EVALUATION OF A COMPUTER-BASED APPROACH TO TEACHING ACID/BASE PHYSIOLOGY

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Because acid/base physiology is a difficult subject for most medical and veterinary students, the first author designed a software program, Acid/Base Primer, that would help students with this topic. The Acid/Base Primer was designed and evaluated within a conceptual framework of basic educational principles. Seventy-five first-year veterinary students (of 81; 93% response rate) participated in this study. Students took both a pre- and posttest of content understanding. After completing the Acid/Base Primer in pairs, each student filled out a survey evaluating the features of the program and describing his/her use and experience of it. Four pairs of students participated in interviews that elaborated on the surveys. Scores improved from 53 ± 2% on the pretest to 74 ± 1% on an immediate posttest. On surveys and in interviews, students reported that the program helped them construct their own understanding of acid/base physiology and prompted discussions in pairs of students when individual understandings differed. The case-based format provided anchors and a high degree of relevance. Repetition of concepts helped students develop a more complex network of understanding. Questions in the program served to scaffold the learning process by providing direction, accentuating the relevant features of the cases, and provoking discussion. Guidelines for software development were generated on the basis of the findings and relevant educational literature.


Key words: medical education; computer-based instruction; educational technology; scaffolding; hypermedia

Acid/base homeostasis is arguably one of the most difficult of the subdisciplines of physiology for veterinary and human medical students to master. There are several reasons for this. Typically, the approach to this material is highly quantitative and based on the physical characteristics and fundamental behaviors of acids and bases, which can be off-putting to veterinary and human medical students. Neophyte students are also often intimidated by acid/base physiology, because it is patently integrative. Students quickly realize that understanding the data in a blood gas panel requires an appreciation for not only acids and bases, but also ventilation, gas exchange, dynamics of electrolyte and water movement, plasma composition, respiratory control, and renal mechanisms of hydrogen ion, electrolyte, and water excretion. In addition, it is essential that the student develop an understanding of a host of other organ, metabolic, and structural dysfunctions that can potentially contribute acid or base loads to the extracellular fluid. Preclinical students learning acid/base physiology for the first time are often unprepared in many of these areas.

At the College of Veterinary Medicine, Cornell University, the first year and a half of the professional curriculum is taught via modified problem-based...
learning. There is no single case or problem designed to address acid/base physiology specifically. Rather, during the course “Function and Dysfunction,” issues relating to acid/base physiology are seamlessly incorporated into cases that have a major organ system as their primary focus. Students, working individually and in groups, are expected to develop an understanding of acid/base physiology by using these cases along with library resources and consultations with faculty. A one-hour lecture introduces students to some fundamental concepts, including fluid compartments, pH, blood buffers, overview of acid/base disturbances, and renal handling of hydrogen ions. Because acid/base physiology has historically been a difficult subject, we endeavored to provide additional support for students via a case-based computer program.

Computer technology is likely to play an increasingly important role in teaching and is viewed as having the potential for transforming both teaching and learning (8). Considering the potential role of technology in higher education (3) and, in particular, medical education (17), it is imperative that we understand those features of software programs that will promote and, conversely, impede learning. Despite the initial euphoria about educational technology, strong evidence for its effectiveness as a learning tool is lacking (8). The presupposition underlying the present study is that a well designed program must be based on sound pedagogical principles. The present study was aimed not at examining how a computer program compares with a traditional format but rather at learning how students interacted with the program, what impediments they encountered, and those features of the program that helped them learn. The results will be discussed in terms of guiding principles for future development of educational software.

**EDUCATIONAL DESIGN GOALS**

Medical professionals require a well organized, deep knowledge base and the ability to use that knowledge to solve new problems. There are several educational principles that can be incorporated into an instructional environment that can help students begin to develop the knowledge and problem-solving ability required of experts (10). We sought to use these principles in the design of the *Acid/Base Primer* to facilitate students’ understanding of acid/base physiology and foster their ability to use that understanding to solve new clinical problems involving acid/base disturbances with clinical presentations different from those in the *Acid/Base Primer*.

