Title
Interactive computer-assisted instruction in acid-base physiology for mobile computer platforms

Journal
AJP: Advances in Physiology Education, 38(1)

ISSN
1043-4046 1522-1229

Author
Longmuir, K. J

Publication Date
2014-03-01

DOI
10.1152/advan.00083.2013

Interactive computer-assisted instruction in acid-base physiology for mobile computer platforms

Kenneth J. Longmuir

Advan in Physiol Edu 38:34-41, 2014. doi:10.1152/advan.00083.2013

Adv Physiol Educ 38: 34–41, 2014;
doi:10.1152/advan.00083.2013.

Interactive computer-assisted instruction in acid-base physiology for mobile computer platforms

Kenneth J. Longmuir
Department of Physiology and Biophysics, School of Medicine, University of California, Irvine, California

Submitted 24 July 2013; accepted in final form 28 October 2013

Longmuir KJ. Interactive computer-assisted instruction in acid-base physiology for mobile computer platforms. *Adv Physiol Educ* 38: 34–41, 2014; doi:10.1152/advan.00083.2013.—In this project, the traditional lecture hall presentation of acid-base physiology in the first-year medical school curriculum was replaced by interactive, computer-assisted instruction designed primarily for the iPad and other mobile computer platforms. Three learning modules were developed, each with ~20 screens of information, on the subjects of the CO_2-bicarbonate buffer system, other body buffer systems, and acid-base disorders. Five clinical case modules were also developed. For the learning modules, the interactive, active learning activities were primarily step-by-step learner control of explanations of complex physiological concepts, usually presented graphically. For the clinical cases, the active learning activities were primarily question-and-answer exercises that related clinical findings to the relevant basic science concepts. The student response was remarkably positive, with the interactive, active learning aspect of the instruction cited as the most important feature. Also, students cited the self-paced instruction, extensive use of interactive graphics, and side-by-side presentation of text and graphics as positive features. Most students reported that it took less time to study the subject matter with this online instruction compared with subject matter presented in the lecture hall. However, the approach to learning was highly examination driven, with most students delaying the study of the subject matter until a few days before the scheduled examination. Wider implementation of active learning computer-assisted instruction will require that instructors present subject matter interactively, that students fully embrace the responsibilities of independent learning, and that institutional administrations measure instructional effort by criteria other than scheduled hours of instruction.

medical education; computer-assisted instruction; e-learning; acid-base physiology; iPad; mobile computing; active learning; interactive learning; independent learning

ACID-BASE PHYSIOLOGY is an integral part of the teaching of physiology in a first-year medical education curriculum. At this level, the content typically includes a discussion of the CO_2-bicarbonate buffer system under physiological conditions, a discussion of the other physiologically important buffer systems, and a presentation of the physiological classifications of acid-base disorders. The disorders are typically illustrated with examples of clinical findings.

In recent years, there has been increasing emphasis in medical education programs to incorporate active learning (1, 4, 8, 9, 11, 14, 19) and independent, self-directed learning (2, 15, 16). The inclusion of active learning and self-directed learning activities are mandatory components of undergraduate medical education accreditation standards (12). Computer-assisted instruction, often called "e-learning," is potentially well suited as a platform to address these contemporary instructional interests (18). However, currently, the great majority of computerized resources for medical education are passive learning activities. These include recorded lectures (podcasts), electronic textbooks, PowerPoint presentations, and course notes. Some efforts are underway to develop more interactive multimedia instruction in physiology, including a recent report of a multimedia e-learning resource for clinical instruction in electrolyte and acid-base disorders (6).

Tablet and laptop computers are now exceptionally powerful resources that can be used for the robust multimedia presentation of physiological concepts. To achieve a highly interactive, active learning experience for the student, considerable programming is required by the instructor or the instructional programming team. In the past few years, menu-driven, graphical interface, instructional authoring software has become available. These programming platforms now allow an individual instructor to create interactive multimedia instruction in the academic setting, without reliance upon costly programming assistance.

This report describes the development and student use of interactive multimedia instruction in acid-base physiology for first-year medical students.[1] The entire project was programmed and implemented solely by the author. The resulting instructional modules were very well received by the students. Students cited the interactive, active learning features of the instruction as the most important aspect of the presentation.

METHODS

Authoring software. The computer-assisted instruction was implemented using the authoring software AppCobra, developed by Kookaburra Studios (Capalaba, Queensland, Australia; www.appcobra.com). This software has numerous features highly suitable for the implementation of interactive computer learning in an academic setting. The user interface is entirely menu driven and does not require line-by-line programming, although this feature is available as an application programming interface for more sophisticated applications. For this implementation, no line-by-line coding was required.

The AppCobra software exported the finished applications in fully HTML5-compatible format. This means that the instructional modules could be viewed by the learner using a variety of mobile computing devices, such as the iPad tablet. Alternatively, the modules could be viewed using traditional laptop and desktop computer systems with standard internet browsers. At the University of California-Irvine School of Medicine, all first-year medical students are provided with iPad tablet computers upon entry. This mobile computing resource is

Address for reprint requests and other correspondence: K. J. Longmuir, Dept. of Physiology and Biophysics, School of Medicine, Univ. of California, Irvine, CA 92697-4560 (e-mail: longmuir@uci.edu).

