ILLUMINATIONS

Avoiding the chopping block in curricular reform: reimagining physiology laboratories in the era of integrated medical curricula

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For the past 100 yr or so, the Flexner 2+2 model of medical education has been the dominant paradigm for undergraduate medical curricula (4). The recognition of disadvantages with this approach has prompted a growing movement of curricular reform, beginning with a focus on pedagogical format and, more recently, resulting in the transition to integrated curricula designed to foster a stronger connection between the basic and clinical sciences (1). While curricular reform has taken many forms, several thematic trends have underwritten this progress, including early meaningful exposure to the community of practice in health care environments, a shift from a structured, discipline-based curricula to one that integrates basic with clinical science, and, in some cases, reduction in the traditional 2-yr period of preclerkship instruction (3).

In 2011, the basic science and clinical faculty at the F. Edward Hebert School of Medicine at the Uniformed Services University of the Health Sciences (USUHS) engaged in a collaborative curricular reform effort. This resulted in the implementation of an integrated, organ-based curriculum that emphasized early clinical engagement (10). In addition to changing the overall philosophy of the curricular design, a key component of reform was a reduction in the preclerkship phase from the traditional 2 yr to approximately 18 mo. Subsequent experience with this integrated curriculum has demonstrated many benefits, including a seemingly stable trend of historically peak performance on high-stakes certifying examination, as well as improved clinical performance in the clerkship phase of the curriculum.

A balanced view of this reform effort will illustrate several potential unintended consequences. One common concern is the effect that this reform effort has had on active, experiential-based learning activities (6). In particular, a significant reduction in laboratory-based experiences was observed. Before integration, there were ~392 h of laboratory instruction in the disciplines of physiology, anatomy, histology, pathology, and pharmacology. This has been reduced to ~340 h in the new integrated curriculum. Reduced time for laboratory instruction has occurred across all disciplines. However, physiology laboratories were almost completely abolished, and this is not a phenomenon unique to our curriculum or university (8, 11, 12). It is difficult to measure the effect of discontinuing the physiology laboratory exercises on learning. In comparisons of dissection-based vs. prosection-based or computerized anatomy instruction, it is unclear whether there is any tangible difference in test performance associated with a specific modality (9, 14). Similar results are observed when comparing live animal laboratory exercises with video or computer simulations (2). Although these are important observations, physiology laboratories at our institution were not replaced, but abolished. At USUHS, it was generally perceived by faculty that students viewed physiology material as an esoteric concept reserved for bench scientists with little appreciation for the real world clinical implications and applications of physiological concepts and measurements. In addition to this, the advent of e-learning technology, lecture capture software, and other technological innovations has widened the divide between learners and teachers (5). Significant declines in lecture attendance rates and the growing use of third-party educational tools and social media underscores this cultural shift in the way medical students in the modern era learn (7).

Why is the use of physiology laboratories in medical education declining? The reduction or elimination of “wet lab” physiology experiments in medical education is becoming the norm rather than the exception (3, 8, 9, 11, 13). Naftalin (8) posits several possible reasons for the decline in physiology teaching, including the increased utilization of problem-based learning exercises and reorganization of traditional physiology department organizational structures. At USUHS, there has been no single rationale for the discontinuation of physiology laboratories, but really an amalgam of reasons that gradually led to the removal of these active-learning exercises from the curriculum.

Time constraints and faculty availability were major factors leading to laboratory discontinuation (13). Some of the exercises that were conducted required a time block of 4 h. In an increasingly streamlined curriculum, 4 h is a substantial amount of time to devote to a single exercise, particularly when a fair bit of the time is spent waiting to collect or process samples. In addition, some activities required a minimum of 7–10 faculty members to oversee the exercise and assist small groups of ~20–30 students. With increased demands outside of the education arena, obtaining this time commitment from faculty proved burdensome. Moreover, there has been an overall decline in the percentage of faculty with training...
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Urine volume (mL) *

Flow rate (mL/min) *

Specific Gravity *

Urine osmolality (mosm/L) *

Urine pH *

Urine glucose (mg/dL) *

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expertise, and interest in physiology during this “genomic” era in biomedical research (1, 11). Thus physiology laboratories that require active student participation and engagement in collecting and interpreting scientific results have yielded ground to passive learning techniques grounded in “more efficient” lecture-based approaches.

