UNDERGRADUATES' UNDERSTANDING OF CARDIOVASCULAR PHENOMENA

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Undergraduates students in 12 courses at 8 different institutions were surveyed to determine the prevalence of 13 different misconceptions (conceptual difficulties) about cardiovascular function. The prevalence of these misconceptions ranged from 20 to 81% and, for each misconception, was consistent across the different student populations. We also obtained explanations for the students' answers either as free responses or with follow-up multiple-choice questions. These results suggest that students have a number of underlying conceptual difficulties about cardiovascular phenomena. One possible source of some misconceptions is the students' inability to apply simple general models to specific cardiovascular phenomena. Some implications of these results for teachers of physiology are discussed.

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Students studying any science discipline come into the classroom with naive conceptions, preconceptions, or alternative conceptions about the subject matter that impact mastery of that discipline (5, 10, 11). These terms are not, of course, synonyms, since each of them carries a different set of assumptions. However, for teachers, the most important thing that they all have in common is the interference with learning that they are known to cause.

As teachers, we become aware of the existence of these preconceptions, alternative conceptions, or misconceptions when we ask a student a question, receive an answer, and then reflect on the possible implications of that answer. Such questions can *diagnose* the existence of *conceptual* or *reasoning difficulties,* and the student's incorrect answers thus serve as *diagnostic signs* of those difficulties. That is, the student's answers suggest that there is some conceptual difficulty causing the wrong answer. To determine what underlying conceptual difficulty is present, we ask additional questions to get the student to elaborate on his/her thinking. It is not uncommon to find that even a follow-up question to a correct answer reveals that the student has significant difficulty thinking about the issue at hand (i.e., the question was answered correctly, but for the wrong reason).

Misconceptions (conceptual difficulties) have been studied extensively in physics but less so in chemistry and biology (see Ref. 8 for a bibliography of studies of misconceptions in science). The biology topics that have been studied most frequently include photosynthesis, genetics, evolution, and the circulatory system. Mintzes and colleagues (1, 5) have examined the differences that are present in students' understanding of the circulatory system at different educational levels (4th grade to college) and observed that some alternative conceptions are quite resistant to change, whereas others become much less prevalent in older students. However, they studied a relatively narrow range of concepts, and some of the questions they asked students seem directed more at factual knowledge than conceptual understanding.

Previously, we (2, 4) studied the prevalence of misconceptions that students have about concepts in respiratory physiology. In these studies, we gave the students a set of respiratory diagnostic questions and asked them to answer the question and then offer an explanation of that answer. In some studies, this was done in writing, whereas in other studies this was done with a follow-up multiple choice question. We used these explanations to attempt to determine the underlying conceptual or reasoning difficulty that led the students to the incorrect answer (diagnostic sign). We found that the prevalence of these respiratory misconceptions was quite consistent across a wide spectrum of undergraduate populations. We also found some significant patterns in the conceptual or reasoning difficulties that seemed to underlie some of the inability of students to answer respiratory questions correctly; one of these patterns has been pursued in the present study (see below).

In our present study, we determined the prevalence of misunderstandings about certain concepts related to the cardiovascular system (which shares certain similarities with the respiratory system but is nevertheless sufficiently different that there will be a quite different set of possible misconceptions present) in a large and diverse population of undergraduate students. We identified the underlying conceptual difficulties associated with these misunderstandings by collecting written explanations of their reasoning and through the use of multiple-choice follow-up questions. We also hypothesized that at least some conceptual difficulties in understanding cardiovascular physiology arise from the students' inability to reason about simple physical and chemical systems, what Modell (6) has called general models, that are applicable to specific situations in the cardiovascular system. Our results offer some support for this hypothesis and suggest further experiments to explore this idea.

METHODS

Members of the Physiology Educational Research Consortium (PERC) contributed lists of cardiovascular topics that, in their experience (class interactions with students, examination results), students found difficult. From this list, a set of multiple-choice diagnostic questions was written that probe for the existence of conceptual or reasoning difficulties. We specifically selected questions that were diagnostic for difficulties that can seriously interfere with students' mastery of the topic at hand. Diagnostic questions were generally of the form: "If X increases, then will Y increase/decrease/show no change?" In several of the early surveys, students were asked for brief written explanations of their answers. The written explanations were collected and analyzed to determine the students' underlying conceptual and/or reasoning difficulty. These written explanations were also used to help generate multiple-choice follow-up explanations that were used in later surveys.