[1] The acid-base physiology modules described in this report are available online for review by individual educators interested in this project. Please contact the author by e-mail at longmuir@uci.edu; a URL and a password will be provided.

made possible by a generous donation from the John and Mary Tu Scholarship Fund. For this reason, the instructional modules were designed primarily for use with the iPad platform. Each screen of each module was implemented with 1024 × 640-pixel resolution in landscape orientation. On the iPad, this allowed for viewing a full screen of information using the Safari browser, with up to three lines of browser menu bars, without any vertical scrolling.

Server platform and other institutional services. The project produced a total of 8 instructional modules and 3 question-and-answer review modules, each with ~20 screens of information. The servers for hosting the modules were provided by the University of California-Irvine Educational Electronic Environment system (EEE), which is supported by the campus Office of Information Technology (eee.uci.edu). EEE is the campus electronic course management system.

Several resources offered by EEE were essential for the successful implementation of the project. Website creation for the instructional modules was fully automated and did not require programmer assistance. User access to the instructional modules could be restricted either by password (chosen for this project) or by domain. Uploading of the instructional modules to the EEE servers was by a secure file transfer protocol from the author's office desktop computer. Typical of webpage programming, individual objects (graphs, text, symbols, and drawing objects) were each a separate file. As a result, each module consisted of several hundred files. With menu-driven secure file transfer protocol software (FileZilla), an entire instructional module could be uploaded in under 10 s from the author's desktop computer to the EEE server. This rapid transfer capability was exceptionally important during the development and testing process.

EEE also provided the resources for the menu-driven creation of an online survey. At the end of the instruction in respiratory/renal/acid-base physiology, students were asked to complete an eight-question survey about the online instruction in acid-base physiology. Students were also asked to enter any comments they wished to make about the online instruction. The EEE survey system collected the responses and presented the distributions of student responses as bar graphs.

Data collection involving students consisted of *1*) recording the number of times each instructional module was accessed on a daily basis ("hit counters") and *2*) electronic data collection of the student responses to the online survey. In both cases, the information was recorded anonymously, and no data item that was collected could be associated with an individual identifiable student. These data collection procedures were reviewed administratively by an Institutional Review Board analyst at the University of California-Irvine Human Research Protections office. The review confirmed that the data were collected anonymously and could not be related to identifiable human subjects. No further Institutional Review Board review was required.

RESULTS

Organization of content. In previous years, the author was responsible for the teaching of acid-base physiology for the first-year medical school physiology course. The instruction consisted of three classroom lecture hours on the subjects of *1*) the CO_2-bicarbonate buffer system, *2*) buffer systems other than the CO_2-bicarbonate buffer system, and *3*) physiological classifications of acid-base disorders.

The three traditional classroom lectures were replaced with 3 online interactive learning modules, each with ~20 full screens of content. Table 1 shows the specific topics covered in each of the learning modules. Review questions and answers for the three learning modules were implemented as three separate, stand-alone modules. For the CO_2-bicarbonate module and the other buffer systems module, the reviews consisted of five questions, usually from old exams. For the acid-base disorder module, in addition to old exam questions, the review contained multiple screens where the learner was asked to identify the primary acid-base disorder and the appropriate compensation, given arterial blood chemistry values of pH, bicarbonate, and arterial P_{CO_2}.

Five modules were implemented, where each module was a clinical case study of an acid-base disorder. All were developed from cases reported in the clinical literature. The purpose of the case studies was not to teach diagnosis and treatment. The diagnosis was given, and, while the treatment was discussed in the case, that was only for information purposes. Instead, the purpose of each study was to demonstrate that the literature cases are best understood by relating the clinical findings to the concepts the students learn in first-year respiratory, renal, and acid-base physiology. In medical education, this instruction is usually referred to as clinical correlation. Each case described in the literature provided a wealth of opportunities to show the importance of physiological concepts to the understanding of the clinical findings. The specific acid-base disorders and the physiological concepts discussed in each case are shown in detail in Table 2.

Interactivity. For the three learning modules (Table 1), it was found that the most educationally important interactive learning was the step-by-step presentation of a complex concept that could be illustrated graphically. An example of this type of interactive instruction is shown in Fig. 1. Toward the end of the second module (buffer systems other than the CO_2-bicarbonate system), the learner was presented with a step-by-step time

Table 1. *Content of the three interactive learning modules for acid-base physiology*

Topic	Number of Steps	Number of Interactions	Subtopics
CO_2-bicarbonate buffer system	22	23	Units of measure. Strong acids versus weak acids. CO_2-bicarbonate equilibrium. Challenging the system with a noncarbonic acid. The pH-bicarbonate diagram. P_{CO_2} isobars on the pH-bicarbonate diagram.
Other buffer systems	21	38	Why we need other buffer systems. The other buffer systems. Time courses of buffering. The buffer value. Buffer lines on the pH-bicarbonate diagram. Base excess/base deficit.
Acid-base disorders	28	42	Definition of an acid-base disorder. Compensation. Metabolic alkalosis. Metabolic acidosis. Respiratory acidosis. Respiratory alkalosis. Review of acid-base disorders on the pH-bicarbonate diagram.