Reintroducing physiology experiments in an integrated curriculum. In our experience, no one lamented the loss of the exercises in the early years of adopting an integrated curriculum. However, based on faculty interactions in the classroom, during review sessions for major examinations, and during remediation, it seemed that students began to lack the practical knowledge and experience that comes from performing experiments compared with earlier classes that had a more traditional preclerkship curriculum with frequent physiology-based laboratory exercises. While core physiological concepts continue to be taught in didactic lectures, students seemed to struggle to translate an “academic” understanding of a concept like urination into an understanding of the practical aspects of the physiological process. For example, students routinely overestimated the parameters like the volume of a typical urine void.

Because of these perceived deficiencies, we began a concerted effort to reintroduce physiology experiments into the curriculum. Our first step was to design an experiment that would meet our initial goals and objectives, and test its feasibility and efficacy in meeting these objectives in a pilot trial. In implementing these experiments, we tried to adhere to three core objectives. We set out to design exercises that 1) illustrate a fundamental physiology concept in a practical way; 2) apply the scientific method to a problem or question; and 3) demonstrate the physiological rationale of a clinically relevant test. In addition to these core objectives, we sought to construct experiments that would engage student interest. Based on this initial experience, in the future we plan to pursue further experiments that would engage student interest and that could be executed easily with little specialized equipment.

Our first objective was to design an exercise that illustrates a common physiological (and clinically important) process. In our integrated curriculum, cardiac, pulmonary, and renal systems are taught together in a 9-wk module. One of the laboratory exercises that was not retained during curriculum integration was a renal physiology laboratory illustrating the role of antidiuretic hormone in regulating urine flow and concentration. Because of the importance of the renal system in everyday medicine and clinical practice, we set out to design an experiment to illustrate its physiology.

Our second objective was to design an experiment that applied scientific principles to answer a problem or question. Incorporated throughout the curriculum are presentations of experimental data that have led to the current understanding of renal physiology and current treatment strategies used in the clinic. Rather than forming a fundamental basis for effectively practicing medicine, students seem to view the core basic science principles as a necessary evil that they must remember to pass the national board exams. In part, this is likely due to the failure of both basic and clinical faculty members to help students make the connection between the two. However, the removal of laboratory exercises from the curriculum usually necessitates a prime focus on the outcome of experiments rather than the experimental process. Therefore, we focused on developing an experiment that would require the students to develop a hypothesis and expectations, with a clear plan to test the hypothesis.

Finally, laboratory testing remains a fundamental tool in identifying the basis of human disease (2, 10). Ultimately, laboratory tests are scientifically designed to probe specific physiological mechanisms; however, this is usually not discussed during didactic instruction. Typically, the results of clinically relevant tests that are essential for assessing physiology in a patient appear to be perceived as abstract ideas, rather than practical applications of the scientific method. Instead, the discussion of laboratory tests is typically focused on results in the context of pathology (i.e., if the test gives X result, suspect Y disease). Using this type of results-centered approach can lead to misinterpretation of test results, particularly when there are problems with the testing methodology. Our observations that students routinely struggled to give reasonable estimates of urine volume implied that students may have difficulty assessing data quality, a skill that can be uniquely practiced in a laboratory exercise. This project was reviewed by the USUHS Institutional Review Board and found to be exempt.

A case study: “drink & pee” laboratory illustrating renal physiology and body fluid homeostasis. We designed a new experiment that we hoped would engage student interest and that could be executed easily with little specialized equipment. The experiment was designed to compare the effectiveness of water vs. a typical sports drink in regards to the rate of hydration. We presented a case to students that the combination of water, sugar, and electrolytes in a standard sports drink increases the rate of water absorption similar to the principles of oral rehydration therapy. To illustrate the application of the scientific method, we set the stage for the experiment with a handout describing the following:

- The question: Does a sports drink get absorbed faster than water alone?
- The hypothesis: A sports drink will be absorbed faster than water.
- The experimental plan to test this hypothesis: We will use the rate of urine production and concentration to monitor fluid uptake.

