Prevalence of blood circulation misconceptions among prospective elementary teachers

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Since the 1980s, a number of important studies have confirmed that a student’s prior ideas can pose an obstacle to learning when those ideas conflict with the science content taught in class (7, 11). An idea that impedes learning has been called a misconception, defined as “a vague and imperfect or mistaken understanding of something; one that is commonly held by learners, is difficult to teach away, and is at variance with current scientific knowledge” (19). Misconceptions can arise from the students’ prior experiences, alternative belief systems, use of analogies by teachers and students, and confusion between the scientific meaning of a term and its common meaning (12). Errors that interfere with learning have also been described as naïve beliefs, preconceptions, incomplete ideas, and faulty mental models (11). It is important to identify ideas students bring to class to facilitate new learning.

Studies to detect student ideas that hinder learning have been conducted with students across a wide range of science subject areas (for a bibliography, see Ref. 8). Misconceptions about human physiology have been associated with the way teachers and textbooks present information and with the incorrect use of language in class (12, 16). For example, Buckley (4) found that when children explain blood circulation, they often have misconceptions similar to those portrayed in textbook illustrations. Michael et al. (13) used a diagnostic multiple-choice test with written justification for the choices to detect 13 different misconceptions about cardiovascular function that were consistent among undergraduate students in college physiology courses. Similar misconceptions were held by at least half of the students across a range of undergraduate institutions. Findings suggest that students are unable to apply models to physiological situations or are missing critical facts such as the right and left ventricle contracting at the same time.

Misunderstanding about human blood circulation can escalate when elementary or secondary school teachers hold their own misconceptions. Yip (20) evaluated science teacher knowledge of the circulatory system. Teachers were asked to underline incorrect statements about blood circulation and provide justification for their choices. Most teachers were unable to relate blood flow, blood pressure, and blood vessel diameter. More experienced teachers often had the same misconceptions as less experienced teachers. Although teacher education programs focus on teaching principles, methodology, and practice, few provide deep understanding of science content (20). This study looks at blood circulation misconceptions as a first step in helping college students who will become
elementary teachers learn to explain the blood circulation ideas they will teach.

Traditional modes of instructional delivery and assessment such as multiple-choice and written essay exams may not reveal misconceptions that interfere with learning. Instructional protocols are being developed by science educators to help faculty find out what students are thinking during the instructional process so that students can be assisted in modifying their incomplete or erroneous ideas (7, 12, 13). Using materials similar to those developed by Arnaudin and Mintzes (1) and Reiss and Tunnicliffe (15), we wrote assignments about human blood circulation to reveal student thinking in three ways (see the APPENDIX). Each protocol encouraged students to examine their own errors and to reflect on their learning progress while showing the faculty what corrections should be made. First, we adopted the diagram prompt method because flaws are exposed when students integrate their visual and verbal understanding of human blood circulation (9). Second, we wrote an assignment for students to construct essays about human blood circulation for peer review using Calibrated Peer Review. This method encourages students to organize and express their understanding in writing (5, 14). The third assignment we wrote was a debate about models of blood circulation using the Web-based Knowledge Integration Environment to encourage oral expression in a collaborative environment where students gather evidence to build upon or reorganize their experiential knowledge (2). The drawing, writing, and oral debate protocols expose student thinking as they present their evidence and construct explanations. We expected reflection during learning activities to result in students finding and correcting their errors (6). Instead, we found that the real power of these activities is in showing faculty what problems require them to intervene.

Objectives

The purpose of this study was twofold: 1) to investigate the prevalence and persistence of blood circulation misconceptions among undergraduate students who are prospective elementary teachers and 2) to evaluate the effectiveness of learning activities for discovering what undergraduate students know and can explain about blood circulation and lung function. Five categories of human blood circulation errors were found to be prevalent among prospective elementary teachers. At the end of their undergraduate biology course, the undergraduate students in this study still held erroneous ideas about the dual blood circulation pathway, blood vessels, gas exchange, gas transport and utilization, and lung function.

