---------------------------|---------|--------------------------|------------|----------------------------------|-----------|
| 1        | 10                        | Mean arterial pressure is regulated  | 531/736   | 72.2<sup>*</sup> | 38 ± 11              | B 22.4    |
| 2        | 6                         | Right and left ventricular output  | 695/734   | 94.7<sup>*</sup> | 45 ± 18.7             | A 35.1    |
| 3        | 13                        | Equation: CO = HR × SV              | 435/729   | 59.7<sup>*</sup> | 26 ± 8                | C 21.1A 14.6 |
| 4        | 11                        | Equation: SV × HR = CO or venous return  | 466/725   | 64.3<sup>**</sup> | 49 ± 10.4             | A 42.6    |
| 5        | 12                        | Anatomical knowledge: flow in pulmonary and systemic circulations | 406/732   | 55.5<sup>**</sup> | 53 ± 6.5              | C 42.1    |
| 6        | 1                         | Equation: parallel resistances       | 362/730   | 49.6<sup>**</sup> | 36 ± 9.4              | A 42.6    |
| 7        | 7                         | Capillary and arteriolar pressures   | 654/732   | 89.3<sup>**</sup> | 34 ± 6.5              |           |

Comparison between medical students (n = 736) in the present study and data from undergraduate students (n = 1,076) from Michael et al. (4). Notably, undergraduate data of Michael et al. (see Table 5 of that publication) were converted from the published percent incorrect (prevalence) data to percent correct in our table (last column). The question numbering (i.e., Q1–7) refers to the order in which questions were presented in this study, whereas the CVDQ refers to the numbering from Michael et al. (4). Inclusion of the raw correct/total responses data is for statistical reporting and any future replication studies or meta-analyses. CO, cardiac output; HR, heart rate; SV, stroke volume; ns, not significant. *Significant difference (P < 0.05).

### RESULTS

**Comparison of Medical Versus Undergraduate Students**

The individual data from the undergraduate and medical students are informative. Analyzing the undergraduate students’ data alone demonstrated low performance, below 55% for all questions, ranging from 26–53% correct answers. On the other hand, medical students’ performance was >70% on questions 1, 2, 7, and 8, and <65% correct on questions 3–6 (Fig. 1), with performance ranging from 49.6% to 97.6% correct. (Fig. 1). Overall, the number of medical students choosing to respond to each question (response rate) was high, ranging from 96.7% to 100% of the entire class (Table 2). This indicates that medical students found specific content difficult, whereas the undergraduates found all of the content challenging.

Misconceptions would be evident by little change in question performance between the two groups. Interestingly, there was no significant difference between the two groups for Q4–6 (Fig. 1). As such, these concepts appear resistant to education level and prior instruction and are thus sources of misconceptions.

Preconceptions were identified via increases in medical versus undergraduate student performance on specific questions. Medical students’ performance was significantly different from that of undergraduates for Q1–3 and Q7 (P < 0.05) (Fig. 1). Misunderstandings in these questions were due to preconceptions, and thus amenable to change with additional education. Differences in performance in this study could either be due to the increased level of education of the medical students or the teaching of content before being presented with questions in the lecture.

**Effect of Education Level**

Increased education level is one difference between the two groups which could explain the differences in performance on some questions (i.e., indicating preconceptions). A direct
comparison between the two groups is possible, albeit using just one question. Similar to the methodology used in the undergraduate study of Michael et al. (4), Q1 was presented to the medical students before instruction. Medical students performed significantly better on Q1 than undergraduates (34.2% difference) (Fig. 1), indicating that increased education level enhances performance on these difficult concepts.

In the present study, students were not asked to explain their rationale for their responses. An alternate way of deducing the student’s thought process is to analyze the incorrect answer choices, or distractors, for this question. Similar data are not available in the undergraduate study. In Q1, the wrong choice B, mean arterial pressure and cardiac output, was selected by 22.4% of the medical students. This suggests that cardiac output’s dynamic nature and its representation by an equation, \( CO = HR \times SV \), lead to misunderstandings, but that medical students had a better grasp of these concepts. While these are only data from one question, they suggest that a higher education level is associated with increased question performance.