The list of possible diagnostic questions was circulated to all PERC members, and each was asked to identify a set of questions that would be appropriate for use with students in his/her classes. Because the courses to be surveyed spanned the range from introductory anatomy and physiology at community colleges to advanced physiology courses at research universities, it was essential that each site use only diagnostic questions that corresponded to the educational objectives of their course(s). It would not be useful, for example, to probe for a conceptual or reasoning difficulty about "inotropic state" from students who are not expected to know what this means. Thus, although some diagnostic questions appeared on all of the surveys administered, others were used at only two or three institutions. Table 1 contains the 13 diagnostic questions (DQs) used in this study. For each question, we have indicated some possible underlying difficulties for which the question might be diagnostic solely on the basis of an analysis of the physiology involved.

We also wrote questions (GMDQ1–3; Table 2) that tested the students' ability to reason about three different general models (6): pressure/flow/resistance, elastic structures, and mass balance. Each question described a relatively simple, nonphysiological system. For each of the general model questions, there was a matched cardiovascular diagnostic questions (CVDQ1–3, Table 1) that required application of the general principle to a specific cardiovascular phenomenon.

Every survey also contained a specific respiratory diagnostic questions from our earlier studies (2, 4), which had identified a conceptual difficulty whose prevalence was consistent across diverse populations of students. This question provided us with a benchmark with which to assess the consistency of our methods and the student populations being studied.

The cardiovascular diagnostic survey was administered either at the beginning of each course or just before the class began the topic of cardiovascular physiology.

Table 3 lists the eight institutions (and the 12 participating courses) at which the cardiovascular diagnostic survey was administered. A total of 1,076 students participated. Table 4 provides a basic description of the characteristics of the total population of students that we studied.

RESULTS

Prevalence of respiratory diagnostic sign. Among the students surveyed in the present study (n = 1,052), 57.6% had some conceptual and/or reasoning difficulty about the determinants of minute ventilation. The prevalence of this difficulty in individual courses ranged from a low of 40.2% to a high of 70.6%. These results are very similar to our previously reported findings (2, 4).

Prevalence of cardiovascular diagnostic signs. Table 5 shows for each diagnostic question: *1*) the percentage of each student population studied that *did not answer correctly*, *2*) the percentage of the total population (all institutions and courses) that had answered incorrectly or had conceptual difficulty with the question, and *3*) the mean prevalence and standard deviation for all of the courses.

The number of students from whom we have data varies from question to question, because not every diagnostic question was administered at every site and because of student errors in coding their answers on the answer forms used.

The prevalence of particular cardiovascular diagnostic signs varied considerably; the most prevalent difficulty (CVDQ4: CARDIAC OUTPUT AND RESISTANCE) was exhibited by 81% of the students studied, whereas the least common (CVDQ2: HEMORRHAGE AND VENOUS PRESSURE) was exhibited by only 20% of the subjects. The prevalence of any particular diagnostic sign tended to be consistent across the individual student populations; the largest standard deviation was 18.7% for CVDQ6.

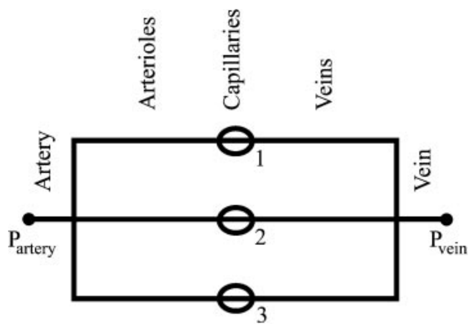
What are the underlying difficulties that lead to the diagnostic signs we obtained? In three of the earliest surveys (SU3a, SU4, SU5; Table 3) students were asked to provide written explanations for their answers to four of the diagnostic questions (CVDQ1, -4, -6, and -8). For each question, we looked for patterns in the explanations offered for both wrong answers (diagnostic signs) and correct answers. We examined ~300 written responses. Some typical explanations are presented in Table 6.

Question CVDQ1 (Table 1) asked students about the change in pressure, if any, that occurs downstream of a vasoconstriction. Pressure in the venules will decrease because the added resistance will increase the pressure drop that occurs. Students who predicted that pressure would be increased exhibited considerable confusion about pressure, flow, flow velocity, and blood volume in a segment of the circulation and how they relate to the concept of resistance. On the other hand, students who predicted that pressure downstream would not change argued that altering one segment of the circulation would not affect an-

TABLE 1

Cardiovascular diagnostic questions and the conceptual difficulties they point to (* indicates correct prediction)