DESIGN AND PROCEDURES

The subjects of this study were 88 students enrolled in a one-semester introductory biology course for prospective elementary teachers. They elected this undergraduate course to fulfill the biology prerequisite for a graduate elementary education teaching credential program. The curriculum for the combined laboratory and lecture course followed the Biological Sciences Curriculum Study Biological Perspectives program (3). The study included five sections where the course was taught alternately by two professors at a state university during the fall 2001 semester and the spring and fall 2002 semesters. The sample population included 88% of the enrolled students. Those excluded from the study were under 18 yr of age, did not complete the course, or did not agree to participate in the study. The participants’ mean age was 19 ± 2.4 yr (range 18–38 yr), and their mean college grade point average was 3.27 ± 0.42 SD (range 2.3–4.0). The student sample consisted of 50% freshmen, 44% sophomores, 1% juniors, and 5% seniors with 45% Caucasian, 36% Hispanic, 16% Asian, and 2% Middle Eastern ethnicities. Most of the participants spoke English as their primary language, although Spanish, Pashti, Romanian, or Korean were the primary languages for 12% of the students. The sample was 97% female and 3% male and is reflective of the overall undergraduate enrollment in science courses for prospective elementary teachers at the state university.

Quantitative and qualitative data were collected from the three learning activities and two exam assessments (see the APPENDIX). The intent of the learning activities was to reveal errors and provide feedback to students about the following:

1) The pathway of human blood circulation and
2) The function of blood related to the respiratory system.

The activities were used as both learning resources and to complement lectures. The instructor was assumed to be only one of several sources of knowledge. In addition to the lecture material, students consulted the textbook, other books, Web resources suggested for each activity, and their peers.

Students first completed the pretest drawing with their written explanation of human blood circulation and lung function (Fig. 1A). The topics were then studied in a human body unit during 1 wk of the semester (three 2-h class sessions). Because of time constraints, students in three of the five sections wrote and then peer reviewed essays about blood circulation. Students in the other two sections debated opposing assertions about models of blood circulation. After instruction and feedback, all students were assessed by an essay exam where they explained how blood circulation facilitates exchange between the body and the external environment. Part of the final exam was an interview using the same diagram prompt from the pretest (Fig. 1B). The drawing helped students gather their thoughts and gave them confidence. They had plenty of time to draw and write about the blood pathway and lung function before they were individually interviewed about their drawings in a quiet room.

Videotapes of the debates and interviews were converted to MPEG digital format and given a unique file name. The debates and interviews were transcribed using vPrism software and exported as text to a Microsoft Excel spreadsheet. Student essays were written and submitted by computer. The digital files were compiled in a Microsoft Excel spreadsheet. Finally, data sources were reviewed for errors without identifying individual students.

Development of a Coding Scheme for Erroneous Ideas

A qualitative research method was used to characterize individual kinds of errors as well as the categories of errors. Three reviewers independently identified erroneous ideas starting with a random subset of the data that included each assessment for 15 of 88 students. The reviewers included a biology graduate student who worked in a blood bank, a senior biology major who had completed course work in physiology and in human anatomy, and a physiology professor. Each
reviewer recorded the errors, placed them into groups with similar ideas, and then further grouped the ideas into broader categories using a grounded theory approach (18). The reviewers then considered the data together and came to a consensus on categories for the erroneous ideas. In each category, the idea expressed had to be completely correct to be coded as “correct.” Any error within a response was sufficient to code the student as having an “error” for that category.

Analysis

Reliability. The coding scheme was tested by the reviewers on one complete set of the data from a random representative sample of 20 of 88 students. Interrater reliability was at least 96% for data from each source: explanations of the pretest drawing, peer review essays, debate transcripts, the essay exam, and transcripts of the drawing interview.

Descriptive statistics. The number of different kinds of erroneous ideas in each category was reported for each data source. The frequency of students with each individual error and the frequency of students with an erroneous idea in each category were compiled for each data source. Only errors expressed by 2 or more of the 88 students are reported here.

Statistical analysis. For each of the five categories, the students who revealed erroneous ideas or correct ideas on the written essay and interview exam were counted and statistically compared using χ²-analysis, with significance defined as P < 0.05.

RESULTS

Categories of Erroneous Ideas

The groups of blood circulation errors detected among prospective elementary teachers fell into five categories.