**Effect of Prior Teaching of Concepts**

Erroneous concepts that can be corrected via prior instruction (e.g., lectures) are termed preconceptions. It is likely that improved performance on Q2, 3, and 7 in the medical students is due to prior teaching of concepts, and thus represents the effects of preconceptions. On the other hand, misconceptions are more concerning. Even with prior teaching of the concepts during the lecture, medical students’ performance on Q3–6 was < 65%, compared with the other questions where performance was >72% correct. Importantly, for Q4–6, medical student performance was not significantly different than that of undergraduates. Overall, these data suggest that the problematic concepts probed by these questions were resistant to increased levels of education and prior instruction with a lecture. As such, performance on these questions was hindered by misconceptions.

Analysis of the incorrect answer choices, or distractors, also reveals students’ misunderstandings. Three of the misconceptions probed by Q3, 4, and 6 are related to equations. The concepts addressed by these questions are described in Tables 1 and 2 and Fig. 2. For Q3, distractor A, has increased, was selected by 35.1% of the students. Similarly to Q1, this suggests that cardiac output’s dynamic nature and its representation by an equation, \( CO = HR \times SV \), lead to confusion. For Q4, the distractors C, remain the same, and A, increase, were chosen by 21.1% and 14.6% of students, respectively, which may indicate guessing. This question concerned relating flow to volume in venous return, suggesting difficulty with rates versus volumes, similar to the above Q3. For Q6, distractor A, increase, was chosen 42.6% of the time. The specific misconception was the relationship between the pressure gradient and resistance (\( Q = \Delta P/R \)). Of note, in the short answer written responses used in Michael et al. (4), and not this study, 60% of the undergraduates selected this incorrect answer [306/510; see Table 7 of Michael et al. (4)].

We will note that incongruity in Q6 may have caused confusion, where the question asks about venule pressures, but the associated diagram has veins instead of venules. Students may have been confused if they did not know what a venule was at that time. Nonetheless, several misconceptions were related to physiological formulas.

On the other hand, Q5 is related to flow in the pulmonary and systemic circulations. Here, 42.1% selected distractor C, “less than.” This suggests that the students had difficulty with the anatomy of the dual serial flow paths of the systemic and pulmonary circulations.

**Misconception Groupings**

Overall, the questions can be sorted into two types: those related to anatomy and those related to equations. Q5 is related to the anatomy of blood flow in the circulation, or dual flow. On the other hand, questions Q3, 4, and 6 concern equations. The underlying causes for these misconceptions will be addressed in detail in the **DISCUSSION**.

**DISCUSSION**

Misconceptions, preconceptions, and the effect of education level in large populations of medical and undergraduate students were identified by analyzing performance on a panel of previously published questions. These questions were designed to probe difficult cardiovascular concepts, which include the path of blood flow through the circulation and equations such as Ohm’s law of fluid flow (\( Q = \Delta P/R \)) and cardiac output (\( CO = HR \times SV \)) (4, 6–13).

Preconceptions were identified as increased performance both within the medical student group and also when compared with the undergraduate group. Misconceptions were identified through having comparable poor performance in both cohorts. Misconceptions are important to study because they can interfere with students’ future understanding of the cardiovascular system (9, 13, 22). They have been studied in diverse student populations at elementary, high school, undergraduate (4, 7, 11, 12), and medical school levels (5, 6, 13). To our knowledge, there have been no studies directly comparing the performance using the same question panel with large numbers of undergraduate and medical students.

The results herein are supported by other studies that compare different levels of education. Misconceptions persist regardless of education level but with fewer misconceptions associated with increasing levels of education. Examples of reduced misconceptions have been found in studies comparing elementary school versus university students (11), students in different years of medical school (6, 13), and medical students, residents, cardiologists, and physiology residents (22). However, some of the misconceptions remained (22). Indeed, misconceptions have been described as “amazingly tenacious and resistant to extinction” (7). It has been suggested that, in some cases, formal learning, with incorrect prior knowledge forming during lectures or due to simplification of concepts in textbooks, contributes to misconceptions (3, 4, 11, 12, 23, 24).