A "step" is a screen of information, without vertical scrolling. Examples are shown in Figs. 1 and 2. "Interactions" are learner-initiated activities other than navigation between steps. Examples include buttons for further information, buttons to sequentially view explanations of concepts presented graphically (Fig. 1), and question-and-answer activities in a variety of formats.

Table 2. *Content of the five interactive cases for acid-base physiology*

Case	Number of Steps	Number of Interactions	Basic Science Topics in Respiratory, Renal, and Acid-Base Physiology
Asthma	21	19	Acute respiratory alkalosis. Acute respiratory acidosis. Alveolar air equation. Alveolar-arterial O_2 difference. Causes of arterial hypoxemia. Base excess. ECF buffering. Cellular buffering. Time courses of buffering.
Chronic obstructive pulmonary disease	15	18	Chronic respiratory acidosis. Renal compensation. Glomerular filtration and reabsorption of bicarbonate. Urine bicarbonate. Renal H^+ secretion. Renal ammoniagenesis. Renal adaptations to chronic elevations of P_{CO_2}. Intracellular acidification.
Diabetic ketoacidosis	18	24	High anion gap metabolic acidosis. Hyperventilation compensation. Serum electrolytes. Calculation of serum anion gap. "Unmeasured" anions. Transcellular K^+-H^+ exchange. Combined metabolic acidosis and respiratory acidosis. ECF buffer line.
Diarrhea	23	26	Normal anion gap (hyperchloremic) metabolic acidosis. Hyperventilation compensation. Review of bicarbonate gastrointestinal physiology. Serum electrolytes. Calculation of the serum anion gap. The urinary anion gap. Distal nephron H^+ secretion. Combined metabolic acidosis and respiratory alkalosis. Control of ventilation. Cerebrospinal fluid adaptation to chronic metabolic acidosis.
Bicarbonate ingestion	15	19	Metabolic alkalosis. Hypoventilation compensation. Serum electrolytes. Creatinine and glomerular filtration. Cl^- depletion and K^+ depletion maintenance of metabolic alkalosis. Distal nephron bicarbonate secretion. Transcellular K^+-H^+ exchange.

ECF, extracellular fluid.

course of buffering in response to a carbonic acid challenge (hypoventilation and respiratory acidosis). As shown in Fig. 1*A*, the learner was first presented with a screen showing the pH-bicarbonate diagram, with the physiological normal pH and bicarbonate values of 7.4 and 24 mM (P_{CO_2}: 40 mmHg). By touching/clicking on the four buttons, the learner was then shown the time course of changes in pH and bicarbonate values in response to hypoventilation (P_{CO_2}: 70 mmHg). The first button displays the acute phase of the hypoventilation, where the changes in pH and bicarbonate values follow the extracellular fluid buffer line. The second button displays the effect of cellular buffering over several hours, where the new values of pH and bicarbonate proceed up the P_{CO_2} isobar (70 mmHg) to a higher level of bicarbonate and a more normal pH. The third button displays the effect of renal compensation over several days, where the values of pH and bicarbonate continue to proceed up the P_{CO_2} isobar to a higher level of bicarbonate and a nearly normal pH. The fourth button shows the physiological advantage of these buffering and compensation processes, which is that extracellular and arterial blood pH is returned toward the normal range. The final screen of information, where all four buttons have been activated, is shown in Fig. 1*B*.

Figure 1 also shows the multiple navigation features of the modules, which permitted significant learner control of the direction, sequence, and pace of the learning process. Each learning module consisted of ~20 pages (screens) of instruction, with the current page number shown in the upper bar. The subtopic under consideration is also shown on the upper bar. The lower bar contains buttons for forward/back one page and for exiting to the main menu of modules. For the iPad, forward and back single page swiping was also implemented. Finally, touching the thumbnails button displays a panel of thumbnails of all pages of the module. The user could touch the thumbnail button again to return the same screen or touch an individual thumbnail to go directly to that page.

For the case studies, the interactivity consisted primarily of step-by-step question and answer. These question-and-answer screens guided the learner through the various features of the