Blood pathway. These are errors about the pathway a drop of blood takes as it leaves the heart and travels through the body and lungs. A typical correct answer explains dual circulation with blood from the left side of the heart going to a point in the body and returning to the right side of the heart, where it is pumped to the lungs and back to the left side of the heart.

Blood vessels. These are errors about the veins, arteries, and capillaries. A correct response has blood traveling in veins to the heart and arteries carrying blood away from the heart, and the response recognizes that arteries feed and veins drain each capillary bed in an organ.

Gas exchange. These are errors about the dependence of gas exchange on diffusion between the blood capillary and alveolar or cell space. A correct response indicates that a concentration gradient between two compartments drives the net transport of gases across cell membranes.

Gas molecule transport and utilization. These are errors about the mass transport of oxygen by the blood to the cells of the body or about the production of carbon dioxide by the cells and transport to the lungs. A correct response explains that oxygen is transported by blood to the cells of the body and carbon dioxide is transported from the cells where it is produced and eventually back to the lungs.

Lung function. These are errors with functions other than gas exchange assigned to the lungs or lung functions assigned to other organs. A correct response explains that lungs get oxygen from the air and eliminate carbon dioxide from the body.

Two Case Studies

To illustrate how ideas unfolded for each category, the responses of two students with typical ideas are examined in detail. The first subject, referred to as Tony, was enrolled in a class that performed the debates several weeks after the pretest drawing on human blood circulation. The second subject, referred to as Kim, constructed an essay for peer review instead of performing debates. The names are pseudonyms to protect individuals.

Table 1. Errors and correct ideas expressed by a typical student, Tony, during instruction and assessment in a section that implemented classroom debates

<table>
<thead>
<tr>
<th>Instructional Activities</th>
<th>Assessments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pretest drawing</td>
</tr>
<tr>
<td>Pathway</td>
<td>E</td>
</tr>
<tr>
<td>Blood vessels</td>
<td></td>
</tr>
<tr>
<td>Gas exchange</td>
<td></td>
</tr>
<tr>
<td>Gas utilization/transport</td>
<td></td>
</tr>
<tr>
<td>Lung function</td>
<td>C</td>
</tr>
</tbody>
</table>

C, correct idea; E, error. Unmarked categories were unclear or insufficient to make a judgment.
The ideas Tony expressed were tracked over time (Table 1). Tony started out with the round trip idea by drawing the path of blood as a continuous circle around the body on the pretest (Fig. 1A). During the debate, Tony held on to this erroneous idea:

“The blood is circulating at all times. It begins in the heart and it goes everywhere around your body and it eventually ends up at the heart again. The blood takes 20 s to pump to every cell in the body.”

When Tony wrote about the blood pathway on the essay exam, the idea was corrected:

“The circulatory system has a specific pathway. The blood starts off on the right half side of the heart and it is pumped to the lung, where it is oxygenated and the carbon dioxide is removed. Then it is returned to the left half of the heart. From there it leaves through the arteries to its designated place. It returns back to the heart through a vein.”

Even though Tony’s ideas had improved, the essay still lacked connections between arteries, capillaries, and veins. On the final interview, Tony made these connections and distinguished arteries from veins:

“It [the blood] leaves the heart through an artery, the aorta. Then from arteries it turns into capillaries and capillaries to veins and it goes back up to the heart through veins.”

However, Tony’s final drawing of the blood pathway made no reference to the lungs (Fig. 1B), and the interview showed confusion:

“And then in the lungs it goes through the lungs to clean and so then when it leaves the lungs it goes from the right ventricle to the left ventricle and it’s oxygenated blood.”

The distinction between arteries and veins was not extended to the pulmonary circulation when Tony responded on the final interview to a question about blood vessels to and from the lungs with “I don’t know.”

Tony expressed too few ideas about gas exchange or gas utilization/transport during instruction to judge the ideas as correct. The essay exam showed an understanding of gas utilization/transport but did not provide enough information to confirm an understanding of the dependence of gas exchange on concentration gradients.

“The blood transports the muscles’ carbon dioxide out of the lungs at the alveoli. The alveoli interact with the blood to diffuse oxygen in the blood and carbon dioxide out of the blood.”