This experiment clearly illustrates renal physiology and the concept of body fluid homeostasis. In addition, the exercise only requires a few materials. Each student received the following: one 120-ml urine collection vial, 10 urine test strips with color chart (Multistix 10 SG, Siemens), and a pre-prepared beverage (either 20 oz. bottled water or 20 oz. standard sports drink). We supplied the students with all of these materials and asked the students to perform the experi-

Fig. 1. Electronic data entry portal for home submission. Laboratory instructions and electronic data entry portal were supplied via a web page created in Google sites and hosted within our learning management system. Shown is the page containing the data entry portal. Data entered into this Google form were seamlessly transferred to a Google spreadsheet that allowed data aggregation and analysis.
The clinician also discussed the three components of a standard underlying mechanism of oral rehydration therapy for cholera. This review discussed the relevance of body fluid homeostasis and the uptake, the “clinical” portion of the review discussed. Since the exercise was focused on comparing water before beginning the experiment were also presented and uptake in the gastrointestinal tract, and physiological status in reading the test strips, variable rates of fluid ingestion, and caveats for the interpretation of the data, such as inaccuracies review the basic physiological principles leading to the results. The result of the experiment was reviewed during a laboratory wrap-up session that was co-led by a basic scientist and served to reiterate the core findings of the experiment and met the objective of illustrating kidney function and body fluid homeostasis.

RESULTS AND DISCUSSION

We have now successfully conducted the renal physiology exercise with two classes of medical students. In contrast to the expectations of many students, there was no significant difference in the parameters of urine production following ingestion of water or sports drink (Fig. 2). Based on our estimated changes in plasma solute concentration and data from pilot experiments, this was the expected result. It is notable that we could have expected to observe a change in the fractional excretion of H$_2$O; however, it is likely that the margin of error introduced by estimating solute concentration by eye abrogated any changes that we could observe. Nevertheless, the exercise met the objective of illustrating kidney function and body fluid homeostasis.

The results of the experiment were reviewed during a laboratory wrap-up session that was co-led by a basic scientist and a clinician. The “basic” science component of the review served to reiterate the core findings of the experiment and review the basic physiological principles leading to the results. Caveats for the interpretation of the data, such as inaccuracies in reading the test strips, variable rates of fluid ingestion, and uptake in the gastrointestinal tract, and physiological status before beginning the experiment were also presented and discussed. Since the exercise was focused on comparing water and sports drink uptake, the “clinical” portion of the review discussed the relevance of body fluid homeostasis and the underlying mechanism of oral rehydration therapy for cholera. The clinician also discussed the three components of a standard urinalysis, gross examination, dipstick analysis, and microscopic evaluation, two of which the students were instructed to perform in the exercise.

Illustrating the application of the scientific method and increasing student involvement. Our second goal was to design an exercise that applied the scientific method to answer a question or problem. The results demonstrated that there is no measureable difference in urine production or composition following ingestion of water or a sports drink. One concern that arose during the design of the experiment was that there was no difference between the groups. It was thought by some that the students might gain more value out of seeing an effect of the different intervention (i.e., water vs. sports drink). This might be true, and educational exercises are usually designed to elicit a clear difference with treatment or intervention. However, we
felt that the absence of an effect would be just as powerful. In establishing the experimental rationale and design, we clearly suggested that there were reasons to expect that a difference would be observed; even though we knew there would be none. Students are often presented with “positive” results (e.g., if \( X \) drug is given, \( Y \) occurs). We felt that this “negative” result was worthy of consideration, since it is probably a more typical finding in studies. In fact, we view this as a good aspect of this approach.

In the two iterations employed with students so far, we have provided the question, the hypothesis, and the experimental method to test that hypothesis. These were provided to students in the form of written instructions. There are significant benefits to performing the experiment this way. First, it is easy to obtain the necessary supplies for the students. Variations in the experimental protocol could lead to supplies going wasted or unused. We also have experience with performing the experiment in this way; therefore, we know what type of results to expect. However, it is likely that the students would benefit even more from participating in developing the experiment. After two iterations of this experiment in its current form, we are now trying to devise new ways to engage students in the design phase of the experiment.

In a discussion over lunch, two students expressed surprise that there was no apparent difference in the results. During the wrap-up session, student asked about the sensitivity of the experimental approach and other ways that body fluid homeostasis could be assessed. Some suggested that they would like to perform the experiment in other ways (e.g., following exercise) to see if differences between a sports drink and water emerge under these physiological circumstances. In future iterations of this experiment, we are considering presenting the students with historical data under resting conditions and generate their own testing scenarios to compare the results. This type of approach may be difficult logistically and may require some optimization. For example, the renal content is currently delivered over the course of \( \approx 2-3 \) wk. Requiring students to design, coordinate, and execute an experiment, while being presented with the relevant background information, may be too challenging. This approach would likely require a little bit more faculty input and oversight to ensure that students do not design experiments that deviate too far from illustrating the core concepts of renal physiology. Implementation of varied, student-designed approaches may also introduce additional logistical issues in terms of ordering the supplies necessary to carry out each research plan. Nevertheless, increasing student involvement in the scientific planning of the experiment remains an important objective.