In particular, we incorporated four main learning principles into the design of the *Acid/Base Primer* (5). First, we acknowledge that students come to the program with varying degrees of prior knowledge and experience with the topic and that these affect the way in which students interact with new information (1, 2). Activating prior knowledge through discussions, as in collaborative learning situations, facilitates the processing of new information (16, 23). In discussion with a peer, students apply their prior knowledge to the discussion, negotiate the meaning of new ideas, and correct their misconceptions through interactions with a fellow student who understands them differently. A software program allows students to access the program when they are ready for it and to pursue it at their own pace, referring to other materials if needed and discussing new ideas with a peer. As described in the next section, students can also choose when (and if) they want to access definitions and additional explanatory information. Questions were designed to challenge misconceptions of which faculty are aware on the basis of previous interactions with students. Through these mechanisms, students’ knowledge structure is constructed in ways that are personally meaningful.

Second, the context in which learning takes place is important and provides an “anchor” that encourages meaningful, active construction of knowledge (6). Learning that occurs in the context of clinical cases will be more easily retrievable when students encounter similar circumstances later in their careers (4, 7). Six cases, similar to those that students will encounter in clinical practice, form the backbone of the *Acid/Base Primer*. In contrast to sterile problems, the cases provide students with an environment for learning that retains some of the complexity of clinical cases they will encounter later in their training without being overwhelming (13).

Third, research in the development of critical thinking skills suggests that giving students the opportunity to work through several different but conceptu-
ally related problems increases their ability to apply core principles and concepts to new problems later (10, 14). Repetition and reinforcement through feedback enhance learning (9). Although each of the six cases in the Acid/Base Primer exemplifies a different aspect of acid/base physiology, there is overlap among cases, ensuring that students encounter some of the same key concepts in two or more cases. Multiple examples, not only of problems in general, but of specific concepts, enhance students’ ability to transfer knowledge from one problem to another (12, 14). Repeated exposure to these concepts helps students establish the network of interrelated concepts that is important for deep learning (15). Furthermore, students encounter the same systematic approach to interpretation of blood gas panels across all of the cases through the sequencing of a common core of questions. Questions were designed to focus students’ attention on the similarities and differences among cases in the Acid/Base Primer.

Fourth, use of an approach to learning in which questions are used before, during, and after learning, has been shown to improve the degree of learning (1, 2, 22). Questions are a key feature of the Acid/Base Primer. The program requires that students review a brief patient history along with the results of a blood gas panel. They are then asked to respond to a series of questions, each of which is accompanied by feedback as described below.

DESCRIPTION OF PROGRAM AND INTERFACE DESIGN

The Acid/Base Primer consists of six problem sets featuring cases of acute respiratory acidosis, chronic respiratory acidosis, metabolic acidosis, respiratory alkalosis, and two cases involving metabolic alkalosis. All of the problem sets share the same basic structure (Fig. 1). The upper frame contains an abbreviated signalment, history, and, in some cases, relevant results of a physical examination or other laboratory work, followed by a table containing a series of questions (Table 1). The lower frame presents a data set consisting of blood gas results for the patient and a short statement regarding the clinical setting. Two frames are used so that the data will always be visible as the student scrolls through the questions in the upper frame, eliminating frustration that might arise from scrolling back and forth between question and data. In addition, because the data are persistent in the static, lower frame, the importance of the data and history is accentuated.

Program content is aimed at the preclinical student who does not yet appreciate the acid/base consequences of physiological dysfunctions. Therefore, in some cases, a brief description of the key dysfunction cited in the history is accessible via a hyperlink. For example, Problem Set #6 describes a foal with profuse diarrhea. Clicking on the term “diarrhea” in the history statement will display a pop-up window that briefly outlines the implications of diarrhea for acid/base balance:

“Diarrhea results in the loss of electrolytes including bicarbonate. In this case, the diarrhea is described as profuse, suggesting that the loss of bicarbonate and other electrolytes is not trivial.”

Some questions have an associated I (information) icon, indicating that a discussion of material relevant to the current question is available. This information is context sensitive and provides background information to assist the student in answering a specific question. For example, the first question in Problem Set #1 asks about the source of the blood sample (Fig. 1). Clicking the information icon activates a pop-up window that provides information about the implications of sample site for a blood gas panel. Students must then use their knowledge to answer the question in the context of the present data. These information windows are also available independently of the Table of Contents via the “Help Pages” section. Definitions of terms are compiled in a glossary accessed by clicking on a “book” icon. Students can access information and definitions on an “as needed” basis.