The quote above indicated progress toward understanding. On the final interview, new problems appeared. Tony indicated knowledge of concentration gradients but confused osmosis with diffusion.

“From one place . . . it leaves that place to go to a less concentrated place. Where it’s concentrated to a less concentrated place. Well, I’m not sure but I think it’s the one when we exhale we breathe it out . . . I’m not sure if it’s called osmosis when we exhale the carbon dioxide.”

When asked why the levels of oxygen and carbon dioxide are important in the blood, Tony replied, “Cuz that’s how we breathe. That’s what keeps the red blood cells moving,” indicating a blood circulation function for the lungs. Tony also stated that lungs “clean” blood.

Many of the ideas expressed by another subject, Kim (Table 2), were similar to those expressed by Tony. Like Tony, Kim drew the path of blood as a continuous circle around the body on the pretest. On the essay for peer review, Kim distinguished arteries from veins and wrote, “The heart pumps the blood and keeps it moving through what we call the circulatory system.” This did not provide enough information to know if Kim still held the round trip idea about the blood pathway. On the essay exam, Kim described the blood pathway in detail.

“The right half of the heart receives oxygen-poor carbon dioxide-rich blood from the body and pumps it to the lungs, where it is oxygenated and the carbon dioxide is removed. The left half of the heart receives blood from the lungs and pumps it into the aorta. Blood travels away from the heart through arteries. Arteries branch and narrow to become arterioles and the arterioles branch into tiny capillaries. Capillaries form networks of vessels which join to make veins. Veins carry the blood back to the heart.”

By the final interview, Kim revised her ideas about the blood pathway to include the urinary system with the following erroneous explanation of a drawing that showed blood leaving the heart for the toe and then to the lungs before returning to the heart:

“. . . it goes out the heart . . . to flow down the big toe and then it’s going to eventually go back up and it’s going to your lungs and your kidney and up into the left atrium and then go through the whole cycle again . . . The blood when it’s in the lungs it gets the proper nutrients for the blood to be continued on circulating through our whole body.

Like Tony, at the end of the course, Kim indicated that lungs clean and pump the blood. A written explanation on Kim’s pretest drawing, “When the blood travels through the lungs it is getting certain nutrients that are needed,” was similar to the idea Kim still held on the final interview. On the peer review essay, Kim did not mention the lungs when writing about gas exchange, and the essay did not provide enough information to know whether Kim recognized the need for a concentration gradient to drive diffusion:

“Red blood cells take oxygen to the body’s cells and pick up carbon dioxide from them. Diffusion allows the oxygen to go to the capillary. Diffusion is when something penetrates (goes through) a cell membrane and into the cell.”

Gas exchange was coded as an error. Although the statement “Diffusion allows the oxygen to go to the capillary” would be true if Kim were talking about the lungs, the context described
here is capillaries at “the body’s cells,” and this is not where oxygen diffuses into the capillaries. On the essay exam, Kim wrote about lung function:

“In lungs, the gas exchange system filters, it warms and moistens the air coming into the body. It provides oxygen to the body’s cell and removes carbon dioxide waste. It regulates acidity of blood.”

Instead of these important lung functions, in the final interview, Kim assigned incorrect functions to the lungs. “If we’re lacking oxygen then our blood is not going to be able to flow through us as quickly.” The drawing for the final interview also had an incorrect written explanation:

“The blood is cleansed when going through the lungs and also gets the nutrients it needs. And then flows out the right atrium to the toe and comes back up through the left atrium. The lungs serve as the pump. If your lungs go bad your blood is not being circulated to your body properly.”

Different Errors Detected by Instruments

Both Tony and Kim expressed errors on their final interview that did not appear on their essay exam. This result was consistent for all 88 students. The interview about student drawings revealed almost twice as many different kinds of errors as the other data sources (Fig. 2). Thirty-two different errors were expressed by at least 2 of 88 students (Tables 3–7). The interview detected all but one of the gas transport/utilization errors. In contrast, the essay exam detected only four of six blood pathway errors, four of five blood vessel errors, five of seven gas exchange errors, none of the six gas transport/utilization errors, and three of eight lung function errors. The learning activities were sensitive for detecting different errors in one or two categories. For example, the pretest drawing revealed over half of the blood pathway errors and lung function errors but almost none of the gas exchange or transport/utilization errors. The peer review essay revealed over half of the pathway errors and most of the gas exchange errors but very few of the blood vessel, gas utilization, or lung function errors. The debate revealed most of the blood pathway and blood vessel errors but almost none of the lung function errors.

