ILLUMINATIONS

The use of the 5E instructional design strategy to teach respiratory physiology to first-year medical students

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INTRODUCTION

Physiology is a difficult discipline for many learners to understand, yet it is the foundation for pursuing a career in health sciences. A previous survey study showed the most frequent factors contributing to the difficulty of learning physiology are as follows: properties of the discipline, educators’ teaching style, and the students’ abilities (14). A learner must be able to reason through causal mechanisms and think about dynamic systems to understand physiology. Additionally, learners need to recognize that physiology is both integrative and conceptual in nature. To further complicate the issue, most textbooks are descriptive and not mechanistic. Educators can also perpetuate the issue if assessment methods reward memorization of facts, rather than understanding (14). This lack of true understanding leads to flawed mental models and misconceptions that can be persistent (13).

Studies show the prevalence of physiology misconceptions throughout various academic levels (biology, nursing, medical students, etc.) (1, 20). Michael’s study (15) exposed common, but faulty, mental models by asking learners about physiological changes that happen with exercise and high altitude: two situations that students were likely to have experienced. He showed that fallacies were still very prevalent as >50% of students still could not correctly explain the physiology regarding strength of contraction and breathing rate. Furthermore, the incorrect answer explanations suggested that the flawed mental models were a result of something learned in the classroom (15). Michael’s work expanded into studying undergraduate students’ misunderstandings about respiratory physiology, where 11 misconceptions were compiled by a group of physiologists. This study focused on 4 of the most prevalent of the 11. The first was the “tidal volume (VT)/respiratory frequency (f) misconception,” in which the majority of students felt that, if an individual were exposed to an activity that increases minute ventilation such as exercise, the increased breathing rate would limit how much that person could inhale. The second was the “Sa/PO2 misconception,” in which students make the mistake of believing that the partial pressure of oxygen (PO2) is determined by the hemoglobin saturation (Sa). The third was the “O2/CO2 misconception,” in which students incorrectly believe that increased oxygen leads to higher CO2 or that O2 replaces CO2 in the lungs. The fourth was the “met/vent misconception,” in which students did not see the connection between metabolism and ventilation.

The study found that for three of the four, the prevalence was >50% (16). In 2006, Cliff (4) performed a case analysis study aimed at remediating respiratory misunderstandings and reported that only one, the “Sa/PO2 misconception,” was remediating and was temporary. More recently, Palizyan et al. (20) reported that at least four cardiovascular physiology misconceptions were very high (>69%) and concluded that university teaching did not address them. For health sciences education, basic science knowledge is critical for developing clinical reasoning skills; therefore, incorrect mental models could lead to diagnostic errors (24, 26). Utilizing teaching methods that encourage students to confront their mental models is essential for elucidating and addressing misconceptions.

An underlying issue is that most basic science and clinical faculty involved in medical education do not have formal training in the science of learning or instructional design (10). This lack of preparation may result in suboptimal teaching, as instruction is based on intuition and experience rather than research and theory (9, 11). Merrill (12), an instructional designer, has identified five instructional design principles that have been shown to enhance learning environments. These principles are as follows: 1) learners should be solving real-world problems; 2) existing knowledge is activated as a foundation for new knowledge; 3) new knowledge is demonstrated to the learner rather than being told; 4) new knowledge is applied by the learner; and 5) new knowledge is integrated into the learner’s world. There are numerous instructional design strategies that can be used to frame a learning environment based on the aforementioned principles. Since medical students are applying basic science to patient care, using these principles is an opportunity to facilitate their learning process. However, there have been limited studies that report on the use of instructional design principles to guide the development of educational materials in medical education (5, 22).