In its present format, this exercise is amenable to modifications that could potentially expand or enhance its educational value. For example, one modification that we have seriously considered is to run the exercise as a “clinical trial.” In this formulation, we would provide students with a standard consent form as would be used in any standard clinical trial. The consent form would include a summary of the study, the expectations of the participant, and the risks and benefits of participation. This consent form would be used in place of the current instructional material describing the rationale for the experiment. Once students have agreed to participate, we would provide them with instructions for collecting the data. Review of the data in this case would be more directed toward the type of analysis that would be used in assessing a clinical trial. Students receive a robust series of lectures regarding statistics and clinical trial design. The data analysis could be conducted primarily by the students with faculty oversight. We could also ask students to generate new data and provide them with historical data to generate analyses that might be of interest (e.g., sex differences in the results). Conducting our exercise in this way could serve to reinforce the material delivered in statistics lectures by providing a student-led, practical implementation of the concepts.

**Erroneous results provide numerous teaching points and learning opportunities.** Our last objective was to use a clinically relevant test in the exercise. The purpose of this was to try to directly illustrate how the test and the test results relate to the physiology being measured. Urinalysis is almost an ideal way to accomplish this goal, since there is a direct correlation of urine volume with volume intake. The responses we observed were robust and illustrated the processes effectively. One of the most instructive parts of the renal exercise was the number of results that clearly deviated from the average response. Despite giving clear instructions that vigorous exercise should not be performed immediately before the renal experiment, several students apparently did not heed this instruction. As a result of mild dehydration following exercise, there was little effect of drinking either beverage on urine production or concentration (Fig. 3). While this was a frustrating result because students

![Fig. 3. Exemplar data that were included in the analysis and wrap-up presentation. This is an example of an individual data set that was presented as a physiological variation from the mean. A: urine flow rate was markedly reduced compared with the mean response (total urine volume during experiment = 108 mL). B: however, concentration measurements were maximal and unchanged during the course of the experiment. This result suggests that the student was dehydrated before beginning the experiment, representing a normal variation. During the laboratory wrap up, several students reported that they had exercised immediately before beginning the experiment, suggesting one possible explanation for this data.](http://advan.physiology.org/)
experiment uniquely exposed these problems and nearly one-third of the laboratory wrap-up was spent discussing why some results were clearly wrong, namely, because they did not make physiological sense, and reinforcing the idea that care in collecting and analyzing data is required to deliver the highest quality patient care.

Erroneous data sets were only addressed during the wrap-up session. We did not identify, seek out, or follow up with individuals who entered erroneous or false data. This represents an opportunity for improvement in future iterations of this exercise. Given the decline in the use of laboratory time in medical education as well as reports of several recent high profile cases of improper scientific conduct related to research, this observation emphasizes the need to formally address these issues as part of the learning objectives for these types of exercises. This sort of feedback and instruction should be framed as part of the competency of professionalism in medical education. Given that these types of exercises typically occur in the preclerkship phase of medical curricula, feedback directed at this phenomenon may serve an instrumental role in professional identity formation.

Student feedback and further study. Student feedback about these exercises has been generally positive. To assess student satisfaction and learning effectiveness, we created a brief survey modified from the Learning Effectiveness Survey. This survey included scales that assessed knowledge, skills, attitudes, learning effectiveness, and process improvement indicators. The survey was administered to learners after the experiment was completed and reviewed, although they were not compelled to complete the survey. Access to the survey was provided during the week before the final exam and was available for 2 wk after completion of the exam. A total of 23 learners (13%) completed the survey. This response rate invalidates any attempt to make statistical inferences on learners’ responses. However, on reviewing these responses, we were able to glean that, on average, our learners indicated that the

failed to follow instructions, the results at least made physiological sense and provided a talking point for consideration during the faculty-led wrap-up session, namely that patients do not always follow instructions.