One common error detected by all assessments and activities was the round trip idea where blood flows in a continuous circle from the heart around the body before returning to the heart again. On the pretest drawing, one student wrote “After it leaves the heart it goes to your big toe first, then it circulates throughout the rest of your body.” The same depiction was found on 15% of the drawings for the final interview.

Another common error detected on all assessments except for the pretest drawing was the idea of conversion between carbon dioxide and oxygen. On the essay exam, a student wrote, “It [blood] flows to the arterioles and then the capillaries where through diffusion ‘trades’ with the cells oxygen for carbon dioxide.” Variations of this idea also appeared on the peer review essays. For example, when explaining the function of hemoglobin, a student wrote, “While in the lungs the hemoglobin found in the blood picks up oxygen and delivers carbon dioxide that it has collected on its journey.” During the debate, a student explained gas exchange with an analogy:

“Carbon dioxide in the lungs exchanges for oxygen. By definition like with a shirt if you go to a store you can’t exchange part of a shirt and get something else, you have to exchange the whole shirt to get something else. The same is with oxygen exchange for carbon dioxide. In the lungs all the carbon dioxide exchanges for new oxygen. You have to get rid of all of one to get the other.”

Another student explained, “There must be an exchange of carbon dioxide leaving the cell and oxygen entering.” Although this error was corrected during instruction, the idea still appeared on the final interviews. At the end of the course, one student explained, “It has to be balanced. There can’t be complete carbon dioxide on one side and oxygen on the other. Carbon dioxide gets replaced with oxygen.”

Table 3. Portion of students with erroneous ideas about the blood pathway by assessment

<table>
<thead>
<tr>
<th>Blood Pathway Errors</th>
<th>Pretest drawing (n = 88)</th>
<th>PR essay (n = 48)</th>
<th>Debate (n = 40)</th>
<th>Essay exam (n = 85)</th>
<th>Drawing interview (n = 88)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round trip around hands and then feet</td>
<td>43</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>Blood travels from heart to lungs to body</td>
<td>18</td>
<td>5</td>
<td>3</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Blood travels from body to lungs</td>
<td>7</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>Right and left side of heart reversed</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Blood goes to/through the bronchioles</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>All blood goes through each organ</td>
<td>3</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Values are percentages of students; n is the number of students in total.
Blood devoid of oxygen is oxygenated 5 2 0 4 15
Carbon dioxide converted to oxygen 0 28 5 17 24

students with correct ideas was found on the exams. On the
instructional activities, in most cases, a high incidence of
the course for any of the five categories. But, in contrast to the
oxygen (Table 5), and other problems about gas diffusion
"vein" (Table 4), the idea of carbon dioxide conversion to
round trip blood pathway (Table 3), problems with the term
held in spite of confrontation (Tables 3–7). These include the
time, across different learning activities, and were robustly
(Table 6, third column). Several erroneous ideas persisted over
tests were uncovered by the pretest drawing (Tables 3, 4, and
the idea that lungs “filter” or “clean” the blood were less
problems about carbon dioxide exchanging with oxygen persisted throughout
problems with the term “vein” instead of “artery” and
idea that lungs “filter” or “clean” the blood were less prevalent but also persisted throughout the course.

### DISCUSSION

Blood circulation errors were persistent among undergraduate students planning to become elementary teachers. The prevalence of errors appears low, yet the actual numbers may be much higher, because students often provided answers without elaboration. It was surprising to find a high prevalence of errors about the blood pathway or gas exchange on the final exam, but the lower prevalence on the written exam may be deceiving. The probing interview as a final exam exposed ideas that students were unsure about or held tentatively. Such ideas were more easily concealed during instructional activities or on a written exam. For example, the numbers left out of Table 8 were more easily concealed during instructional activities or on a written exam. For example, the numbers left out of Table 8 were