Every question has one or more associated “answer buttons,” each of which activates a pop-up window providing immediate feedback that either affirms the student’s choice or supplies information, including addressing commonly held misconceptions. Feedback can be as simple as “That’s correct. Acidemia is present simply because the blood pH is below the normal range.” Other feedback explanations are more extensive, however, taking students through several logical steps that may take some time to assimilate.
The first problem set in the Acid/Base Primer shows the basic format for the problem sets and cases. A series of questions guides the student through the displayed data. Underlined terms represent links to a glossary. I (after the first question) represents a link to background information designed to help students understand the question. Each of the answer options accesses a pop-up window containing information that will either confirm the student's judgment or correct misinformation.
Table 1
Case descriptions and questions posed in the Acid/Base Primer

<table>
<thead>
<tr>
<th>Case Description</th>
<th>Questions</th>
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| 1. Tracheal collapse in a cat hit by car-acute respiratory acidosis | - From what type of vessel was the blood for this sample drawn?  
- The patient has an . . .  
- What fundamental physiological process has caused the P\text{CO}_2 to rise?  
- Why is the bicarbonate increased?  
- Which component is responsible for the acid/base disturbance in this patient?  
- What abnormal physiological process is responsible for the acid/base disturbance in this patient?  
- Based on the answers to the previous two questions, this patient has a . . .  
- Let's reflect on the answer to the last question . . . . Based on the data alone, how do you know there has been a loss of acid? |
| 2. Eight-month-old puppy with 12-hour history of vomiting - acute metabolic alkalosis | - From what type of vessel was the blood for this sample drawn?  
- The patient has an . . .  
- Why is the bicarbonate increased?  
- Since HCO_3^- has increased, the bicarbonate buffer equation CO_2 + H_2O ⇄ H^+ + HCO_3^- is driven to the left, increasing the P\text{CO}_2.  
- Which component is primarily responsible for the acid/base disturbance in this patient?  
- What abnormal physiological process is responsible for the acid/base disturbance in this patient?  
- Based on the answers to the previous two questions, the patient has a . . .  
- Let's reflect on the answer to the last question . . . Based on the data alone, how do you know there has been a loss of acid? |
| 3. Six-year-old dog with pneumonia - chronic respiratory acidosis | - The patient has an . . .  
- What fundamental physiological process has caused the P\text{CO}_2 to rise?  
- Why is the base excess changed in this respiratory case, but not in the respiratory case of Problem Set #1?  
- In general, what 2 processes could potentially result in an increase in HCO_3^-?  
- Which of these 2 processes is primarily responsible for the high bicarbonate and how do you know?  
- Bicarbonate has increased. What do you predict has happened to BuF?  
- Which component is primarily responsible for the acid/base disturbance in this patient?  
- What abnormal physiological process is responsible for the acid/base disturbance in this patient?  
- Based on the answers to the last two questions, you would classify this acid/base disturbance as a . . .  
- Why has this foal caused/allowed its P\text{CO}_2 to drop?  
- Compare this data with that from Problem Set #5. Both sets of data have a low P\text{CO}_2, low bicarbonate, and a negative base excess. Problem Set #5 was classified as a respiratory alkalosis with renal compensation. How would you classify Problem Set #6 and why?  
- The patient has started to compensate for the acid/base disturbance. |
| 4. Long-term furosemide therapy - chronic metabolic alkalosis | - The patient has an . . .  
- What fundamental physiological process has caused the P\text{CO}_2 to rise?  
- In general, what 2 processes could potentially result in an increase in HCO_3^-?  
- Which of these 2 processes is primarily responsible for the high bicarbonate and how do you know?  
- Why is there a base excess?  
- Which component is primarily responsible for the acid/base disturbance in this patient?  
- Based on the answers to the previous two questions, you would classify this acid/base disturbance as a . . .  
- Why is there a negative base excess?  
- Why has this foal caused/allowed its P\text{CO}_2 to drop?  
| 5. Nine-year-old dog with diffuse pulmonary thromboembolism (hyperventilation) - chronic respiratory alkalosis | - The patient has an . . .  
- Calculate the T\text{CO}_2:  
- Why is there a negative base excess?  
- What fundamental physiological process has caused the P\text{CO}_2 to fall?  
- In your judgment, is the change in P\text{CO}_2 a primary physiological process or is it secondary (compensation)?  
- Which component is primarily responsible for the acid/base disturbance in this patient?  
- What abnormal physiological process is responsible for the acid/base disturbance in this patient?  
- Based on the answers to the last two questions, you would classify this acid/base disturbance as a . . .  
- Compare this data with that from Problem Set #5. Both sets of data have a low P\text{CO}_2, low bicarbonate, and a negative base excess. Problem Set #5 was classified as a respiratory alkalosis with renal compensation. How would you classify Problem Set #6 and why?  
- The patient has started to compensate for the acid/base disturbance. |
| 6. Three-week-old foal with profuse diarrhea of 4 days' duration - chronic metabolic acidosis | - Calculate the T\text{CO}_2:  
- The patient has an . . .  
- What physiological process has caused the P\text{CO}_2 to fall?  
- Why is there a negative base excess?  
- Why has this foal caused/allowed its P\text{CO}_2 to drop?  
- Compare this data with that from Problem Set #5. Both sets of data have a low P\text{CO}_2, low bicarbonate, and a negative base excess. Problem Set #5 was classified as a respiratory alkalosis with renal compensation. How would you classify Problem Set #6 and why?  
- The patient has started to compensate for the acid/base disturbance. |
The program prohibits students from selecting more than one answer for a given question, reducing the possibility that students will indiscriminately click on all the buttons. The cases contain seven to nine questions each. Five questions are the same in at least five of the cases. However, for each question, the text associated with the answer buttons is context specific. For example, each of five cases poses a question regarding the physiological basis for increases in $Pco_2$. Selecting one of the answer buttons for each of these questions accesses information that is specific to that particular problem. The narratives in the pop-up windows vary in length from one word to several paragraphs.