The anatomical oversimplification of depictions in textbooks can account for one previously identified misconception, related to the systemic and pulmonary circulations’ dual, serial flow paths (5, 6). In our study, this misconception persisted despite both an increased level of education and prior instruction, as identified by Q5. An underlying cause of this misconception may be the...
oversimplification of the circulatory systems depicted or described in textbooks (3, 4, 11, 12, 23, 24), where the focus on anatomical correctness obscures the fundamental physiology. An example of this oversimplified, anatomically correct depiction is shown in Fig. 3A. Perhaps emphasizing the physiological detail that the two parallel systems are connected via a crossover, as in Fig. 3B, may overcome this misconception. It has been suggested that students may have an "illusion of understanding" because of such prior erroneous knowledge, which results in resistance to conceptual change (6).

Difficulties with equations or physiological formulas account for most of the misconceptions in this study and are exemplified by the data from Q3, 4, and 6. The equations in question outline the relationship between pressure gradient and resistance, or Ohm’s flow equation (Q = ΔP/R) (4–6, 9, 10), and cardiac output (CO = SV × HR) and venous volume (4). With regards to the flow down gradients in the circulation,
students generally focus on the upstream absolute pressures and not the pressure gradients, but it is the gradient that drives the flow (27). Students may have difficulty with causal reasoning because equations represent dynamic processes with multiple variables that change independently (1), are continuous, and co-occur (2). Additionally, these concepts may be taught using analogies, which can also lead to errors (9). Since students may not have a mental classification or category for such dynamic processes, they may have difficulty shifting this information into alternative categories (2). Finally, a simpler explanation is that students may memorize the equations and not apply them to different situations.

**A Change in Education is Needed**

The present and previously published results clearly indicate that the current methods of teaching the basic science of cardiovascular physiology do not eradicate misconceptions. The fact that teaching is part of the problem is not contested and has been previously identified (4, 6, 12, 28). A change needs to start with the teachers and educators to work toward correcting the problem. Teachers may not be aware of the typical misconceptions that hinder student learning (6, 11, 29), a phenomenon that has been termed the “expert blind spot” (30). For example, experts may forget the problems and difficulties involved with the initial learning of basic biomedical knowledge (31). Additionally, teachers might not consider alternate instructional strategies or methods that can be used to improve the instruction of difficult concepts (6, 23). In light of the above, a discussion of potential teaching methods to eradicate misconceptions is warranted.

**Possible Teaching Methods to Overcome These Misconceptions**

Misconceptions are barriers to students’ understanding of the cardiovascular system and are thus important to address (9, 13, 22). It is not enough for teachers to only identify misconceptions and the underlying reasons for their persistence, they must also facilitate conceptual change by adjusting the method of instruction, since ordinary instruction is often unsuccessful in overcoming them (17, 18). Overcoming misconceptions requires incitement of cognitive conflict between students’ prior knowledge and new, incompatible ideas (15). Several educational theories have discussed approaches to overcoming misconceptions, such as the Mezirow’s transformative theory of learning as well as Piaget’s accommodation (29, 32–34). While these theories provide guiding principles, they need to be transformed into practice or outline instructional design or teaching methods that can be applied to overcome misconceptions. The educator must create activities to expose misconceptions, create conceptual conflict, and affect cognitive accommodation or change (7, 17, 18, 29).

Activities to overcome misconceptions can be related to the “5 E’s,” instructional design principles of Engagement, Exploration, Explanation, Elaboration, and Evaluation (35). The sequence involves solving a real-world problem, exploring students’ knowledge and skills, explaining and clarifying misconceptions, and elaborating or discussing in student groups, which culminate with reflective evaluation of students’ own comprehension. One can see a general similarity of the “5 E’s” to Kolb’s experiential learning cycle (36). Some suggested teaching activities to overcome misconceptions include the following:

1) Engagement and exploration of questions based on difficult concepts. This can be used to probe for misconceptions, as in the present study an additional study by Michael et al. (1, 23) using PERC questions. Identification of misconceptions allows for student exploration of their mental models. It creates cognitive dissonance, or disequilibrium between faulty, resilient prior knowledge (misconceptions) and correct new information (7, 28, 35). This teachable moment allows the professor to explain where the students went wrong. The students can then complete
the remaining “I’e,” elaboration and exploration, to restore equilibrium between prior knowledge and the real-world experience (37, 38).