(CVDQ1) VASOCONSTRICTION AND DOWNSTREAM PRESSURE



Consider the small piece of the circulation shown to the *left*. The pressure gradient across the circulation (P_{artery}-P_{vein}) is constant. If the arterioles in path 1 VASOCONSTRICT (get smaller), then pressure in the venules of path 1 will:

a. increase
b. decrease*
c. not change

Diagnostic for: pressure/flow/resistance general model

(CVDQ2) HEMORRHAGE AND VENOUS PRESSURE

A large vein in the leg of an accident victim is cut, and the individual loses 2 liters of blood. The pressure in her veins will:

a. increase
b. decrease*
c. remain unchanged

Diagnostic for: elastic structures general model

(CVDQ3) DECREASED METABOLISM AND VENOUS O_2 CONTENT

Arterial blood flows through an organ of the body at a constant rate. If the metabolic activity of that organ is DECREASED, the amount of oxygen in each milliliter of blood leaving the organ in the vein will:

a. increase*
b. decrease
c. remain unchanged

Diagnostic for: mass balance general model

(CVDQ4) CARDIAC OUTPUT AND RESISTANCE

If cardiac output (the volume/min ejected from the heart) increases significantly, then the resistance of the arterioles will:

a. immediately and directly increase significantly
b. immediately and directly decrease significantly
c. not change directly to any significant extent*

Diagnostic for: determinants of vessel resistance

(CVDQ5) ATRIAL AND VENTRICULAR CONTRACTION

The ventricle fills:

a. ONLY when the atrium contracts
b. ONLY when the pressure in the ventricle is less than the pressure in the atrium*
c. ONLY when the papillary muscles contract and open the A-V valve

Diagnostic for: structure/function relationships of valves in heart; cardiac cycle

(CVDQ6) R AND L VENTRICULAR OUTPUT

When the heart beats:

a. the right and left ventricles pump the same volume of blood each beat*
b. the right ventricle pumps less blood each beat than does the left ventricle
c. the right ventricle pumps more blood each beat than does the left ventricle

Diagnostic for: circulation is closed, circular system; Frank-Starling

(CVDQ7) CAP AND ARTERIOLAR PRESSURES

The blood pressure in the capillaries is ______ than the blood pressure in the arterioles.

a. greater than
b. less than*
c. the same as

Diagnostic for: structure of circulation; presure/flow/resistance

TABLE 1—*Continued*
Cardiovascular diagnostic questions and the conceptual difficulties they point to (* indicates correct prediction)

(CVDQ8) DENERVATE HEART
If all of the nerves innervating the heart are cut, the heart will:
a. stop beating
b. continue beating at the same rate
c. continue beating, but at a different rate*
Diagnostic for: function (properties of) SA node; function of innervation of heart

(CVDQ9) TIMING OF R AND L VENTRICULAR CONTRACTION
The left ventricle contracts NOW. The right ventricle contracts ____ the left ventricle did:
a. before
b. after
c. at the same time as*
Diagnostic for: structure/function of cardiac conduction system

(CVDQ10) MAP IS REGULATED VARIABLE
The cardiovascular system holds ____ essentially constant:
a. mean arterial pressure*
b. mean arterial pressure and cardiac output
c. mean arterial pressure, cardiac output, and heart rate
Diagnostic for: control general model

(CVDQ11) VENOUS RETURN AND VENOUS VOLUME
The rate at which blood is pumped out of the veins by the heart is increased. If the rate at which blood enters the veins is maintained constant, the volume of blood in the veins will:
a. increase
b. decrease*
c. remain the same
Diagnostic for: reservoir general model

(CVDQ12) FLOW IN PULMONARY AND SYSTEMIC CIRCULATIONS
The flow (ml/min) through the pulmonary circulation is ____ the flow through the systemic circulation (the rest of the body):
a. the same as*
b. greater than
c. less than
Diagnostic for: structure of circulation; Frank-Starling

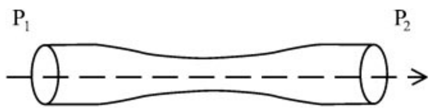
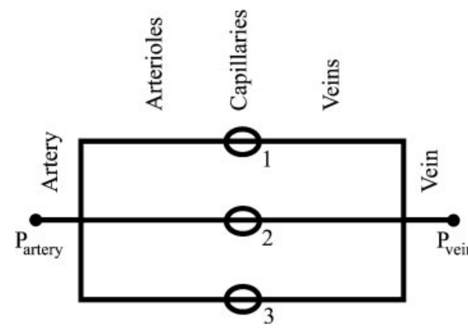
(CVDQ13) CARDIAC OUTPUT/STROKE VOLUME
You measure Mr. X's cardiac output and determine that it is increased above its normal value. This MUST mean that stroke volume has:
a. increased
b. decreased
c. no change
d. can not be determined from the data given*
Diagnostic for: implications (qualitative) of multiplicative relationship defining CO

other segment (they thought they are independent of one another). Both groups of students frequently found it difficult to incorporate into their problem solving the fact that the P_a-P_v pressure gradient was stated to be constant across the vascular bed.

Explanations offered by students who correctly predicted that the downstream pressure would decrease commonly revealed incorrect thinking about hemodynamics. Despite their correct prediction, these students were often confused about the relationships among flow, flow velocity, resistance, and blood volume. Some explanations for the correct prediction presented ideas that were simply irrelevant (changes in fluid movement across the walls of the capillary).