Although it is never explicitly stated within the program, a major goal is to assist students in developing an approach to acid/base problems. For each case, the sequence of questions leads students through a proper interpretation of blood gas data. Many of these questions are repeated verbatim in multiple problem sets, giving students repeated practice with a specific line of thinking. Although the questions are the same, the answers differ for each case because the case context has changed. Given a new context, the student must exercise judgment based on first principles to arrive at the correct conclusion. For example, Problem Sets #3, 4, 5, and 6 each pose a question about base excess. Problem Set #3 introduces the concept of base excess, and Problem Set #4 gives the student an opportunity to work with the concept again. These two problems, one a chronic respiratory acidosis and the other a chronic metabolic alkalosis, involve very different pathologies, but both are characterized by a base excess. Faced with these two cases, the student cannot hold to the misconception that “base excess means alkalosis.” In Problem Sets #5 and 6, the pH and the history are the only data that differ substantially between the two problems. The student must account for the remarkable similarity in the data from two patients with very different pathophysiological conditions. While Problem Set #6 is being used, the program allows, and explicitly suggests, that students display the data from Problem Set #5 for a direct comparison. These two problem sets juxtapose a chronic respiratory alkalosis and a chronic metabolic acidosis, both of which have base deficits. Each case asks, “Why is there a base excess?” This strategy serves to challenge the students’ understanding of base excess. The final question in both of these problem sets asks students to classify the disturbance in patients whose blood gas data are almost identical. The striking contrasts and similarities between these two cases are brought into sharp focus to induce students to question their preconceptions about the meaning of base excess.

**METHODS**

**Subjects and general information.** Of 81 first-year veterinary medical students enrolled in the class, 75 participated in the study in the fifth week of the course “Function and Dysfunction.” None of the students had had any previous experience with the *Acid/Base Primer*. Each of the students completed a pretest independently before working through the *Acid/Base Primer* in pairs. As students worked through the program, which took from approximately two to four hours to complete, they freely discussed their questions, observations, conclusions, and what they were learning. Immediately after finishing the program, each student completed a posttest and filled out a survey about his/her experience with the program. Eight students (four pairs) volunteered to participate in interviews, as pairs, upon finishing the program.

**Tests.** Two different tests, labeled “apple” and “orange,” were constructed for this study. The format of the tests was case based, and questions used were similar to the multiple-choice questions used in the *Acid/Base Primer* itself (Table 1). Each test took students approximately 10 minutes to complete. One-half of the participants took apple as a pretest, whereas the other half used the orange version. Distribution of the two versions among students was random. Pretests were scored but not returned to students until after the study was completed to minimize use of the instrument as a study guide. The pretests were used to establish a baseline of content knowledge of a range of acid/base topics. Students who had taken apple as a pretest then took orange as a posttest, and vice versa. This was done to control for differences in the level of difficulty between the two versions. Furthermore, using different tests before and after allowed us to test for learning based on the *Acid/Base Primer* while minimizing the learning that
might otherwise have occurred if students had taken the same test twice.

Statistics. Descriptive statistics are reported as means ± SE. Analyses of data were performed using Student’s *t*-tests, Pearson correlation, or ANOVA using Minitab, version 13.1. Differences were considered significant for *P* values ≤0.05.