3) Concept maps aid the creation of mental models, testing the models against real-world problems and refining or correcting their models (27). For example, they can be used to visualize regulatory systems and demonstrate the physical interactions of all relevant parameters (27), which may aid in students’ understanding and application of the equations. Importantly, concept maps can expose knowledge gaps (5).

4) Laboratory sessions (39), PBL (40, 41), “think, pair, share” (42, 43), and case-based learning (44, 45) are all “hands-on,” active learning, student-centric methods.

Conclusions

This study identified preconceptions that were amenable to change, as well as misconceptions surrounding specific concepts that were not abolished by education and prior lecture instruction. The persistence of these well-known misconceptions in cardiovascular physiology led to a discussion of potential education methods for improvement of education. Eradication of misconceptions in cardiovascular physiology basic science is especially crucial so as to facilitate later acquisition of clinical knowledge.

APPENDIX I: LECTURE OBJECTIVES FOR THE INTRODUCTORY CARDIOVASCULAR LECTURE

The learning objectives for the lecture were derived from the broader US Medical Licensing Examination content outline, cardiovascular system, and organ structure and function: cardiac conduction hemodynamics, including blood volume and systemic, and vascular resistance circulation in specific vascular beds, including pulmonary and coronary (46) (see Table A1).

ACKNOWLEDGMENTS

Former address for L. V. Murray: Dept. of Physiology, Neuroscience, and Behavioral Sciences, St. George’s Univ. School of Medicine, St. George’s, Grenada.

DISCLOSURES

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

AUTHOR CONTRIBUTIONS

I.V.M. conceived and designed research; I.V.M. performed experiments; S.J.B., R.M., J.D.H., and I.V.M. analyzed data; S.J.B., R.M., and I.V.M. interpreted results of experiments; S.J.B. and I.V.M. prepared figures; S.J.B., R.M., and I.V.M. drafted manuscript; S.J.B., R.M., J.D.H., Y.L., and I.V.M. edited and revised manuscript; S.J.B., R.M., J.D.H., Y.L., and I.V.M. approved final version of manuscript.

REFERENCES

1. Michael J. What makes physiology hard for students to learn? Results of a faculty survey. Adv Physiol Educ 31: 34–40, 2007. doi:10.1152/advan.00057.2006.

| Table A1. Learning objectives |
|--------------------------------|
| **Learning Objectives**        |
| Compare and contrast features that distinguish the pulmonary and systemic circulations. |
| Explain why left and right heart output must almost match. |
| Define cardiac output and stroke volume. Explain how SV is calculated. |
| Define venous return. Explain the concept of capacitance vessels. |
| Understand the interrelationships between flow, pressure, and resistance. |
| Write down the basic law of flow, “Darcy’s law.” |
| Explain how pressure regulates flow in the circulatory systems. |
| Understand resistance arterioles. |

SV, stroke volume.