#### Table 4. Portion of students with erroneous ideas about blood vessels by assessment

<table>
<thead>
<tr>
<th>Blood Vessel Errors</th>
<th>Pretest drawing (n = 88)</th>
<th>PR essay (n = 48)</th>
<th>Debate (n = 40)</th>
<th>Essay exam (n = 85)</th>
<th>Drawing interview (n = 88)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Term “vein” to describe all sorts of blood vessels</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>Reversal of the terms “artery” and “vein”</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>From arteries into veins-no capillaries</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Wrong ideas about capillary beds</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Wrong vessels to and from the heart</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>6</td>
</tr>
</tbody>
</table>

Values are percentages of students; n is the number of students in total.

#### Table 5. Portion of students with erroneous ideas about gas exchange by assessment

<table>
<thead>
<tr>
<th>Gas Exchange Errors</th>
<th>Pretest drawing (n = 88)</th>
<th>PR essay (n = 48)</th>
<th>Debate (n = 40)</th>
<th>Essay exam (n = 85)</th>
<th>Drawing interview (n = 88)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide converted to oxygen</td>
<td>0</td>
<td>28</td>
<td>5</td>
<td>17</td>
<td>24</td>
</tr>
<tr>
<td>All the carbon dioxide is cleared</td>
<td>0</td>
<td>4</td>
<td>13</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Blood devoid of oxygen is oxygenated</td>
<td>5</td>
<td>2</td>
<td>0</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>Term osmosis used instead of diffusion</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Direction for diffusion reversed</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Gas exchange as an active process</td>
<td>3</td>
<td>2</td>
<td>10</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>“Diffuse” means distribute throughout body</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Values are percentages of students; n is the number of students in total.
Misconceptions

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Table 6. Portion of students with erroneous ideas about gas transport and utilization by assessment

<table>
<thead>
<tr>
<th>Gas Transport/Utilization Errors</th>
<th>Pretest drawing (n = 88)</th>
<th>PR essay (n = 48)</th>
<th>Debate (n = 40)</th>
<th>Exams</th>
<th>Drawing interview (n = 88)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen is a fuel or nutrient</td>
<td>1</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Carbon dioxide is poisonous</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Carbon dioxide turns hemoglobin blue</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Waste carbon dioxide turns lungs black</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>White blood cells carry carbon dioxide</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>The blood stream has space for air</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Values are percentages of students; n is the number of students in total.

to explain diffusion when probed about how oxygen is added to the blood during the final exam interview. In assessing the effectiveness of instructional protocols for discovering what students know about the blood pathway or gas exchange, it became evident that no single activity revealed all of the erroneous ideas. Multiple data sources were necessary to expose many errors about circulatory structures and functions. Drawings combined with individual interviews provided the richest source of information about student thinking. Relying solely on the essay exam would not have uncovered the magnitude of the problem.

This research points to some possible causes for difficulties students have learning the blood pathway and gas exchange: problems with underlying knowledge, imprecise language use, or faulty mental models. Although some incorrect ideas were factual errors and not misconceptions, problems were interwoven in a way that challenged these learners and interfered with their developing ability to explain blood circulation ideas to the children they will teach.

Problems with Underlying Knowledge

Although one might expect learning about gas exchange to progress as a simple accumulation of new knowledge, results show a more complex development. Students incorporate their prior knowledge when making sense of gas exchange and gas transport. For example, some students thought that waste carbon dioxide turned the lungs black, and a number of students considered carbon dioxide to be poisonous (Table 6). The discovery that students associate air pollution and smoking with carbon dioxide was unexpected. The drawing interview exposed errors about gas exchange as a major problem, with the highest prevalence of errors at the end of the course.

Learning must be built upon a foundation of prior knowledge (16). Many students in this study did not possess the underlying knowledge needed to understand human blood circulation. Examples include a deficient knowledge of arteries and veins, conservation of energy, the function of concentration gradients to drive diffusion, conservation of chemical substances, and the particulate nature of oxygen and carbon dioxide. Some failed to recognize the relationship between oxygen or carbon dioxide as components of air. Understanding cell respiration and the roles of oxygen and carbon dioxide in metabolism might have helped students recognize as a faulty model the idea that lungs convert oxygen to carbon dioxide.