There were also a number of data sets that deviated from the typical response, without any physiological explanation. What was clear from analyzing the results was that students paid little attention to the actual values, recording them in the data sheet without really understanding what they meant or, importantly, whether they made physiological sense. This led to the entry of data that were almost certainly erroneous (Fig. 4). For example, one student reported individual urine volume at a single time point of nearly 5 liters! There are a number of possible reasons for this kind of entry: failure to read the volume appropriately from a standard sample collection vial, inappropriate entry of the data into the data submission form, or making up the data. Fundamentally, however, what this illustrates is either carelessness or a relatively poor ability to correlate the results of a laboratory test with the underlying physiology. The number of flawed data sets was somewhat surprising to us. In the first class, 15% (26/174) of responses were rejected for being physiologically flawed; 16% (29/176) were rejected in the second iteration. There were no repercussions for these mistakes in this innocuous laboratory exercise. However, any one of these problems could result in poor quality care, or worse, in the clinic. The use of this laboratory

Fig. 4. Exemplar data of two data sets that were excluded from analysis but presented during the wrap-up session. This is an example of an individual data set that was presented during the wrap-up session as an erroneous record that was discarded from further analysis. A: reported urine flow rate was markedly increased compared with the mean response (total urine volume during experiment = 5,275 ml). B: however, concentration measurements were maximal and unchanged during the course of the experiment. If the urine flow rate had been as high as 60 ml/min, the urine concentration should have been significantly lower in a normal, healthy individual. Possible explanations for this result are misreading of volume on the collection vessel or mistyping of results into the data entry sheet.

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<th>Table 1. Qualitative feedback from students regarding at-home exercise</th>
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<td>• I believe that having results that are expected to deviate from the baseline are important to show the physiology behind that process, while using the baseline as a starting point for explaining “normal” fluid homeostasis. Overall, thank you very much for organizing this trial and offering the at-home assessment method! Please keep doing relevant laboratories like this—the explanations and opportunity to apply our lessons are fantastic!</td>
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<td>• I really enjoyed this experiment. It was a little time-intensive (the time between measurements wasn’t really productive) but I think it’s worth it. I was very interested in the final results and I would have liked to know more about why so many results were excluded from the analysis. It took a little getting used to the timing and interpretation of the dipstick but it wasn’t too difficult. I thought the instructions were clear and I appreciated having all the materials so easily available.</td>
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<td>• I find learning from experiments like this to be very helpful. I wish it was possible to incorporate more learning opportunities like this one into the curriculum.</td>
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<tr>
<td>• Great exercise! Keep doing it. The worst part was not being able to eat/drink for 2.5 h in the morning when you wake up (makes for a serious caffeine headache). I’d really have liked to see the effects of exercise, caffeine, ETOH &amp; NS. If that were the case I think students would volunteer to get IVs of NS in the MDL, but otherwise doing it at home is nice. I also would have liked to know how the rate of fluid intake affected the urine volume output. (Does chugging 2 L of water after a 5 mile run affect how the water is absorbed when compared to say taking a few sips every 1/2 mile?) The more variables you add, the more relatable it becomes to the students!</td>
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exercise promoted their understanding of the underlying physiological knowledge and skill principles "somewhat" to "quite a bit." The majority of students found it to be "moderately true" to "quite true" of themselves when asked about attitude indicators aimed at assessing their beliefs about the value of the laboratory exercise. Almost all students who responded indicated that the directions and relevance of the laboratory was high (process improvement indicators). Only one student felt that the laboratory should not be required for the following class. No student indicated that the laboratory would be better conducted on campus compared with at home. A sample of free text submissions is provided in Table 1.

Conclusion. In summary, we described our reimplementation of physiology laboratory exercises into the recently integrated preclerkship curriculum at USUHS. By developing exercises that illustrate normal physiology using the scientific method and applying a standard clinical laboratory test, this type of approach ties together many basic and clinical concepts in an integrated manner. Conducting this type of exercise using a clinically relevant laboratory test has helped to bring together the material in a practical way to illustrate the relevance of physiology to the clinical setting and the role of scientific analysis in clinical approaches. Our case study also revealed critical deficiencies in student ability to process and interpret laboratory data. This type of interactive physiology laboratory provides a unique opportunity for students to practice this skill. Student feedback suggests that they want more of these types of opportunities, and we are currently designing more of these exercises for other portions of the preclerkship curriculum.

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

DISCLAIMERS
The views expressed in this paper are solely those of the authors and not necessarily the views of the Uniformed Services University of the Health Sciences, the US Air Force, or the US Department of Defense.

AUTHOR CONTRIBUTIONS

REFERENCES