2. Chi M, Roscoe R. The Processes and Challenges of Conceptual Change. Pittsburgh, PA: Kluwer Academic Publishers, 2002.
3. Chi MT, Slotta JD, De Leeuw N. From things to processes: a theory of conceptual change for learning science concepts. Learn Instr 4: 27–43, 1994. doi:10.1016/0959-4752(94)90017-5.
4. Michael JA, Wenderoth MP, Modell HI, Cliff W, Horwitz B, Mchale P, Richardson D, Silverthorn D, Williams S, Whitescarver S. Undergraduates’ understanding of cardiovascular phenomena. Adv Physiol Educ 26: 72–84, 2002. doi:10.1152/advan.00002.2002.
5. Mikkila-Erdmann M, Sodervik I, Vilppu H, Kaapa P, Okinuera E. First-year medical students’ conceptual understanding of and resistance to conceptual change concerning the central cardiovascular system. Instr Sci 40: 745–754, 2012. doi:10.1007/s11251-012-9212-y.
6. Anpeito L, Mikkila-Erdmann M, Okinuera E, Kaapa P. A follow-up study of medical students’ biomedical understanding and clinical reasoning concerning the cardiovascular system. Adv Heal Sci Educ 16: 655–668, 2011. doi:10.1007/s10459-011-9286-3.
7. Arnaudin M, Mintzes J. Students’ alternative conceptions of the human circulatory system: a cross-age study. Sci Educ 69: 721–733, 1985. doi:10.1002/sce.373069013.
8. Belloni FL. Teaching the principles of hemodynamics. Adv Physiol Educ 22: 187–202, 1999. doi:10.1152/advances.1999.277.6.s187.
9. Carroll R. Cardiovascular pressure-flow relationships: what should I be taught? Adv Physiol Educ 25: 8–14, 2001. doi:10.1152/advances.2001.25.2.8.
10. Chi M. Commonsense conceptions of emergent processes: why some misconceptions are robust. J Learn Sci 14: 161–199, 2005. doi:10.1207/s15327809jls1402_1.
11. Özgur S. The persistence of misconceptions about the human blood circulatory system among students in different grade levels. Int J Env Sci Educ 8: 255–268, 2013. doi:10.2973/ijese.2013.206.a.
12. Palizvan MR, Nejad MR, Jand A, Rafeie M. Cardiovascular physiology misconceptions and the potential of cardiovascular physiology teaching to alleviate these. Med Teach 35: 454–458, 2013. doi:10.3109/0142159X.2013.774331.
13. Södervik I, Mikkila-Erdmann M, Chi M. Conceptual change challenges in medicine during professional development. Int J Educ Res 98: 1–12, 2019. doi:10.1016/j.ijjer.2019.08.004.
14. Anderson RC, Spiro RJ, Anderson MC, American S, Summer N. Schemata as scaffolding for the representation of information in connected discourse published by: American Educational Research Association Schemata as Scaffolding for the Representation of Information in Connected Discourse. Am Educ Res J 15: 433–440, 1978. doi:10.3109/028128312015093432.
15. Posner G, Strike K, Hewson P, Gertzog W. Accommodation of a scientific conception: toward a theory of conceptual change. Sci Educ 66: 211–227, 1982. doi:10.1002/sce.3730660207.
16. Rumelhart DE. Schemata: The Building Blocks of Cognition in: Comprehension and Teaching: Research Reviews. Newark, DE: International Reading Assoc., 1982.
17. Lucariello J. How Do I Get My Students Over Their Alternative Conceptions (Misconceptions) for Learning? Washington, DC: American Psychological Assoc., 2010.
18. Lucariello J. How Do My Students Think: Diagnosing Student Thinking Understanding Misconceptions Is Key Early Step. Washington, DC: Am. Psychological Assoc., 2010.
STUDENT CARDIOVASCULAR MISCONCEPTIONS