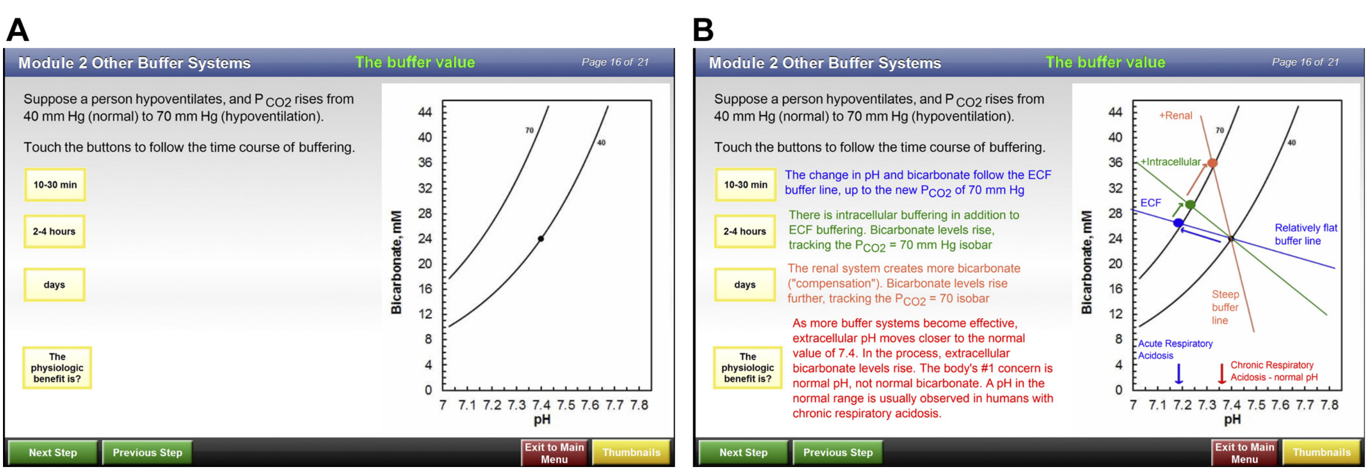

Fig. 1. Screen of information in the second learning module ("other body buffer systems") showing the step-by-step time course of body buffering in response to an increase in P_{CO_2} in the arterial blood. *A*: the screen of information that is first viewed by the student, showing the normal values of pH and bicarbonate as well as the buttons that the student is asked to press to view each step of the buffering process. *B*: the screen showing all information provided to the student after all buttons are activated. ECF, extracellular fluid.

clinical case. In the process, the question-and-answer exercise provided an extensive review of the various respiratory, renal, and acid-base physiology concepts relevant to that case. Figure 2 shows an example, in a case of asthma, of the interactivity. On this screen, learner is presented with the arterial blood chemistry. The learner is asked to place the value of pH and bicarbonate observed in this case on the pH-bicarbonate diagram, identify the primary acid-base disorder (respiratory alkalosis), identify the compensation that is occurring (none), and submit the answer. The program then responds by either saying that the answer is correct and moving to the next page or asking the learner to try again.

Student use and performance. The instructional modules were introduced to the students in a 20-min lecture hall presentation, as part of a lecture in respiratory physiology (CO_2 as a blood gas). Students were given a brief overview of e-learning as an instructional science and were shown how to access the acid-base online instruction using the campus EEE course management system. This presentation took place 3 wk before the exam that covered the subject matter of respiratory, renal, and acid-base physiology. Students were informed that the previously scheduled classroom lectures in acid-base physiology (scheduled for ~1 wk before the exam) were cancelled. All acid-base physiology was to be learned online and would involve 14% of the examination. The learning modules were allocated three points each on the exam. Each clinical case was allocated one point. The clinical case questions were straightforward and central to the case: to see if the students had studied the case at all.

Use of the instructional modules was monitored by counting the number of times each module was accessed (hit counters) per day. The total numbers of hits each day for the 3-wk period between the introduction and examination are shown in Fig. 3. No views for any of the modules were recorded during the first week after the in-class presentation described above. Some activity was observed ~1 wk before the scheduled examination, during the time period where the classroom lectures had been previously scheduled.

The examination was scheduled for a Tuesday morning after a 3-day weekend. Most of the use of the acid-base online modules occurred during the 4-day period (Friday through Monday) before the exam. Twice as many hits were recorded during the final day before the exam compared with any other day. On a per student basis, the viewing of the three learning modules was 2.0 hits per module per student, with 58% of the hits occurring during the 4-day period before the exam. The viewing of the clinical cases was 1.3 hits per student for each case, with 75% of the hits occurring during the 4-day period before the exam. Students viewed the first two cases more than the last three cases. The views of the last three clinical cases were 1.0 hits per case per student. Given the likelihood that at least some students accessed a clinical case more than once, it was evident that a significant number of students did not view several of the clinical cases.

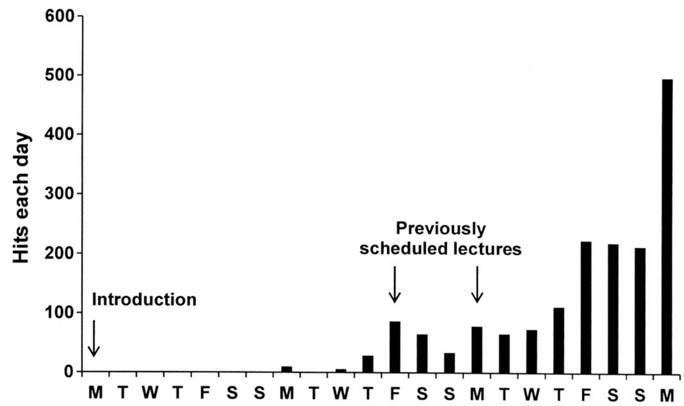

Fig. 3. Views per day ("hits") for all acid-base computer-assisted instruction modules. Values are the number of hits per day for all 11 modules (3 learning modules, 3 associated question-and-answer modules, and 5 clinical cases). The first day ("Introduction") corresponds to the day that students were instructed in class how to access and use the computer-assisted instruction. "Previously scheduled lectures" indicates the 2 days of acid-base physiology lectures that were cancelled and replaced with the computer-assisted instruction. The last day is the 24-h period before the Tuesday morning exam in respiratory, renal, and acid-base physiology.