CVDQ4 asked students to predict the immediate and direct (not via a reflex) effect on arteriolar resistance of an increase in cardiac output. There is essentially no change in resistance. Arteriolar compliance is relatively low, and the change in volume that occurs is small. Thus there is an insignificant change in the

TABLE 2
Matched general model and cardiovascular diagnostic questions (* indicates correct answer)

	General Model Question	*Physiology Question*
Pressure/flow/resistance	***(GMDQ1)*** A fluid is flowing through the tube shown below in the direction of the dashed arrow. If the tube is pinched as shown and the pressure P_1 is kept constant, the pressure P_2 will:  a. increase b. decrease* c. remain unchanged	***(CVDQ1)*** Consider the small piece of the circulation shown to the right. The pressure gradient across the circulation (P_{artery}-P_{vein}) is constant. If the arterioles in path 1 VASOCONSTRICT (get smaller), then pressure in the venules of path 1 will:  a. increase b. decrease* c. not change
Elastic structures	***(GMDQ2)*** You blow up a balloon so that it has a volume of V_1. Two minutes later, you take the same balloon and inflate it to a larger volume V_2. The pressure inside the balloon is now (at volume V_2) ____ the pressure that was present initially (at volume V_1). a. higher than* b. lower than c. the same as	***(CVDQ2)*** A large vein in the leg of an accident victim is cut, and the individual loses 2 liters of blood. The pressure in her veins will: a. increase b. decrease* c. remain unchanged
Mass balance	***(GMDQ3)*** You have 5 fish in an aquarium. Water containing a certain amount of food per milliliter is entering the tank. Water is leaving the tank at the same rate that it enters it so the level of water in the tank is constant. If you add 5 more fish to the tank and the flow of water into the tank remains constant, then the rate at which food is leaving the tank will: a. increase b. decrease* c. remain the same	***(CVDQ3)*** Arterial blood flows through an organ of the body at a constant rate. If the metabolic activity of that organ is DECREASED, the amount of oxygen in each milliliter of blood leaving the organ in the vein will: a. increase* b. decrease c. remain unchanged

radius of the vessel (which is more importantly determined by sympathetic inputs and the concentration of local tissue metabolites). Students who predicted either increases or decreases in resistance commonly explained their predictions either by asserting that flow and/or pressure are direct determinants of vessel resistance, or they invoked some sort of regulatory response (i.e., reflex) to the change in cardiac output, even though the question explicitly stated that reflexes were NOT involved in the response to be thought about.

Although many students who predicted no immediate, direct change in resistance correctly identified

TABLE 3
Undergraduate student populations studied

Type of Institution	Type of Course	Number of Students
SU1	"***Human Physiology***": one semester, comprehensive, intermediate level; totally lecture based	152
SU2	"***Systemic Physiology***": one quarter, upper division comprehensive, first course for physiology majors and non-majors, lectures only	142
SU3a	"***Elementary Physiology***": one semester; comprehensive; majors, pre-professional, non-majors	152
SU3b	"***Introductory Biology***": animal physiology and development; for biology majors; lecture and laboratory	139
SU3c	"***Introductory Biology***": animal physiology and development; for biology majors; lecture and laboratory; summer offering	52
SU3d	"***Mammalian Physiology***": cardiovascular and respiratory physiology; upper division; lecture only	56
SU4	"***Principles of Physiology***": one semester, comprehensive, advanced (400 level); mainly lecture based	90
SU5	"***Vertebrate Physiology II***": second semester of two-semester course, upper division, comprehensive; lecture only	106
PU1	"***Human Anatomy and Physiology***": two semesters, comprehensive; 200 level; lecture based (employs case studies)	42
CC1	"***Human Anatomy and Physiology II***": second semester of two-semester sequence; intermediate level (200 level); lecture and laboratory	34
CC2a	"***Human Anatomy and Physiology I***": first semester of year-long course for health-oriented students; lectures and labs	93
CC2b	"***Elementary Physiology***": introductory survey of human physiology; baccalaureate students in allied health areas; lecture only	18
	Total number of students	1,076

SU1–SU5, state research universities (Carnegie category I); PU, private university (Carnegie category IIA); CC1 and CC2, public community colleges (Carnegie categories IV and III, respectively).

the determinants of resistance (length, viscosity, radius), others were unable to generate a coherent explanation.