19. St. George’s University School of Medicine. Enrollment and Demographics (Online). https://www.sgu.edu/enrollment-and-demographics-school-of-medicine/. [2020].
20. Rhoades R, Bell D. Medical Physiology: Principles for Clinical Medicine (5th ed). Baltimore, MD: Wolters Kluwer, 2017.
21. Klabunde R. Cardiovascular Physiology Concepts (2nd ed.). Baltimore, MD: Lippincott Williams and Wilkins, 2012.
22. Kaufman DR, Keselman A. Changing Conceptions in Medicine and Health. In: Handbook of Research on Conceptual Change, edited by Vosniadou S. Mahwah, NJ: LEA, 2012.
23. Michael JA, Richardson D, Rovick A, Modell H, Bruce D, Horwitz B, Hudson M, Silverthorn D, Whitescarver S, Williams S. Undergraduate students’ misconceptions about respiratory physiology. Am J Physiol 227: S127–135, 1999. doi:10.1152/advances.1999.277.6.S127.
24. Pelaez NJ, Boyd DD, Rojas JB, Hoover MA, Nancy J, Boyd DD, Rojas JB. Prevalence of blood circulation misconceptions among prospective elementary teachers. Adv Physiol Educ 29: 172–181, 2005. doi:10.1152/advan.00022.2004.
25. Wikipedia. Circulatory System. https://en.wikipedia.org/wiki/Circulatory_system#media/File:2101_Blood_Flow_Through_the_Heart.jpg.
26. Thoracic Key. Circulatory System: The Pulmonary Circulation: Bringing Blood and Gas Together. https://thoracickey.com/the-pulmonary-circulation-bringing-blood-and-gas-together/.
27. Michael J, Cliff W, McFarland J, Modell H, Wright A. The Care Concepts of Physiology. New York: Springer, 2017.
28. Michael J. Misconceptions—what students think they know. Adv Physiol Educ 26: 5–6, 2002. doi:10.1152/advan.2000.47.2001.
29. Nussbaum J, Novick S. Alternative frameworks, conceptual conflict and accommodation: toward a principled teaching strategy. Instr Sci 11: 183–200, 1982. doi:10.1007/BF00414279.
30. Nathan MJ, Petrosino A. Expert blind spot among preservice teachers. Am Educ Res J 40: 905–928, 2003. doi:10.3102/00263120040004905.
31. Boshuizen H, Schmidt H, Custers E, Van De Wiel M. Knowledge development and restructuring in the domain of medicine: the role of theory and practice. Learn Instr 5: 269–289, 1995. doi:10.1016/0959-4752(95)00019-4.
32. Christie M, Carey M, Robertson A, Grainger P. Putting transformative learning theory into practice. Aust J Adult Learn 55: 9–30, 2015.
33. Mezirow J. New Directions for Teaching and Learning-Transformative Learning: Theory to Practice. San Francisco, CA: Jossey-Bass Publishers, 1997.
34. Piaget J. Piaget’s Theory in: Piaget and his School. Berlin: Springer, 1976.
35. Daines B, Berry A, Darowalla F, Hirumi A, Harris D. The use of the SE instructional design strategy to teach respiratory physiology to first-year medical students. Adv Physiol Educ 43: 546–552, 2019. doi:10.1152/advan.00116.2019.
36. Kolb D. Experiential Learning: Experience as the Source of Learning and Development. Eaglevood Cliffs, NJ: Prentice Hall, 1984.
37. Braun LT, Schmidmaier R. Dealing with cognitive dissonance: an approach. Med Educ 53: 1167–1168, 2019. doi:10.1111/medu.13955.
38. Meyer J, Land R. Threshold concepts and troublesome knowledge: linkages to ways of thinking and practising within the disciplines. In: Enhancing Teaching-Learning Environments in Undergraduate Courses Project, Occasional Report 4, ETL Project, Universities of Edinburgh, Coventry and Durham, 20031-12 (Online). http://www.etl.tla.ed.ac.uk/publications.html.
39. Modell HI. Helping students make sense of physiological mechanisms: the ‘view from the inside’. Adv Physiol Educ 31: 186–192, 2007. doi:10.1152/advan.00079.2006.
40. Allen DE, Donham RS, Bernhardt SA. Problem-Based Learning. Wiley Periodicals Inc, 2011.
41. Savery JR, Duffy TM. Problem based learning: an instructional model and its constructivist framework. Educ Technol 35: 31–38, 1995.
42. Lyman F. The responsive classroom discussion: the inclusion of all students. In: Mainstreaming Digest, edited by Anderson A. College Park, MD: University of Maryland Press, 1998, p. 109–113.
43. Mazur E. Peer Instruction: A User’s Manual. Upper Saddle River, NJ: Prentice Hall, 1997.
44. Cliff W. Case-based learning of blood oxygen transport. Adv Physiol Educ 30: 224–229, 2006. doi:10.1152/advan.00003.2006.
45. Colthorpe XK, Abe H, Ainscough L. How do students deal with difficult physiological knowledge? Adv Physiol Educ 42: 555–564, 2018. doi:10.1152/advan.00102.2018.
46. National Board of Medical Examiners. USMLE Content Outline (Online).https://www.usmle.org/pdfs/usmlecontentoutline.pdf. [2020].

Advances in Physiology Education • doi:10.1152/advan.00220.2020 • http://advan.physiology.org 249