The average score on the respiratory/renal/acid-base exam was 77% correct answers (100 points total). The average score for the questions for the three acid-base learning modules (9 points total) was 78%. The average score for the clinical case questions (5 points total) was 62%, confirming the likelihood that many students did not take the time to study the clinical cases.

Results of the student survey. After the exam, students were invited to complete the survey concerning the online instruction; 56 of the 106 enrolled medical students completed the survey. Table 3 shows the responses of the students to the eight multiple-choice questions on the survey. Several of the responses were somewhat unexpected. First, despite the fact that all students are provided with iPad tablet computers upon entry to medical school, less than half of the students used the iPad for online instruction. Many students preferred the greater versatility of laptop and desktop computers. Second, students strongly preferred to study the content on their own rather than in group study. Third, students were overwhelmingly favorable of the interactive aspect of the online instruction. Fourth, students indicated that it took less time to master the required content with online instruction compared with lecture hall instruction. Finally, students strongly preferred the online in-

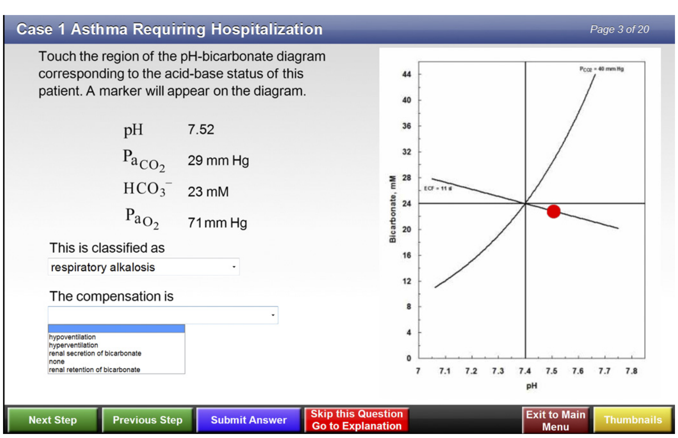

Fig. 2. Screen of information regarding a clinical case of asthma. The interactivities asked of the student are to *1*) touch the location on the graph to indicate the location of the clinical values of pH and bicarbonate on the pH-bicarbonate diagram, *2*) identify the primary acid-base disorder, and *3*) identify the compensation that is occurring in response to the primary acid-base disorder. Pa_{CO_2}, arterial P_{CO_2}; Pa_{O_2}, arterial P_{O_2}.

Table 3. *Survey of student use and opinions of the interactive online instruction of acid-base physiology*

Question	Response %	Response Mean ± SD
What type of computer did you use the most for viewing the online modules in acid-base physiology?		
Desktop or laptop computer	56	
iPad	42	
Tablet computer/mobile device other than an iPad	2	
Did you study the online acid-base modules by yourself or in groups?		
Always by myself	84	
Primarily by myself but also in group study	16	
Primarily or always in group study	0	
How did the amount of time spent learning the content by online instruction compare to the time you would have spent learning the material by classroom lecture?		
It required less time to learn the material online	74	
It required about the same time	20	
It required more time to learn the material online	6	
Was the interactive nature of the online instruction of value?		
It improved the learning experience	93	
It made little to no difference in the learning experience	7	
Given the demands of the first year medical school curriculum, do you feel you were able to spend enough time studying the acid-base physiology?		
I did have sufficient time	80	
I did not have sufficient time	20	
How do you rate the quality of the three learning modules (not the clinical cases)? (Scale: 1–5; see *footnote 1*)		4.60 ± 0.60
How do you rate the quality of the clinical cases?		4.49 ± 0.72
On a scale of 1 ("worst preference") to 5 ("best preference"), how would you prefer to learn acid-base physiology? (You can use the same value more than once.)		
Online, interactive instruction		4.56 ± 0.79
Self-study with a textbook		3.18 ± 1.25
Classroom lecture		3.05 ± 1.33
Small-group discussion		2.65 ± 1.77

n = 56 for all questions. For the measure of quality of the learning modules and the clinical cases, *1* = unacceptable, *2* = below average, *3* = average, *4* = above average, and *5* = excellent.

struction compared with learning the subject matter by classroom lecture, textbook learning, or small-group discussion.

In addition to the multiple-choice survey questions, students were asked to "make any comments they would like about the online instruction in acid-base physiology." Twenty-six students submitted written comments. These responses were reviewed by the author and the Associate Dean for Curricular Affairs. A summary of the student comments was prepared (to further protect student confidentiality) and provided to the students along with the other survey results. This summary of comments is presented here below.