Imprecise Language Problems

Precise language is required for students to distinguish scientific concepts from everyday usage (12). In this study, imprecise use of the terms circulation, vein, air, diffusion, and exchange were associated with many errors. Students did not understand the term “circulation” as the movement of blood through a network of blood vessels and instead talked about blood movement in a circle. Confusion about the function and structure of veins and arteries was prevalent on the final exam interview, where many students referred to all blood vessels as “veins” (Table 4). Similarly, a discussion of “air” without referring to its gaseous components could simply reflect an imprecise use of language. A surprising miscommunication occurred with a conflict between the scientific definition and student use of “diffuse” to mean “distribute” throughout the

Table 7. Portion of students with erroneous ideas about lung function by assessment

<table>
<thead>
<tr>
<th>Lung Function Errors</th>
<th>Pretest drawing (n = 88)</th>
<th>PR essay (n = 48)</th>
<th>Debate (n = 40)</th>
<th>Exams</th>
<th>Drawing interview (n = 88)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood is cleaned in the lungs</td>
<td>16</td>
<td>5</td>
<td>0</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td>Gas exchange happens in the heart or kidneys</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Oxygen cleans the blood</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Lungs give blood nutrients</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Lungs pump the blood</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Lungs create new blood</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Lungs warm the blood</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Blood helps your lungs create oxygen</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

Values are percentages of students; n is the number of students in total.
body, as in the student notion of blood diffusing oxygen throughout the body (Table 5). An interesting problem with gas exchange stems from the meaning of the word “exchange” in common usage as “trading one object for another.” One molecule of oxygen is not traded for a carbon dioxide molecule in the lungs. More intervention is needed to help students to assimilate the scientific meaning of blood circulation terms.

**Faulty Mental Models**

At the end of the course, many students were still unable to explain dual blood circulation where blood leaves the heart on a trip to a capillary bed in the body and then returns to the heart to be pumped to the lungs and back. According to the pretest drawing, almost half of the students envisioned the round trip idea of blood flowing in a continuous circle around the body before returning to the heart. The drawing interview most effectively revealed errors about the pathway of blood. Confusion about the function and structure of veins and arteries was prevalent in the final interview as was the error that blood travels from the body to the lungs without first returning to the heart. The essay exam was less effective at showing these types of errors.

Faulty mental models were associated with errors that were hard to correct. According to Michael et al. (13), students need correct models to solve problems about changes in the heart and respiratory pump functions. Students in this study exhibited several faulty models about respiration and blood flow. Some thought of the heart as a symbol but not as an organ connected to arteries and veins. Many need help interpreting stylized textbook diagrams that seemed clear to an expert. Associated with a misunderstanding of the term “circulate” was an oversimplified drawing in the text that may have confused the students. They did not notice the details that would help them correct their mental model of blood traveling around the body to each extremity before returning to the heart. An instructor could point out the necessary features in a diagram to make the pathway of blood clear to the students.

**Implications**

Instructors are often unaware of misconceptions that interfere with learning (12). The variety of instructional activities and assessments used in this study revealed errors to both student and professors. An easily administered drawing prompt was sensitive for revealing inaccurate ideas about lung function but not about diffusion or gas exchange in the lungs. Although requiring considerable time to evaluate, an essay exam was effective at revealing inaccurate ideas and their distribution, but the prevalence appeared low. The combination of a drawing and interview was most sensitive for showing a greater variety and higher prevalence of problems than any other data source. This time-consuming assessment involved conducting, transcribing, and coding the interviews. The amount of time is beyond the scope of most college science courses. However, the interviews were worth the effort because the ideas reported here may also present problems for students of other introductory biology courses.

Because no control group was included in this study, the claim that the instructional activities reported here reduced the frequency of errors held by students cannot be made. However, results can be used in several ways. Prompts from the student interviews may help faculty detect their students’ ideas about blood transport and gas exchange. A better understanding of student ideas can serve to focus tutorial discussions. When textbooks or visual illustrations fail to meet students’ information needs (12, 13), assignments written using on-line tools such as Calibrated Peer Review or the Knowledge Integration Environment can be shared to fill the deficiencies. Finally, faculty need knowledge of prevalent errors among a particular student population to target learning objectives, select questions, and develop activities or scaffolds to help students understand scientific concepts. Linn and Songer (10) reported seven curricular revisions that improved student learning fourfold. The present study constitutes a first step in a series of instructional design adjustments to help students test and improve their ideas about human blood circulation.