RESULTS

In the survey, we asked students to estimate the total number of hours they had devoted to study of acid/base physiology during the previous five weeks of the course. Self-reported time estimates ranged from 0 to 10 hours and averaged 4.7 ± 0.4 hours. The correlation between time invested in studying acid/base physiology and performance on the pretest was not significant (*P* = 0.55). The pre- and posttests asked students to rate their level of confidence (comfort), on a scale of 1, “minimally confident,” to 5, “very confident,” with acid/base physiology. There was no correlation between hours of previous study time and confidence with acid/base physiology before students went through the *Acid/Base Primer* (*P* = 0.59). However, confidence level rose significantly (*P* < 0.001) from a mean of 2.2 ± 1.0 on the pretest to 3.5 ± 0.8 on the posttest, which was taken immediately after completion of the *Acid/Base Primer*.

The test labeled “orange” was apparently more difficult than the “apple” test. Students who took the orange version as the pretest had lower scores (46 vs. 59%; *P* < 0.001) compared with students who took the apple test (Table 2). Those who used the orange version of the pretest also had larger improvements (*P* < 0.001) in their scores (46 ± 3 to 79 ± 3%) compared with students who took the apple version first (59 ± 2 to 71 ± 2%). Nevertheless, scores for all students improved significantly (*P* < 0.001) between the pre- and posttests, regardless of version, from 53 ± 2 to 74 ± 1%. Because of the differences in difficulty between the two versions of the test, data were further analyzed using an ANOVA model that allowed us to determine whether scores improved while controlling for the sequence in which students took the tests. This analysis showed that, regardless of which test a student used as a pretest, scores improved significantly (*P* < 0.001). Moreover, the interaction between test and sequence was not significant (*P* = 0.25). This result was consistent with that obtained when data were pooled and analyzed using a Student’s *t*-test, a much less robust statistical model.

With the exception of three students who took the more difficult, orange test as a posttest, individual scores improved for all students. There was a modest but statistically significant (*P* < 0.05) trend for students who scored lower on the pretest to show the largest gains on the posttest.

Feedback from the surveys and interviews was grouped around the following themes: areas of confusion, clinical reasoning processes, the role of repetition, the case-based nature of the program, reflections on learning, the role of partners, and the computer as an instructional medium.

**Areas of confusion.** On the basis of feedback in the interviews, base excess and compensation were two issues that students found difficult and still lacked confidence in at the end of the program. The definitions of these two concepts are straightforward. However, the program challenged students’ understanding on repeated occasions in which the clinical circumstances were slightly different.

“Compensation. . . it was hard to figure out what is compensating and what isn’t.”

“Base excess. . . I was confused about it and then there came a point where I thought I knew it and then there’d be a question and I’d get it wrong.”

**Clinical reasoning processes.** We asked interviewees how they would describe the major goals or objectives of the program. All of the students recognized that the program implicitly modeled an ap-

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Pre- and posttest results</th>
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<tbody>
<tr>
<td>Version</td>
<td>Pretest</td>
</tr>
<tr>
<td>Apple</td>
<td>59 ± 2</td>
</tr>
<tr>
<td>Orange</td>
<td>46 ± 3</td>
</tr>
</tbody>
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Values are means ± SE. Students who took the Apple version of the test as a pretest, took the Orange version as a posttest and *vice versa*. 

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JUNE 2002
proach to blood gas data, helping them to appreciate the thought processes they should be engaging in when confronted with a possible acid/base disturbance.

"[The program] made you realize . . . these are the questions I need to ask myself to figure out what is going on . . . what is the main component that is causing this . . . or what I should be thinking about when I look at the base excess."

"Rather than just feeling overwhelmed by 'look at all these numbers . . .' now I have to figure out what they're supposed to mean. And [the program] didn't come out and say, 'Now these are the steps you need to approach these things' but just the way that it phrased the questions you realized you [were getting] a pattern of the way you have to work through it."

The program helped students build a working understanding of acid/base physiology. Students realized that the program focused on meaningful learning and higher-order thinking about clinical problems rather than rote memorization.

"I think the point of it was also to understand and not just memorize . . . It's useful to understand the mechanisms."

The program allowed students to build their own understanding of the relationships among the various values found in a blood gas panel and to relate them in a meaningful way to the clinical signs. The program did not tell students how to approach a blood gas panel. Students had to construct this on their own, in their own words, and at their own pace.

**Repetition.** Students (17%) praised the repeated reinforcement of concepts in the program. Relatedly, 54% of students mentioned the availability and quality of the explanations as an asset of the program. While using the program, students would "forget" concepts, but the program forced them to repeatedly engage those same concepts.