The 5E instructional strategy, developed by the Biological Sciences Curriculum Study (BSCS), was used in this study to apply Merrill’s design principles and correct misconceptions of respiratory physiology. This instructional strategy emerged from a study in the mid-1980s for the science and health curriculum and is grounded in constructivist learning theory, where people construct knowledge from experiences (3). The 5
“phases” or “E’s” are Engagement, Exploration, Explanation, Elaboration, and Evaluation, and are described in Table 1. Most research studies about the 5E Instructional Model have evolved from the K–12 literature. Balci et al. (2) illustrated that students who received the 5E Instructional Model had a significant increase in correct responses about conceptual understanding of photosynthesis compared with students who received traditional teaching. Another study by Tuna and Kacar (23) showed that students achieved higher scores in trigonometry when the 5E Instructional Model was utilized. Although the 5E instructional design strategy has been shown to be effective in helping students master scientific knowledge, there have been no studies in medical education utilizing the 5E instructional design strategy, to our knowledge. The purposes of the present study are to describe how the 5E instructional design strategy was applied to respiratory physiology teaching and determine whether it could facilitate remediation of common, previously established misconceptions.

**METHODS**

**Participants and curriculum.** This research study was considered exempt by the Institutional Review Board from the University of Central Florida (UCF). One hundred and nineteen first-year medical students at the University of Central Florida were recruited to participate in this study. One hundred and eleven of them enrolled (93%) and are included in the analyses. The UCF MD Program curriculum is integrated, and the students in this study were in the “Structure and Function” module, which consisted of anatomy and physiology as the major disciplines. This module spans 16 wk from months 3 to 7 in the curriculum.

**5E instructional design to teach respiratory physiology.** Table 1 shows how the 5E instructional design strategy was used to scaffold the respiratory physiology experience. In our study, the Engagement

| Phase          | Summary and Learning Goals from 5E Instructional Model (Ref. 3) | Teaching Approach for Respiratory Physiology |
|----------------|-------------------------------------------------------------------|---------------------------------------------|
| Engagement     | The Engagement activity introduces a new problem for students to solve. The activities should make connections to past and future activities. The connections depend on the learning task and may be conceptual, procedural, or behavioral. The role of the teacher is to present a situation and identify the instructional task and learning outcomes. | Enrolled students took a pretest that included questions aimed at common respiratory misconceptions (15). The teacher introduced students to a virtual family that had multiple respiratory conditions/situations (altitude, surfactant deficiency, asthma, and carbon monoxide poisoning). Students were provided a clinical vignette for each family member that included history, physical examination, and laboratory data, as needed. Students were asked to generate a MOD map for each family member, outlining the physiological causal mechanisms for each sign, symptom, or laboratory result. |
| Exploration    | Once activities have engaged students, they need time to explore their ideas and skills. If Engagement brings about disequilibrium, Exploration initiates the process of equilibration. Students have time to explore their knowledge and skills. This phase may require students to recognize new situations and learn new tasks. The teacher initiates the activity and allows the students time and opportunity to investigate materials. A portion of the Exploration phase may center on cooperative learning. | The teacher provided 5 h of curricular time and a list of resources (textbook, manuscript on MOD maps, and short videos on pulmonary physiology topics). During the open time, the teacher was present for guidance or coaching. After students submitted their MOD maps individually, they were tasked to get into their groups and develop a team MOD map for each family member. This was done to enhance peer learning through negotiated understanding. |
| Explanation    | Explanation means the act or process in which concepts, processes, or skills become plain, comprehensible, and clear. In this phase, the teacher directs student attention to specific aspects of the Engagement and Exploration experiences. The Explanation is teacher directed. Teachers have a variety of techniques and strategies at their disposal. | As students were in their groups working to formulate team MOD maps for each family member, faculty walked around to teams for questions and feedback. After 2 h of time, five teams of students (~30 students) relocated to a debriefing room. One team was chosen to present its MOD map, and the faculty and the rest of students provided feedback. |
| Elaboration    | Once students have an Explanation, it is important to involve them in further experiences that apply, extend, or elaborate the concepts or skills. Elaboration activities provide further time and experiences that contribute to learning. Group discussions and cooperative learning situations provide opportunities for students to express their understanding of the subject and receive feedback from others who are very close in their own level of understanding. | The next task occurred a few days later. Teams were asked to develop team MOD maps for two additional family members with more complex conditions (chronic obstructive pulmonary disease and pulmonary fibrosis). Students were provided a clinical vignette that included history, physical examination, and laboratory data, as needed. Students were asked to generate a MOD map for these family members, outlining the physiological causal mechanisms for each sign or symptom. The same feedback system as in the Explanation phase was done for the more complex conditions. |
| Evaluation     | The Evaluation phase encourages students to assess their understanding and abilities and provides opportunities for teachers to evaluate student progress toward achieving the educational objectives. | Students were also assessed on the misconceptions on the summative exam ~4 wk after this event, which served as the posttest. |