Overall, most of the comments were very positive. The most frequent statement was that students appreciated the interactive nature of the online instruction. Students also appreciated the side-by-side presentation of text and images as well as the embedded question-and-answer activity. Other positive comments from students were that they could learn at their own pace, they could stop and start the learning process whenever it was appropriate for them to do so, and they could choose to refer back to previous material or jump to review questions whenever it was best for the learning process. A number of students also felt that it took less time to learn the content with online instruction compared with the lecture hall or at least that the learning process was more "efficient" compared with lecture hall instruction.

Regarding their concerns, several students felt the clinical cases were too involved and needed to be streamlined. Constructive comments were made about improving the formatting, rearranging the locations of the touch buttons, and redesigning the use of pop-up windows, question-and-answer buttons, and menus. The inability to highlight and annotate the content was felt to be a disadvantage of this form of instruction.

By far the most important issue raised by students was the quality of instruction. A number of students expressed their appreciation that the online instruction in acid-base physiology was high quality and well prepared. Importantly, students also pointed out that any online instruction must be high quality to be effective. Without the professor present for immediate question-and-answer clarification, poorly prepared, poorly organized online instruction would be of limited value. Several students were not optimistic that online instruction could be widely implemented across the curriculum unless overall instructional quality improved significantly.

Finally, several students indicated that while online instruction can be highly effective and can be the primary form of instruction in many cases, it should not completely replace other modes of teaching. A variety of combined teaching formats were suggested. These included *1*) online instruction, combined with case presentation in the simulation center; *2*) initial presentation of clinical cases online, followed by a discussion of the case by an expert physician in the lecture hall; *3*) online instruction, combined with a small-group or lecture hall question-and-answer session with the professor. Some students felt that given the complexity of the acid-base physiology subject matter, access to the professor in the lecture hall was important. A combination of lecture (to go over the more difficult concepts) and online instruction would be useful. Several students indicated that, regardless of the merits of online instruction and distance learning, meaningful contact between students and faculty members is valued.

DISCUSSION

Interactivity. Students cited interactivity as the most important positive feature of the online instruction in acid-base physiology. It is important that educators considering online teaching carefully understand the various types and levels of interactivity that are possible in multimedia education.

The most frequently cited classifications of multimedia interactivity are those originally defined in a Department of Defense Handbook (7). This guidance document defined four "levels of interactivity." *Level 1* is passive learning, where the learner is only a receiver of information. *Level 2* is defined as limited interactivity, where the learner responds to uncomplicated instructional cues in a simple, straightforward manner. *Level 3* encompasses complex interactivity, where the learner responds to instructional cues with more involved sophistication. Often, the instructional program alters direction based upon the leaner response. *Level 4* interactivity is real-time simulation with complex instructional cues and learner responses.

Currently, most online instruction in academic institutions is passive learning (*level 1*). This includes recorded videos of lectures (podcasts), PowerPoint presentations, instructional materials in the form of word processing documents or Adobe Acrobat .pdf files, and electronic textbooks. There is very limited opportunity for learner interactivity and control beyond "page turning."

For the implementation described here, most of the interactivity is classified as *level 2*, involving straightforward cues and responses. A wide variety of interactions were implemented that were available as features of the authoring software. These included identifying a region of interest on a graph, sequential display of information (usually graphically) under learner control, optional branching to and from separate screens for further information, and robust learner control of navigation throughout each module. Also, the authoring software allowed for a wide variety of interactive question-and-answer formats. These included true/false, identification of a relevant region of an image or graph, single- and multiple-answer multiple choice, drop-down list multiple choice, and free-form text entry. Considerable effort was made to provide extensive discussion and detailed feedback after each response from the learner.

Pedagogical principles in computer-assisted instruction. Over several decades, considerable academic study has been devoted to identifying the design principles that best contribute to effective multimedia instruction. For this project, the principles and guidelines developed by Mayer and co-workers were carefully considered (3, 5, 10, 13). Several design recommendations were followed: *1*) presentation of content on a single screen without the use of scrollbars for further information; *2*) careful side-by-side arrangement of visuals with the associated descriptive text; *3*) omission of extraneous text and visuals; *4*) management of complexity by carefully dividing content into smaller sections; *5*) extensive learner control of navigation, timing, and sequencing of the content; *6*) extensive use of examples, followed by learner practice, followed by extensive feedback; and *7*) use of interactivity to promote critical thinking.

Some multimedia design recommendations were deliberately not followed for this project. By far the most significant omissions were *1*) not to include any audio presentation and *2*) not to include any time-delayed appearance of information (where paragraphs of information appear sequentially at predetermined intervals). These decisions were made because we did not want to impose a throttle on the rate of delivery of information. This was particularly important for review and study for the examination. If a student wishes to review a specific content item shortly before an exam, it is important that the programming not impose any time delay on the student's ability to access the relevant information that he or she is seeking at that moment. Medical students are exceptional, rapid, high-level learners. Placing constraints on their ability to learn at their own pace should be avoided.