". . . how it explained it each time was helpful because if you had forgotten, you could go over it again."

"I didn’t like the redundancy and yet I liked the redundancy . . . [the program] didn’t let you skim over things and not see them again."

**Based on clinical cases.** The use of clinical cases was one of the most highly praised features of the program, with 53% of students mentioning it on the survey. The realism provided by cases made the information seem more applicable and relevant to the needs of the students.

"It wasn’t just numbers; we saw problem-based scenarios."

". . . it’s really good for us to be given examples of why we need to know this."

Not only did the cases provide relevance, but students also encountered new and unanticipated information relating to some common pathologies. The cases helped students integrate the different facets of acid/base balance: the data, the history, and the physiological responses.

"I liked the fact that [the program] gave lots of examples of different types of things and then it actually asked questions without giving you the answers right away. I liked the fact that it used clinical cases to explain vs. just reading definitions . . ."

"The clinical setting makes it more realistic and more applicable to me. It was a real situation. They seemed very real to me."

Finally, students predicted that learning the information in a clinical context would make it easier to retrieve that information later when they were working with real clinical cases.

". . . if we learn it in a bubble, it might be harder to immediately relate it to those terms later."

**Reflections on learning.** Many of the students’ comments revealed awareness of and insight into the features of the program that are consistent with the educational design principles discussed in the introduction. For example, feedback that addressed common student misconceptions was appreciated. In Problem Set #2, an example of metabolic alkalosis in
which bicarbonate is increased, we asked the following true/false question: “Since $\text{HCO}_3^-$ has increased, the bicarbonate buffer equation $\text{CO}_2 + \text{H}_2\text{O} \Leftrightarrow \text{H}^+ + \text{HCO}_3^-$ is driven to the left, increasing the $\text{PCO}_2$.” This statement leads students to address a common misconception about the nature of the extracellular fluid as an open, vs. a closed, buffer system.

In the context of Problem Set #1, an acute respiratory acidosis, the program’s feedback opens with the following: “The thinking often goes, ‘Well, if we’ve got an acid-base problem, then surely the base excess should be changed.’” The program then goes on to explain why this line of reasoning is not appropriate. That the program attempted to anticipate student misconceptions was clear to students:

“Instead of saying, ‘This is how it is,’ [the program] would say, ‘Well you might think it’s this, but that’s not true because of this,’ which is good, because even when you would know what’s the right answer, you need to know sometimes what the wrong one is. There should be an explanation as to why those are the wrong choices.”

The program asked students to compare cases, prompting them to explain differences as well as similarities. An example of this was described at the end of the section Description of program and interface design in regard to Problem Sets #5 and 6. Students noticed and appreciated this structure as a learning aid:

“[The program] wasn’t just looking at the isolated case but understanding why this case was different from the previous one.”

Students attempted to establish “rules” by which they could interpret blood gas data. Using multiple, similar cases gave the students the opportunity to repeatedly test their rules and, in the process, construct a fuller understanding of the basic physiological principles. Often they would find that their initial attempt at a rule failed, requiring adjustment or refinement:

“There were times when we first started working it out that we thought we had it completely understood, but when we went to the next question, [the program] changed one parameter and that would alter how base excess was changed . . . . Again, we figured, ‘this is how it happens,’ and there was no chance for variation [in the rule], and then we got to the next case and our rule changed . . . . We were thrown at first, but after we went through [all the cases,] we understood it.”

Fifty-four percent of students reported that interactive questions and immediate feedback were important aspects of the program:

“The best aspect of this was getting to answer the questions instead of just reading text. It makes the process more interactive and gives us more incentive to think about the concepts.”

“Having lots of questions where we had to work to get an answer really tested our comprehension.”

Finally, students described the need for rehearsal and elaboration of the material. Most of the interviewees indicated that they intended to return to the program or their notes later.

Working with partners. On the survey, students were asked to rate the value of working in pairs on a scale from “1 = a hindrance” to “5 = very helpful.” The mean rating was 4.5 ± 0.1. All but two students reported that they discussed questions with their partner before selecting an answer to a question. The value of working in pairs apparently had three components. First, working in pairs slowed down students’ progress through the program, giving them time to contemplate what they were learning and ensuring that they didn’t skip over areas that they might have convinced themselves (erroneously) that they understood. Second, students valued the process of explaining a concept to someone else, because that helped them discover whether they understood it:

“You can give [your partner] an explanation . . . . then you might realize that you don’t really know . . . . Trying to explain things to someone else is a very effective tool to figure out if you’ve actually learned it.”