MOD, mechanism of disease.
phase consisted of a pretest and instructions for students to create mechanism of disease (MOD) maps for each family member who had a specific respiratory disease or stresses. The faculty member also presented an example MOD map on a person with heat-related illness as a model to show how the basic knowledge of blood pressure regulation is applied to that patient. Family members were presented from simple stresses to more complex disease states. An example of a MOD map for the family member in the high-altitude case is shown in Fig. 1. This applies Merrill’s principle that the instruction should be directed toward real-world problems as well as the principle that new knowledge is demonstrated. In the Exploration phase, students were provided curricular time to explore the resources provided by the instructor to create an individual MOD map, which was the application principle. Resources included a textbook (Costanzo’s Physiology; Ref. 5a), a series of short e-learning videos created by faculty (Adobe Articulate), and manuscripts on MOD maps and misconceptions. These resources, along with students’ past experiences, served as a basic foundation knowledge that is consistent with Merrill’s principle around activation. During the Explanation phase, students worked in groups to generate and submit a group MOD map. Feedback was provided in a small-group setting by faculty, as well as interaction in the classroom. This applied Merrill’s principle for integration. For the Elaboration phase, groups of students were tasked to generate MOD maps for more complex family members. For the Evaluation phase, groups of students were provided feedback in a small-group setting. Additionally, summative questions on the midterm were designed to test new knowledge.  

Pretest and posttest summative questions. To test for learning effectiveness of the 5E Instructional Model on misconceptions, a pretest/posttest study was conducted. These questions are provided in the APPENDIX. A pretest was administered at the beginning of the respiratory physiology experience. Three of the pretest questions were identical to those used by Michael (13) and Cliff (4) in their respective papers on misconceptions: the “VT/f misconception,” “Sa/PO2 misconception,” and the “O2/CO2 exchange misconception.” The other question on the pretest was designed to address an additional misconception outlined by Michael et al. (15) that inspired PO2 (PIO2) is independent of altitude. We changed the PIO2-altitude misconception to inspired O2 fraction (FIO2)-altitude misconception based on experience that students typically have trouble with the PIO2 component of PO2 in our curriculum. The posttest questions on the midterm summative exam were written by an author of this paper (DH) and validated by a physiologist and pediatric nephrologist. The midterm summative exam was given about 5 wk after formal respiratory physiology teaching.

Data analysis. Pretest and posttest data were compared using a paired t test in Microsoft Excel. Differences were considered significant if P < 0.05.

RESULTS

A pretest/posttest approach using questions on respiratory misconceptions was used to assess the effectiveness of the 5E instructional design strategy and are included in the APPENDIX. The pretest was administered to determine the prevalence of misconceptions of first-year medical students before respiratory physiology teaching. The four misconceptions chosen were the VT/f, Sa/PO2, O2/CO2, and the FIO2-altitude. Figure 2 shows that >50% of students had baseline misconceptions in all four.

VT/f misconception. The same question from Michael’s original respiratory misconception study (15) was used for the pretest question for this misconception. Fifty-seven percent of the students in our study (SD 0.50) answered this question incorrectly, which is very similar to Michael’s results (56.7%). Two posttest questions were asked on this misconception.