CVDQ6 asked students to compare the volume pumped by the right and left ventricles with each beat. The volumes pumped by the two sides of the heart are the same; the output of the right ventricle fills the left ventricle and the output of the left ventricle ultimately fills the right ventricle. If the outputs are not identical, a change in filling will result that will make the two outputs equal. Of the 34 students who predicted that the output of the left ventricle was greater than the output of the right ventricle, 16 explained this by noting that the left ventricle is bigger than the right ventricle. In some cases, the students indicated that they had seen this in a laboratory dissection experiment. Fourteen of the 34 students explained their prediction by noting that the left heart output has to supply blood to the whole body (thus requiring a larger output), whereas the right ventricle output supplies blood only to the lungs. Other students actually offered both arguments for this answer. Interestingly, students who answered that the right ventricle output was greater than the left ventricle output offered the same explanations (size and destination) but had apparently confused the right and left sides of the heart when they inspected it in the lab.

Not a single student who correctly said that the right and left ventricles pump the same volume per beat offered a fully correct explanation for that phenomenon. Several observed that the volumes are the same even though the pressures developed by the two ventricles are different. Although this statement is correct, and perhaps an appropriate observation to make about this general phenomenon, it does not

TABLE 4
Characteristics of the student population studied*

Gender	
Female	69%
Male	31%
Age, yr	
<16	1%
16–19	19%
20–24	53%
25–29	16%
30+	11%
Ethnicity	
Native American	2%
Asian	17%
Black	3%
Hispanic	3%
White	69%
Other	5%
First language spoken	
English	82%
Not English	18%
Previous academic background	
Physiology course	13%
Human anatomy and physiology	36%
Biology with significant physiology content	11%
None in physiology	39%

* No data available for students at SU3b, SU5, and CC1.

constitute an *explanation* for their prediction. Many more students seemed to understand that if the volumes were not the same there would be a change in volume in different parts of the closed circulatory system and that this would possibly result in a change in pressure. Again, this is correct, but at best this is a teleological explanation for their prediction. However, most students simply argued that the input (what goes into the ventricles) and the output (what is pumped out of the ventricles) had to be the same and therefore the two sides must pump the same volumes (as an explanation this is more or less circular).

Finally, CVDG8 asked students to predict whether denervating the heart would cause the heart to stop beating, continue at the same rate, or continue beating at a different rate. The heart would beat at a different, faster rate. The spontaneous firing rate of the SA node is higher than the resting heart rate, which is normally slowed by parasympathetic inputs. Those students who said that the heart would stop beating quite commonly explained this by stating that the heart is like skeletal muscle and requires a neural input for contraction to occur. Among those who predicted that the rate would stay the same, most invoked the autorhythmicity of the heart (which is, of course, present) and claimed that its beat was therefore independent of the nervous system (not true).

Those students who knew that the rate would change generally had quite spurious arguments to explain this. Many commented on "pacemakers," and several indicated that the nervous system modulated the

TABLE 5
Prevalence of cardiovascular diagnostic signs (incorrect answers to CVDQs)

		DQ1	DQ2	DQ3	DQ4	DQ5	DQ6	DQ7	DQ8	DQ9	DQ10	DQ11	DQ12	DQ13
a.	SU1	73%	21%	47%	89%	57%	50%		58%	59%	53%	57%		82%
	SU2	68%	20%	47%	81%	66%			73%	79%	66%	53%	40%	66%
	SU3a	73%	8%	46%	83%	72%	50%		70%	82%	64%			
	SU3b	62%	13%	43%	75%	73%	42%	75%	72%	75%	59%	49%		
	SU3c	76%	8%	54%	71%		96%	63%	94%					
	SU3d	44%	13%	77%	80%	46%	41%		63%	57%	45%	29%		
	SU4	74%	22%	48%	80%				61%	66%	65%	60%	53%	
	SU5	55%			57%									
	PU		26%	60%	88%	86%	52%	60%	79%	76%	83%	57%		
	CC1	59%	12%	62%										
	CC2A	59%	47%	70%	86%									
	CC2B	61%	50%	67%	61%									
b.	**Total Pop.**	**67%**	**20%**	**53%**	**81%**	**67%**	**52%**	**70%**	**70%**	**68%**	**61%**	**52%**	**45%**	**74%**
c.	***Mean all courses***	***64%***	***22%***	***56%***	***77%***	***67%***	***55%***	***66%***	***71%***	***71%***	***62%***	***51%***	***47%***	***74%***
	SD	***9.4%***	***13.8%***	***10.9%***	***10.0%***	***12.7%***	***18.7%***	***6.5%***	***10.8%***	***9.2%***	***11.0%***	***10.4%***	***6.5%***	***8.0%***

Blank space, question was NOT asked in survey administered to students in this course.