Third, two students may understand a concept in slightly different ways. By sharing their representations, they arrived at a more complete understanding:
“We exchange and give each other copies of our notes (drawings and charts and things like that.) If you’re having trouble figuring it out in your head, [your partner is] another voice saying it in a different way that might click for you.”

Media. Students expressed some dissatisfaction with computer based resources compared with paper-based resources. This is apparently related to two factors. 1) It is easier, for reasons that are not clear, to read from paper, especially when the text is lengthy; and 2) it is not currently possible to “mark up” text in a web browser environment. Students explained that they like to interact with the text by highlighting and annotating it. People also seem to have the tendency to skim or read quickly and cursorily on screen, whereas they may be more deliberate with a paper version. The acts of marking, annotating, and note taking from paper copy contribute to a slower pace. However, as noted above, working in pairs had the effect of creating a more thoughtful pace and interactive environment.

“. . . I’m highlighting right in my book as I go along. That slows me down, and when I read off the computer screen, I read it too fast and I don’t actually stop and think and understand it. When we work through the labs in pairs, we tend to read out loud, and we stop each other and say, ‘Wait, what does that mean? Do you get it?’ So it does slow you down doing the lab in pairs on the computer, just like reading from a book and taking notes in the margins makes me slow down.”

In addition to describing disadvantages of the computer as an instructional medium in general, students identified particular strengths and weakness of the Acid/Base Primer.

Features of the program environment that students liked included:

a) Navigation was clear; students always knew “where they were.”

b) The task was clear; there was no confusing array of buttons and options.

c) The data were always visible.

The survey also requested that students record what they would like changed in the program. Twenty-four percent of students left this question blank or responded by saying they would change nothing. Users were programmatically prevented from choosing more than one answer to a question. If the correct answer were chosen, for example, students would be precluded from reading material related to why the alternative answer was incorrect. Twenty-four percent of students believed they would have benefited from being able to read material that lay behind all answers to a given question. Less than 10% of students reported each of the following: would like a handout; some explanations were too long; words should link directly to a definition, not a glossary; would like more cases; would like animations; would like a summary chart at the end of the program; the entire program was too long for one sitting; or would like to see more than one data set at a time so they could directly compare cases.

DISCUSSION

Development of the Acid/Base Primer and the current study had two objectives. First, we perceived a need to help students develop a deep understanding of acid/base physiology, a level of understanding that requires higher-order cognitive skills, construction of a complex knowledge structure, and a desire to think conceptually rather than simply acquire a large number of facts (21). Although this could be accomplished using more traditional media such as paper-based exercises, computer-based instruction was chosen for specific reasons. Anytime-anywhere access encourages student-driven learning. Computer-based cases are easily modified, replaced, or added. Moreover, a computer-based version can be revisited repeatedly in its original condition, unlike paper handouts, which are marked on by students.

We did not compare this program with other, more traditional didactic media. Reeves (20) has argued extensively that this approach is fraught with difficulties. Dillon and Gabbard (8), in a review of 30 studies concerned with the educational impact of hypermedia technology, concluded that very few found significant improvement in learning with the use of computer-based media compared with traditional media. One possible explanation for this lack of significance
could involve relative inattention to sound pedagogy. Technology is the medium and not the message, the instructional tool and not the instruction itself. Given the increasing presence of computer-based resources in medical curricula, it is important that these materials be based on sound science and appropriate educational principles.

Second, we endeavored to construct a body of design principles that could guide future development of computer-based instructional materials. Friedman (11) has argued that, unless rectified by research, poor software design, among other factors, will have a negative impact on the incorporation of computer-based instruction into medical curricula. Unfortunately, the enthusiasm for use of instructional technology is often not matched by careful evaluation of its value as an educational tool.

**Difficulty of the subject.** Results of the present study confirmed our perception that students find acid/base physiology to be a difficult topic. Their mean confidence rating with acid/base physiology was 2.2 on a 5-point scale at the beginning of the Acid/Base Primer. This low confidence rating is remarkable, because at the point in the course at which this study took place, students had encountered five tutorial cases, all of which involved acid/base content. The lack of significant correlation between time spent studying acid/base physiology and comfort level suggests that either independent study of the topic was insufficient, available textbook resources were inadequate, or students had little confidence in their ability to analyze acid/base problems even if their knowledge base was up to the task. Regardless, we concluded that acid/base physiology was a subject worthy of didactic support within the context of a problem-based curriculum. Completing the Acid/Base Primer contributed significantly to students’ performance on a test of acid/base physiology and to their self-rated confidence with the topic.