![Fig. 1. Example mechanism of disease (MOD) map for the case of high altitude. The shaded boxes indicate the findings that the students were asked to explain. The asterisks indicate the inciting incident, which, in this case, is going to high altitude.](image-url)
There was a significant improvement as only 10% (SD 0.29, \( P < 0.001 \)) and 9% (SD 0.27, \( P < 0.001 \)) of students answered incorrectly on the respective questions. These represented improvements of 47 and 46 percentage points.

\textit{\textbf{\textit{Sa/P0}_2 \textit{misconception}}.} The same question from Michael’s original respiratory misconception study (15) was used for the pretest question for this misconception. Almost 86% of the students in our study (SD 0.42) answered this question incorrectly. This is consistent with Michael’s study, as he showed a strong misconception in 89.9% of the students. There was a significant improvement as 36% of students answered the question incorrectly on the posttest (SD 0.46, \( P < 0.001 \)).

\textit{\textbf{\textit{O2/CO2 \textit{misconception}}.} The same question from Michael’s original respiratory misconception study (15) was used for the pretest question for this misconception. Fifty-nine percent of the students answered this question incorrectly on the pretest (SD 0.50). This is slightly lower than the almost 68% of students who got this wrong in Michael’s study. Two posttest questions were asked on this misconception, and 25% (SD 0.42) and 40% (SD 0.48) of students answered incorrectly on those respective questions. Both questions were a significant improvement (\( P < 0.001 \)).

\textit{\textbf{\textit{FIO2-altitude \textit{misconception}}.} In our experience, students have not understood that the fractional percentage of oxygen is the same at all altitudes. There was no question on the misconception in the Michael paper (15), so we developed one for this concept. Eighty-two percent of students (SD 0.39) responded incorrectly to the question on the pretest for the \textit{FIO2-altitude} misconception. Thirty-six percent of students answered this incorrectly on the posttest question (SD 0.47, \( P < 0.001 \)), which is a 46 percentage point improvement.

**DISCUSSION**

This paper shows how the 5E instructional design strategy was utilized to scaffold respiratory physiology for first-year medical students. It also showed significant improvements on the summative posttest questions in the four selected misconceptions. The data from this study suggest that the 5E instructional design strategy can be an effective educational approach to addressing well-established respiratory physiology misconceptions.

There are many positive benefits to using this instructional design model, although a great benefit most likely rests on the inclusion of active learning. It has been demonstrated that active learning techniques have been shown to improve student performance in multiple disciplines (6, 21). The development of individual MOD maps allowed students to create their mental models with predictions, which is consistent with the need to form predictions and test them (17, 18). In this case, they would “test” them with other team members and challenge their own mental models when they had to submit a team MOD map for feedback. Another strength of the 5E Instructional Design Model in this study was the inclusion of peer-assisted learning, which has been shown to be beneficial to learning (7). Some student comments included, “I think the group sessions were really helpful because it allowed me to correct my misconceptions,” and “It was nice to be able to bounce ideas off of other people and discuss mechanisms.”

**Lessons learned.** One of the lessons learned in this study was the effect of academic culture with this type of teaching. The previous module within our curriculum is very PowerPoint focused, in that all answers on assessments can be found directly on faculty slides. Such traditional lecture-based teaching methods solidify the perception of students equating memorizing with learning. The 5E instructional design strategy is based on a natural inquiry process, where people explore resources to solve the issue at hand. The way students were tasked to explain what they learned with the MOD maps challenged them to create a mental model of a disease. After discussion with other students, a student may change their mental model or need to justify their thinking, which is the basis of social constructivism (25). Negative comments from
students revolved around having to write something down and then change it after they discovered they were incorrect or had a faulty model.

Faculty development, such as training or incentives, is needed to help educators provide materials that promote higher levels of learning to shape a different academic culture. A cultural shift in student perception is also necessary and needs a faculty team approach to help guide this self-regulation.