In summary, the results indicate persistent difficulties that hinder learning about blood circulation among prospective elementary teachers. Learning activities based on drawings, written essays, and oral debates helped us understand the ideas this group brings to the classroom. The instructional activities may have helped students realize discrepancies between their understanding and scientific views of human blood circulation, but none of the errors were completely eliminated. An oral interview as part of the final exam was more powerful than an essay in showing what our students failed to learn: 70% did not understand the dual blood circulation pathway, 33% were confused about blood vessels, 55% had wrong ideas about gas exchange, 19% had trouble with gas transport and utilization, and 20% did not understand lung function (as indicated by the frequency of errors on the final interview exam; Table 8). If we really want to remedy these difficulties, we must assess students in different ways and provide them feedback as they progress through a course.

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**Table 8. Portion of students with completely correct or erroneous ideas by category on each exam**

<table>
<thead>
<tr>
<th>Blood Pathway</th>
<th>Blood Vessels</th>
<th>Gas Exchange</th>
<th>Gas Utilization/Transport</th>
<th>Lung Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Essay exam</td>
<td>Correct Errors</td>
<td>Correct Errors</td>
<td>Correct Errors</td>
<td>Correct Errors</td>
</tr>
<tr>
<td>Essay exam</td>
<td>60 20</td>
<td>60 12</td>
<td>18 21</td>
<td>71 1</td>
</tr>
<tr>
<td>Interview exam</td>
<td>25 70</td>
<td>44 33</td>
<td>14 55</td>
<td>48 19</td>
</tr>
<tr>
<td>P value</td>
<td>&lt;0.001*</td>
<td>&lt;0.01*</td>
<td>&lt;0.05*</td>
<td>&lt;0.001*</td>
</tr>
</tbody>
</table>

Values are percentages of students. Numbers total <100% because students who gave no answer or insufficient information to make a judgment about a category were excluded. *χ² analysis of the prevalence of correct and erroneous ideas detected on the essay versus interview exams.
Evidence from William Harvey’s experiments was provided along with other textbook resources (3): Evidence showing the same blood recirculates through the body in one direction from arteries to veins because of one-way valves.

DEBATE 2: GAS EXCHANGE. For the second debate, students considered what happens when they breathe and as blood travels through the lungs. Before looking at the evidence, they considered two opposing assertions:

1) The lungs clean away all waste carbon dioxide. As blood flows through the lungs, all waste carbon dioxide is completely removed by the lungs.
2) The lungs remove some waste carbon dioxide. As the blood flows through the lungs, only some of the waste carbon dioxide is cleared from the blood by the lungs.

Exam Assessments

An essay exam asked students for an explanation of human blood circulation and how blood facilitates exchange between the body and the external environment. For full credit, they had to include information on 1) the pathway the blood follows, 2) gas exchange when the blood courses through the lungs, 3) some details about gas exchange when the circulatory system interacts with other body systems, and 4) an example of how the circulatory system responds to changing conditions.

As part of the final exam, an interview was conducted using the same pretest drawing prompt (1). Students first drew and wrote about lung and blood function. They were then individually interviewed about their drawings in a quiet room. The following seven questions were developed and modified in our pilot study to elicit details of each student’s mental model of human blood circulation:

1) Describe the path you drew that shows how a little bit of blood moves in the body from your heart to your toe and so on.
2) Does the blood go through the lungs on this trip? Where?
3) What vessels take the blood to and from the lungs?
4) How is oxygen added to the blood? Can you explain the process? Where does it happen?
5) Relate carbon dioxide to the blood. Explain the process.
6) How are gases like oxygen or carbon dioxide carried in the blood?
7) Why is the level of oxygen and carbon dioxide in the blood important?

Only the following probes were used if needed to prompt students to clarify their ideas without introducing new information:

- Is there a word for that place or process?
- What do you mean by that?

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REFERENCES