TABLE 6
Typical examples of written explanations for answers to CVDQ1, -4, -6, -8 (correct answer identified by *)

CVDQ1 (pressure downstream of a vasoconstriction)

will ***increase*** because:
"Volume decrease, pressure increase"
"Pressure increased in arterioles so it must increase in veins"

will **decrease*** because:
"The increased resistance in arterioles will lower pressure"
"Not as much blood getting through"
"Decrease flow so decrease pressure"

will **not change** because:
"Veins are not affected by arteriolar constriction"
"Pressure not affected b/c arterioles and veins are in series"

CVDQ4 (increase CO, arteriolar resistance will directly)

increase because:
"Increased flow = increased resistance"
"Increased volume, increased resistance"

decrease because:
"Flow increases meaning resistance decreases"
"Resistance is indirectly proportional to cardiac output"

not change* because:
"Resistance is only determined by length, viscosity and radius"
"CO doesn't affect arterial pressure"

CVDQ6 (each beat . . .)

the right and left ventricles pump the **same*** volume because:
"The same amount of blood flows into right and left ventricle so they would pump the same volume"
"If the two ventricles pumped different amounts of blood, there would be a buildup of blood in some area of the body, which would be bad and does not happen"

the left ventricle pumps a **larger** volume because:
"The right just circulates through lungs, the left to the entire body"
"In the rat lab it looked as if the L ventricle was larger and thicker, so does more work than the right ventricle"

the right ventricle pumps a **larger** volume because:
"Left side only to lungs, right side-body"
"The right ventricle has a greater wall and thus creating a higher pressure to pump more blood"

CVDQ8 (the denervated heart will)

stop because:
"The heart needs impulses from nerves to beat"
"Heart is a muscle and muscle contractions are nerve regulated"

beat at the **same** rate because:
"The heart has its own pacemaker"
"Cells beat independent of stimulus"

beat at a **different*** rate because:
"The heart has its own independent firing device which keeps it beating. The nerves going to it just regulate the rate."
"The rate will slow down considerably, then eventually stop."

spontaneous (autorhythmic) heart rate. However, none of the respondents knew that the spontaneous rate of the SA node was higher than the resting heart rate in a normal individual, even if they did know that denervating the heart somehow changes it rate.

Five hundred twenty students provided us with explanations for their answers to four of the diagnostic questions (CVDQ1–4) by selecting items from follow-up multiple-choice questions. These students were enrolled in four different courses: SU1, SU2, SU3d, and SU4 (Table 3). Tables 7, 8, 9, and 10 contain the distribution of explanations that were selected.

General model-cardiovascular misconception relationship. To determine whether the inability to use a general model (6) could give rise to a cardiovascular diagnostic sign (incorrect answer on a diagnostic question), three pairs of questions were prepared. The first question in each pair (GMDQ1–3) tested the students' ability to apply a general model to a simple nonphysiological system. The second set of paired questions (CVDQ1–3) required the application of the same general model to a specific cardiovascular situation. Table 2 contains the three pairs of questions.

TABLE 7
Explanations selected for answers to CVDQ1 (correct answer identified by *)

Pressure in venule when arteriole VASOCONSTRICTS will:	
increase (n = 306) because:	
there is more blood in the venules	8.2%
the arteriolar pressure will increase and if the pressure gradient is constant then venule pressure must increase	68.0%
the flow in path 1 is constant	7.2%
blood will be flowing faster through the venules	13.4%
decrease* (n = 151) because:	
more pressure will be lost in the arterioles	12.6%
less blood is flowing through them	42.4%
the blood will be flowing more slowly	9.9%
more blood will be flowing in paths 2 and 3	35.1%
not change (n = 53) because:	
the pressure gradient is stated to be constant	45.3%
venous pressure is the same everywhere	9.4%
arteriolar constriction will have no effect on venules	35.8%
arterioles and venules are parallel with each other	9.4%

TABLE 8
Explanations selected for answers to CVDQ2 (correct answer identified by *)

". . . the individual loses 2 liters of blood. The pressure in her veins will:"	
increase (n = 51) because:	
pressure times volume is constant; if volume decreases then pressure must increase	37.3%
the heart rate increases to make up for the loss of blood	19.6%
of the need to get enough oxygen to the tissues	7.8%
cardiac output increases to compensate for the loss of blood	35.3%
decrease* (n = 373) because:	
the body reduces the pressure to reduce the blood loss	7.8%
there is decreased flow in the veins and hence less pressure	29.3%
there is a smaller volume distending the veins and therefore pressure is reduced	57.8%
the resistance in the veins has been reduced	7.8%
remain unchanged (n = 38) because:	
the body holds the pressure in the veins constant	39.5%
the heart rate increases to make up for the loss of blood	34.2%
cardiac output is reduced, so there is more blood left in the veins	2.6%
increased resistance in the veins compensates for the loss of volume	23.7%

Individual student performance on each question in each of the three pairs of questions was determined. We could, therefore, determine whether students answering the general-model question correctly were more or less likely to answer the matched physiology question correctly. From these numbers, we calculated the percentage of students who answered both the general model and the physiology question correctly. Table 11 contains the results of this analysis. A χ^2 test with computed expected values (9) was performed on these data, and the results are reported below.