Active learning and interactive computer-assisted instruction. It is important to address to what extent interactive computer-assisted instruction can be considered an active learning activity. The most general definition of active learning is any instructional method that engages students in the learning process (17). It requires students to perform meaningful activities and to think about what they are doing. By this definition, the instruction described here is largely an active learning process. It requires learner engagement and learner responses to instructional cues throughout all the modules.

A more stringent view of active learning is to challenge the learner to think critically about the concepts and to use the concepts in problem-solving activities. Problem solving is not part of the learning modules, as the students have yet to learn the concepts. It is, however, the fundamental approach used in the clinical case modules. The students are actively challenged to relate clinical findings to the basic science concepts they are learning in respiratory, renal, and acid-base physiology.

This project does not directly address the medical school accreditation mandates of "self-assessment on learning needs" and "the independent identification, analysis, and synthesis of relevant information" (12). In first-year acid-base physiology, it is difficult for students on their own to identify the inclusive and comprehensive set of learning objectives necessary to master the subject matter. Considerable faculty guidance is required. Instead, the approach implemented here is referred to, in multimedia instruction, as a process of "guided discovery" (5).

Many implementations of active learning involve group study and collaborative learning. Here, a serious concern that was raised in the student survey was the students' great preference to study alone. Almost all students viewed the online instruction by themselves, with some group study. No student reported that group study or collaborative learning was their primary approach to learning. Furthermore, the students indicated that small-group discussion, a format often used for active learning instruction, would be their lowest preference for learning acid-base physiology. It appears that promoting collaborative learning behaviors with online instruction will require more proactive efforts by faculty members and educational leaders.

Student performance. The students were fully responsible for determining and scheduling, on their own, the study of these online instructional modules. The classroom lectures in acid-base physiology, scheduled ~1–1/2 wk before the examination, were cancelled. Those times were left free of other activities. A small percentage of students used that time to access the online instruction. Unfortunately, as the hit counters indicated (Fig. 3), the majority of students delayed viewing the modules until a few days before the examination. It is also clear a significant number of students did not allocate sufficient time to view several of the clinical cases even once.

These behaviors suggested that students assumed the subject matter was such that it could be effectively memorized a few days before a scheduled examination. In reality, acid-base physiology is conceptually complex. It requires a student to allocate sufficient time to first learn the concepts, reflect on the concepts, and then apply the concepts in critical thinking, problem-solving activities. It is now clear that this computer-assisted instruction project should be accompanied with discussions with the students about approaches to learning. These discussions should include *1*) serious statements regarding the expectations of independent study in a medical education program and *2*) a discussion of the conceptual complexity of the subject matter and the time required to master that complexity.

Because of the problematic approach to learning, it is difficult to compare examination scores for this computer-assisted instruction project with scores from previous years, where the content was presented in lecture, and well before the exam. Nonetheless, this year, the student exam scores for the three acid-base physiology learning modules were virtually the same as the scores for the respiratory and renal physiology content that was presented in classroom lecture. This equivalent performance was consistent with the examination scores seen in previous years. Exam scores for the clinical cases were substantially lower, and, as noted above, it was clear that many students did not study the clinical cases at all. It will be difficult to establish the intrinsic value of this computer-assisted instruction until the study skills exhibited by the students are first addressed and improved.

Considerations for further development. Further implementation of effective interactive computer-assisted instruction will require some changes in an instructor's approach to teaching. Also, academic administrations will need to examine how instructional effort is measured.

The major pedagogical change for the instructor will be to decide how to present content interactively from beginning to end. This is a typical feature of small-group discussion teaching. However, in computer-assisted instruction, the interactivity is not spontaneous but preprogrammed. Before the instruction, the instructor must predetermine a step-by-step set of interactions that will occur between the learner and the content, in a way that will be suitable for most students. To do this effectively, it is important that the instructors familiarize themselves with the classifications of interactivity and the principles of effective multimedia design, as noted above.

Also, the instructor should be familiar with the authoring systems for computer-assisted instruction. For this project, a menu-driven, graphical interface authoring system was used, which required no line-by-line programming. As a result, the entire implementation was carried out by the author, using a standard Windows-PC desktop system, and no programming assistance was required. The author found that the implementation process was dominated, from start to finish, by constant decisions and trade-offs regarding how the presentation should be designed versus what the authoring software allowed. These decisions would be more difficult if the content was understood only by the instructor and the authoring software was understood only by the programmer. For example, a recent report (6) described a multimedia development project for electrolyte and acid-base physiology using a multidisciplinary team of developers. The authors reported that the programming effort was challenged by a shortage of skilled programmers, budgetary constraints, and communication difficulties between authors and programmers. It is better that the instructor understand the software, so that the final product captures the full range of features within the software that are appropriate for the instructional project.

The written comments of the students conveyed two serious expectations regarding the further implementation of online instruction. First, the online instruction must be high quality. Students indicated that poorly prepared online instruction would be difficult to use effectively, as this form of instruction removes immediate access to the professor for clarification and further explanation. Second, several students indicated the online instruction should be combined with complimentary activities that involve direct contact with faculty members. For acid-base physiology, these activities could include question-and-answer sessions with faculty members, introductory presentations of the content by faculty members, and further presentations of clinical relevance by expert clinicians.