**Assessment of educational design principles as implemented in the Acid/Base Primer.** The interview and survey results indicated that students used the program as it was designed. The dimensions of the program that students praised were consistent with the educational principles that guided the design of the Acid/Base Primer. Students appreciated the explanations and feedback, particularly those that showed insight into their misconceptions. Their individual understanding of the concepts was the subject of discussion with their partners as they asked each other questions, explained the concepts, and offered alternative representations. These first-year veterinary students praised the case-based nature of the program, using similar rationales for its value as are found in the literature (4, 7). They appreciated the repetition and reinforcement of underlying concepts in different clinical contexts, making use of that design to construct, test, and reconstruct first principles. They understood, too, that the objective of the program was to develop a rich conceptual understanding of the topic (not merely a superficial understanding or a collection of facts) so that it could be transferred to new cases. Similarly, interviewees’ comments suggested that they appreciated learning an approach to diagnosing acid/base disturbances that they could use in the future. Finally, the use of interactive questions with immediate feedback (and answers initially hidden) throughout the Acid/Base Primer was highly praised. Students reflected on the questions and discussed them with a partner before clicking on the answer button.

**Implications for future development of the Acid/Base Primer.** Although we observed significant improvement in scores from pretest to posttest immediately upon completion of the Acid/Base Primer, students still did not perform at a high level. Most of the students whom we interviewed indicated that they planned to go through the program a second time. It is possible that simply repeating and reviewing existing cases during a second session might improve performance on posttests. The present study did not obtain follow-up data to determine the extent to which students revisited the program or the effect of review on their understanding.

Although students’ experiences with the program were consistent with the constructivist view of learning that guided the design of the program, their comments also suggested directions for future development to build on those educational principles further. Given the importance placed on multiple cases and repetition, the Acid/Base Primer might be improved by increasing the number of cases, providing students with much more practice. Doing so would lengthen...
the program, likely necessitating that students complete it in two sessions rather than one. It is possible that simply doing the program in two parts might increase comprehension by building in a break and a review.

Several of the interviewees wished that they had a summary chart of principles or rules at the end of the program. They were actively trying to construct such a set of principles as they worked through the program and wanted to have a concise summary for closure, as final feedback on comprehension of first principles, and as a handout for later review. Providing such a summary at the end in the form of a table or a concept map (18, 19) might be helpful. Additionally, creating a virtual notebook or making a concept-mapping program available alongside the Acid/Base Primer and prompting students to use it to record key concepts and principles as they go along might also help scaffold the development of a complex knowledge structure.

Other implications of this study that are consistent with the guiding educational design principles outlined in the introduction are to 1) create an interface that allows students to easily compare and contrast the data from two cases, 2) explicitly encourage students to work in pairs even if they complete the program independently, outside of a structured, scheduled laboratory time, and 3) write questions that are deliberately intended to improve the quality of discussions between students.

Summary: general guidelines for educational software development. One of the objectives of the present study was to construct a set of principles that could be useful in the development of other computer-based instructional resources. On the basis of the results of this study and the educational literature reviewed in the introduction, the following general guidelines emerge.

Use simple navigation; students don’t want to learn a new piece of software.

On-screen text should appear in relatively short segments or, alternatively, should start with a summary, followed by a more extended discussion.

Use clinical cases, and provide enough cases so that students get sufficient practice with the concepts included in the program.

Repeat concepts in a variety of contexts and from more than one perspective.

Emphasize understanding concepts over rote memorization.

Be explicit with students about the overall goals.

Construct the program and the physical environment so that it encourages collaboration among students and encourages a slow and thoughtful progression through the material.

Provide a means for students to compare and contrast cases or concepts.

Explain why some answers are wrong as well as why the right answer is correct; everything is a learning opportunity.

Encourage transfer of learning between cases, and be explicit that students should be applying previously learned material as they progress through the program.

Provide direction for student learning without usurping student involvement altogether.

At regular intervals, encourage students to reflect on what they have learned thus far about both content and the thought process; this will help them appreciate not only what experts know, but how experts think about the content.

Formulate textual material in the program on the basis of an understanding of students’ preconceptions, areas of ignorance, and misconceptions about the subject matter.

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Received 20 November 2001; accepted in final form 7 March 2002
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