For the pressure/flow matched questions (GMDQ1 and CVDQ1), ~46% of the students who answered the general model question correctly answered the cardiovascular diagnostic question correctly, whereas only 26% of the students who missed the general model question could correctly answer the physiology question. The difference in performance on the follow-up CVDQ as a function of being able to correctly apply the general model was significant ($P < 0.001$).

For the elastic structure questions (GMDQ2 and CVDQ2), the percentage of students answering CVDQ2 correctly was the same for those answering GMDQ2 correctly or incorrectly (75.3% vs. 71.3%); this difference is not significant ($P > 0.10$).

For the mass balance questions (GMDQ3 and CVDQ3), a correct answer on the general model question was associated with a greater likelihood that the answer to CVDQ3 was correct (56.6% vs. 43.2%, $P < 0.001$).

DISCUSSION

Prevalence of the respiratory diagnostic sign. The mean prevalence of the respiratory misconception (diagnostic sign) was essentially identical to that previously seen (2, 4). Individual course prevalence ranged from 40.2% to a high of 70.6%. In the previous study, the prevalences ranged from 31.1 to 69.4%. This suggests that the student population tested here was essentially the same as the population previously

TABLE 9
Explanations selected for answers to CVDQ3 (correct answer identified by *)

" . . . metabolic activity is DECREASED, the amount of oxygen in each milliliter of blood leaving the organ in the vein will:	
increase* (n = 271) because:	
less oxygen is needed by the organ, so more oxygen leaves	29.5%
the same amount of oxygen is entering the organ but less is being used, so more leaves	68.6%
there will be decreased resistance to flow in the organ	1.8%
decrease (n = 137) because:	
when metabolic activity decreases there is less oxygen in the blood	35.0%
there is a smaller demand for oxygen	56.2%
because the organ uses most of the oxygen delivered to it	8.8%
remain unchanged (n = 72) because:	
ventilation decreases in proportion to metabolism so the concentration of oxygen is unchanged	40.3%
oxygen passively diffuses down its concentration gradient	29.2%
oxygen use decreases in proportion to the reduced metabolic activity	29.2%

TABLE 10
Explanations selected for answers to CVDQ4 (correct answer identified by *)

If cardiac output increases significantly, then the resistance of the arterioles will immediately and directly:	
increase (*n* = 236) because:	
pressure will increase which means resistance increased	52.1%
there is too much blood going through the arterioles	24.6%
the arterioles will vasoconstrict (get smaller) to prevent stretching from occurring	5.1%
the arterioles will attempt to counteract the increased pressure that will be present	22.5%
decrease (*n* = 131) because:	
more blood needs to flow through the vessels	47.3%
flow is occurring through more arterioles	6.1%
more blood needs to be returned to the heart	13.0%
the blood vessels are elastic and will expand (get bigger)	32.8%
remain unchanged* (*n* = 84) because:	
vessel size doesn't change significantly under these conditions	22.6%
arterioles are a fixed size and can't change	8.3%
the number of arterioles through which flow is occurring does not change	19.0%
the pressure goes up in proportion to the increased cardiac output	50.0%

studied and that the manner of surveying students had not skewed the present results in some way.

Prevalence of cardiovascular diagnostic signs. The prevalence of the cardiovascular misunderstandings surveyed varied from 20 to 81%, a range that is only slightly greater than the range of prevalence of the four respiratory misconceptions (diagnostic signs) previously reported (4). The least prevalent cardiovascular diagnostic sign (HEMORRHAGE AND VENOUS PRESSURE) deals with a phenomenon about which knowledge is quite widespread regardless of formal studies in physiology (see below). On the other hand, the most prevalent misunderstanding about cardiovascular physiology (CARDIAC OUTPUT AND RESISTANCE) deals with concepts from hemodynamics, a subject that students at all educational levels find particularly challenging.

What are the difficulties that impact students' understanding of cardiovascular physiology? The responses to pairs of matched questions suggest that students who can apply general models to their understanding of cardiovascular phenomena are more likely to be able to correctly answer a related cardiovascular question. For two of the three pairs of questions, answering the general model diagnostic questions correctly was associated with a greater likelihood that the cardiovascular diagnostic questions would be answered correctly. Upon examination of the one exception, the elastic structures questions, it appears likely that students have available to them knowledge about the effects of hemorrhage (the fall in blood pressure) that is independent of their understanding of the behavior of elastic structures (which would be required to *explain* why pressure falls, but not the fact that it does fall) and independent of what they learn in the classroom.