Finally, changes in the measurement of instructional effort must be examined. In most academic institutions, an important measure of teaching activity is hours of scheduled instruction. This information is used extensively for faculty promotion, departmental resource allocation, external review of institutional performance, and as a measure of educational progress in student records. In this project, the three learning modules replaced three scheduled hours of instruction, which allowed for some measure of equivalence. However, with greater implementation of interactive, self-paced computer-assisted instruction, the ability to equate online instructional activity with previously scheduled hours of instruction will soon be lost. Instead of hours of instruction, institutional measurements of instructional effort will require greater emphasis on an analysis of breadth of subject matter, appropriateness of subject matter, quality of instruction, and identification of active learning versus passive learning activities.

ACKNOWLEDGMENTS

The author thanks Dr. Harry Haigler (Associate Dean for Curricular Affairs, School of Medicine, University of California, Irvine, CA) for the administrative assistance and enthusiastic support. The author also thanks Jeff Ingeman (development engineer) for discussions regarding e-learning and mobile computing platforms.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: K.J.L. conception and design of research; K.J.L. performed experiments; K.J.L. analyzed data; K.J.L. interpreted results of experiments; K.J.L. prepared figures; K.J.L. drafted manuscript; K.J.L. edited and revised manuscript; K.J.L. approved final version of manuscript.

REFERENCES

1. **Abate LE, Gomes A, Linton A.** Engaging students in active learning: use of a blog and audience response system. *Med Ref Serv Q* 30: 12–18, 2011.

2. **Abraham RR, Fisher M, Kamath A, Izzati TA, Nabita S, Atikah NN.** Exploring first-year undergraduate medical students' self-directed learning readiness to physiology. *Adv Physiol Educ* 35: 393–395, 2011.
3. **Association of American Medical Colleges Institute for Improving Medical Education**. *Effective Use of Educational Technology in Medical Education. Colloquium on Educational Technology: Recommendations and Guidelines for Medical Educators* (online). https://members.aamc.org/eweb/upload/Effective%20Use%20of%20Educational.pdf [23 December 2013].
4. **Brands MW, Schumacher L.** Active learning strategies to teach renal-cardiovascular integration with high student-to-teacher ratios. *Adv Physiol Educ* 33: 282–285, 2009.
5. **Clark RC, Mayer RE.** *E-Learning and the Science of Instruction* (2nd ed.). San Francisco, CA: Pfeiffer, 2008.
6. **Davids MR, Chikte UME, Haperin ML.** Development and evaluation of a multimedia e-learning resource for electrolyte and acid-base disorders. *Adv Physiol Educ* 35: 295–306, 2011.
7. **Department of Defense**. *Department of Defense Handbook. Development of Interactive Multimedia Instruction (IMI) (Part 3 of 4 Parts)* (online). http://www.au.af.mil/au/awc/awcgate/dod/hbk3.pdf [23 December 2013].
8. **Dietz JR, Stevenson FT.** Active learning in a large medical classroom setting for teaching renal physiology. *Adv Physiol Educ* 35: 456–459, 2011.
9. **Graffam B.** Active learning in medical education: strategies for beginning implementation. *Med Teach* 29: 38–42, 2007.
10. **Issa N, Mayer RE, Schuller M, Wang E, Shapiro MD, DaRosa DA.** Teaching for understanding in medical classrooms using multimedia design principles. *Med Educ* 47: 388–396, 2013.
11. **Larsen DP, Butler AC, Roediger HL.** Comparative effects of test-enhanced learning and self-explanation on long-term retention. *Med Educ* 47: 674–682, 2013.
12. **Liaison Committee on Medical Education**. *Functions and Structure of a Medical School. Standards for Accreditation of Medical Education Programs Leading to the M.D. Degree* (online). http://www.lcme.org/publications/functions.pdf [23 December 2013].
13. **Mayer RE.** Applying the science of learning to medical education. *Med Educ* 44: 543–549, 2010.
14. **Michael J.** Where's the evidence that active learning works? *Adv Physiol Educ* 30: 159–167, 2006.
15. **Murad MH, Coto-Yglesias F, Varkey P, Prokop LJ, Murad AL.** The effectiveness of self-directed learning in health professions education: a systematic review. *Med Educ* 44: 1057–1068, 2010.
16. **Murdoch-Eaton D, Whittle S.** Generic skills in medical education: developing the tools for successful lifelong learning. *Med Educ* 46: 120–128, 2012.
17. **Prince. M.** Does active learning work? A review of the research. *J Eng Educ* 93: 223–231, 2004.
18. **Ruiz JG, Mintzer MJ, Leipzig RM.** The impact of e-learning in medical education. *Acad Med* 81: 207–212, 2006.
19. **Stringer JL.** Incorporation of active learning strategies into the classroom: what one person can do. *Perspect Phys Assist Educ* 13: 98–102, 2002.