Another lesson learned in this study is recognizing how students view feedback. Feedback in this model was provided two ways. One was by faculty walking around the room and addressing any team concerns, questions, or comments. The second mode of feedback was a debriefing session, where one team would present its MOD map to four other teams and a faculty member. Faculty and students provided feedback on their maps as far as missing signs or symptoms as well as faulty connections. Many students did not recognize this as feedback, which is most likely a generational issue in that millennials tend to feel uncertain and prefer continuous feedback, even if positive (19). Comments from students indicated that they wanted a hard copy of the “answers,” and they had concerns about variation among the four faculty members. Future uses of this approach would include faculty development aimed at standardizing faculty facilitator behaviors and feedback. Another possible way is for one faculty to draw out his/her approach to a MOD map and let students adjust theirs in response.

Study limitations. One limitation of the present study is that it does not have a control group. Therefore, we cannot state that our intervention was solely responsible for the improvement in scores. We also do not know what resources students used between the teaching sessions and summative examination. Despite this, the data suggest that the participants were not adversely affected by this teaching strategy.

Another limitation is that only one or two questions were used to assess understanding of a particular concept. To help alleviate this issue, we used questions that were previously used in multiple studies. Although our study was performed on first-year medical students, the results for the pretest were similar to those in the Michael (15) and Cliff (4) studies, who performed their studies on undergraduates. In two of the three previously studied misconceptions (VT/f and Sa/Po2), the pretest score was within 1 percentage point. The other one was ~9 percentage points. (O2/CO2) The level and clarity of the pretest questions is also very straightforward so that questions were not misinterpreted by students. Our posttest questions were developed and validated by physiology faculty. They are written as board style questions with a clinical vignette, so that question performance could be affected due to that, although a lower score would be predicted. The restriction on the number of potential questions and the fact that our exams are multiple choice prevent us from adding more questions. Other means of assessments, such as essays or concept maps, could help to elucidate student misconceptions as well.

Another limitation is the time frame of our study. In our curriculum, the students have 14 h of curricular time devoted to respiratory physiology activities. Our posttest questions were on our summative midterm examination 5 wk after formal respiratory physiology teaching. Therefore, we cannot say that the improved performance on the posttest was due solely to the 5E Instructional Design Model because other resources could have been used within the time frame of the study. However, the strategic approach with the 5E Instructional Design Model is consistent with Cliff’s conclusion (4) that learning strategies need to be structured so that students confront their faulty notions, which will help them overcome misconceptions. The approach we took in this study was to allow students time to create their own maps before comparing them with others in a team format. Students needed to defend or change their conceptual understanding during the time with their team, as teams came up with one MOD map. This study was also only performed in one cohort of students at one institution. Future studies could use other cohorts of students, as well as different variations in strategies, to see if there are any that are more or less effective.

Overall, the 5E instructional design strategy provided strong scaffolding for the respiratory physiology block of teaching. The data from this study show a potential way to use this model for designing educational activities, but other variations could fit within the guidelines of the model to fit multiple needs. This study supports the notion that aligning curricular development with grounded instructional design models enhances learning and should be studied for effectiveness and improvement.

APPENDIX

An asterisk (*) indicates the correct answer.

Pretest questions.

The pretest questions are as follows:
1. (VT/f misconception) A classmate is late for the exam and runs up five flights of stairs into the exam room. When she arrives, you notice that her breathing frequency is increased. At the same time, you notice that her depth of breathing (how much air she takes with each breath) is:
   a. Greater than normal*
   b. Less than normal
   c. Unchanged
2. (Sa/Po2 misconception) Carbon monoxide (CO) bind to hemoglobin much more strongly than does oxygen. As a result of CO being in the blood, less oxygen is bound to hemoglobin, and the partial pressure of oxygen in the blood is:
   a. Increased
   b. Decreased
   c. Unchanged*
3. (O2/CO2 misconception) You are breathing 100% oxygen through a mask. While you breathe from the mask, the amount of carbon dioxide in your lungs:
   a. Increases
   b. Decreases
   c. Stays the same*
4. (FIO2-altitude misconception) As a mountaineer climbs up a mountain, the fractional percentage of oxygen in the atmosphere:
   a. Increases
   b. Decreases
   c. Is equal to seal level fractional percentage of oxygen*

Posttest questions.