These results offer support for our hypothesis that some conceptual difficulties in cardiovascular physiology arise from the students' inability to apply certain general models to specific physiological situations. We will be pursuing this idea in our next survey, which will examine the prevalence of conceptual and reasoning difficulties about renal physiology. If, as we suspect, a significant number of physiology misconceptions are the product of an inability to transfer and apply general models, it will strengthen the argument that improving students' understanding of and ability to use these models can have widespread positive effects on learning this material (6).

There is another source of difficulty that affects our students' understanding of important concepts in cardiovascular physiology. Some of the misconception questions (Table 1) appear to be nothing more than statements of facts about the cardiovascular system. For

TABLE 11
Interaction between performance on general model (GM) question and cardiovascular diagnostic question (CVDQ)

	CVDQ1 Correct	CVDQ1 Wrong	% Getting CVDQ Correct
GM1 correct	92	109	45.7%
GM1 wrong	132	370	26.3%
	CVDQ2 correct	CVDQ2 wrong	
GM2 correct	411	135	75.3%
GM2 wrong	194	78	71.3%
	CVDQ3 correct	CVDQ3 wrong	
GM3 correct	223	171	56.6%
GM3 wrong	183	241	43.2%

example, CVDQ9 deals with the "fact" that the right and left ventricle contract at essentially the same time. One might argue that a wrong answer to this question merely tells us that students do not know this fact. Even if this is the case, it is both surprising and troubling for both the students and teachers. One can feel the beat of ones's heart or one's own pulse and immediately know that the two sides of the heart beat so closely together in time as to be indistinguishable. In addition, every student whom we surveyed studied something about the cardiovascular system in elementary or high school biology. Finally, some of the students surveyed were in upper-level courses and quite likely had had a lower-level introductory physiology course. So the failure of so many students (~70% of those surveyed on this question; Table 5) to "know" that the right and left heart beat at the same time remains puzzling.

We might expect that textbooks would address this topic in a way that would help our students understand this phenomenon. However, an examination of four popular undergraduate and advanced physiology textbooks (not necessarily the textbooks recommended in any of the courses surveyed) reveals that three of them never state that the right and left ventricles contract at the same time, and the fourth textbook states it, but in a way that could easily be overlooked by the reader. How then would we expect students to eventually understand that the right and left heart contract together? It would be possible for students to infer or deduce this from an understanding of the structure and function of the cardiac conduction systems (topics that are extensively covered in all the textbooks), but it seems likely that most students will be unable to make this inference. The result is a misunderstanding of a significant phenomenon based on a model that is quite different from the appropriate mental model—a cardiovascular misconception is present.

What are the implications of these results for teachers of physiology? First, undergraduate students find many cardiovascular concepts difficult to understand, and the prevalence of these difficulties is surprisingly uniform across diverse student populations. It is possible that this prevalence is independent of how advanced the students are in their academic careers.

As teachers, it is essential that we know what our students find hard to understand if we are to succeed in helping them learn. This study and others like it represent the beginning of an attempt to undercover these difficulties in a systemic, broad-based way. In the classroom, we must be aware of these conceptual difficulties and find ways to probe our students' understanding of these concepts.

Second, undergraduate students may "understand" less than they appear to "know." Even when they are able to answer a question correctly, their ability to explain their answer may be so limited as to suggest that they have guessed or memorized a fact about the phenomenon in question, but have not developed a robust understanding of that phenomenon.

As teachers, we need to probe our students' understanding of important physiological phenomena below the superficial level to determine whether our students truly understand what we think they understand. This can best be accomplished in a learning environment in which students are constantly testing their mental models through interactions with one another and with the teacher (7). We also need to use formal assessment tools (multiple choice, short answer, or essay questions, etc.), that measure conceptual understanding, not just memorized information.

Third, one source of conceptual difficulty about many phenomena is the students' lack of understanding of simple general models (6) or the inability to recognize that these models apply to the topic under consideration.

We, as teachers, need to think about general models and organize our teaching to take advantage of the power that this approach provides. This is not something to be done in a single lecture, but something that must be revisited as each new topic arises. Furthermore, we must provide students with the necessary opportunities to practice recognizing and applying these ideas.

Fourth, another source of conceptual difficulty for students is our failure as teachers and textbook writers to appreciate the difficulty that students have integrating knowledge drawn from many disciplines (physics, chemistry, biology) and many levels of organization (molecular, cellular, organ, organismal, etc.) into a robust understanding of a physiology concept. Students need help with such integration. If that help is not provided in the textbooks students read or in the classroom, then their understanding may stay at the level of memorized information "bites" and never achieve the meaningful learning that we say we value (3).

If you have comments or questions about the studies that are reported here, you can post them on the PERC web forum, which can be found at www.physiologyeducation.org/forum*.*

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