The posttest questions are as follows:
1. (VT/f misconception) As part of training for the UCF College of Medicine intramural soccer team, a medical student runs the stadium steps at the football stadium going from bottom to top. What would be the expected changes in respiratory rate (RR), depth of breath (VT), and minute ventilation (Vtotal) in the student immediately after running up the steps?

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2. (O2/CO2 misconception) A 23-yr-old male is brought to the emergency room with a suspected opioid overdose. Opioids reduce the firing rates of neurons within the dorsal respiratory group. What would be the expected changes in breathing frequency (BF), tidal volume (VT), and arterial PCO2 (PaCO2) in this patient?

A. BF: decrease; VT: decrease; PaCO2: increase
B. BF: increase; VT: increase; PaCO2: decrease
C. BF: decrease; VT: increase; PaCO2: decrease
D. BF: decrease; VT: increase; PaCO2: increase
E. BF: increase; VT: decrease; PaCO2: no change

3. (SaO2/PO2 misconception) A set of identical twins (twin A and twin B) are born near full term. Twin A has a hemoglobin concentration of 15 g/dL, whereas twin B’s is 11.5 g/dL (normal: 13.3–19.9 g/dL). Assume that there have been no compensatory changes in twin B. What is the most likely change, if any, in arterial PO2 (PaO2) and hemoglobin saturation (SO2) in twin B compared with twin A?

a. No difference between twins A and B
b. PaO2 decreased; SO2 decreased
c. PaO2 decreased; SO2 same as twin A
d. PaO2 same as twin A; SO2 decreased

4. (O2/CO2 misconception) As part of a research study, a healthy participant was asked to breathe 100% oxygen through a mask. What was the most likely change, if any, in alveolar PO2 (PaO2) and alveolar O2 (PAO2) in this participant compared with breathing room air?

a. PAO2: no change; PAO2: increased
b. PAO2: increased; PAO2: increased
c. PAO2: decreased; PAO2: increased
d. PAO2: no change; PAO2: no change

5. (O2/CO2 misconception) A 46-yr-old male presented to an emergency department with shortness of breath after participating in a scuba dive at 100 feet. He was diagnosed with decompression illness (air bubbles in his blood). The patient was placed in a hyperbaric chamber [pressurized to 1,900 mmHg (2.5 atm) and 100% oxygen]. Assume room air is 760 mmHg (1 atm). What would be the most likely changes, if any, in arterial PO2 (PaO2) and arterial Pco2 (PaCO2) when placed in the hyperbaric chamber compared with room air?

a. PaO2: increased; PaCO2: no change
b. PaO2: increased; PaCO2: increased
c. PaO2: decreased; PaCO2: increased
d. PaO2: no change; PaCO2: no change

6. (FiO2-altitude misconception) A physician is attending to a skier who was feeling ill after taking the gondola to the summit of the mountain in Keystone Colorado (9,173 ft above sea level). The physician recommends transporting the skier to the lodge at lower altitudes to aid the skier’s breathing. What are the changes in fractional inspired oxygen (FiO2) and atmospheric partial pressure of oxygen (Po2) at the summit compared with the lodge?

A. FiO2: no change; PO2: decreased
B. FiO2: no change; PO2: no change
C. FiO2: increased; PO2: decreased
D. FiO2: increased; PO2: increased
E. FiO2: increased; PO2: increased
F. FiO2: increased; PO2: no change

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

AUTHOR CONTRIBUTIONS
A.H. and D.M.H. conceived and designed research; B.D., A.B., F.D., and D.M.H. performed experiments; B.D. and D.M.H. analyzed data; B.D., A.H., and D.M.H. interpreted results of experiments; D.M.H. prepared figures; B.D., A.B., F.D., A.H., and D.M.H. edited and revised manuscript; B.D., A.B., F.D., A.H., and D.M.H. approved final version of manuscript.

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