Curricular Integration of Physiology

Team-based, problem-solving exercises using studies of diarrhea and oral rehydration encourage students to integrate knowledge of systems physiology

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Abstract

We describe an inquiry activity that aims to develop students’ ability to interpret findings that span whole body systems and so encourage the integration of knowledge. The scenario we choose was the physiological challenge posed by diarrhea and the physiological mechanisms that underpin oral rehydration therapy. Before the staff-facilitated inquiry activity, students engage with an online information resource and complete a formative, but mandatory, prelaboratory quiz. These tasks encourage students to develop some mastery of the relevant physiology before the timetabled inquiry activity. The 3-h inquiry activity is driven by a paper workbook containing data from published studies, mainly from veterinary physiology, of the various consequences of diarrhea. Figures from published data are arranged so that, initially, the impact of dehydration on a single system (the cardiovascular system) could be appreciated. Integration with other systems (respiratory and renal systems) is then introduced progressively through the activity. The exercise is designed as a team-based inquiry activity that emphasizes the value of discussion to identify appropriate features for interpretation of the data. Students are obliged to complete a postlaboratory quiz within 5 days of the inquiry activity, serving to consolidate the students’ learning and provide staff with feedback on the attainment of intended learning outcomes. Marks from formative pre- and postlaboratory quizzes typically have a median mark in excess of 80% (pass mark is 50%), and qualitative feedback suggests that the majority of students recognized the value of the activity, despite simultaneously reporting that it was intellectually demanding.

active learning; gastrointestinal; problem solving; systems physiology; team-based learning

BACKGROUND

We outline and discuss a team-based, active learning activity that makes use of the fluid, electrolyte, and bicarbonate loss in diarrhea to explore how the responses of different physiological systems (specifically, cardiovascular, renal, respiratory, and gastrointestinal) interact to maintain function and preserve life. The activity was developed initially for veterinary science students but has been adapted for medical students and would work also for undergraduate physiology students.

Almost universally, systems physiology is taught in distinct and separate blocks, much the same in structure as chapters of a textbook and therein lies a hazard; that students will struggle to make the connections necessary to appreciate the integrated reality of the physiology of the animal as a whole. Staff often make assumptions about what is learned from what is taught, but Dewey warned against this in his essay “How we think,” published over 100 yr ago:

“Teaching and learning are correlative or corresponding processes, as much so as selling and buying. One might as well say he has sold when no one has bought, as to say that he has taught when no one has learned.” (1)

In 1966, West offered an even more focused commentary on the focus on teaching over learning. Based on the findings of several studies, he notes:

“In these careful appraisals of the curriculum in action it was found that students were often well taught but always under challenged. The teachers found it difficult to resist teaching.” (2)

West’s article stands reading in full as elsewhere he reflects that:

“Some of the pressures which lead to an overemphasis on instruction come from the students. At the time they begin their clinical education, they have been graded for years almost exclusively on the basis of what they know and not on their capacities for identifying and solving real problems. Most of them don’t want to be challenged; they want to be taught.”

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Notwithstanding what we might imagine the direction of travel in university learning and teaching to have been since 1966, the same universal truth applies, that scientific knowledge has the potential to improve our capacity to understand new problems and work rationally toward solutions. With the above points firmly in mind, we developed an inquiry activity within a block of teaching on gastrointestinal physiology. Our aim was to encourage teams of first-year students to interpret figures from journal articles and recognize in these figures the links between key elements of cardiovascular, respiratory, renal, acid-base balance, and gastrointestinal (GI) physiology, through recall and application of knowledge gained from formal teaching sessions and independent study. In the UK, the term “integration” is often used in relation to the cognitive effort of making links between elements of learning that are taught separately, echoing chapters in a textbook but are in practice closely and intimately linked. This is not to be confused with the meaning of integration implied by the Edinburgh Declaration (1988) in which integration means only that things that could be taught separately should be combined:

“Integrate education in science and education in practice using problem solving in clinical and community settings as a base for learning.” (3)

UNDERPINNING EDUCATIONAL THEORY

Learning that involves the active participation of the learner is now universally regarded as superior to learning passively from the exposition of an expert teacher (4, 5). It is also becoming clear that explaining one’s reasoning is formative for both student and teacher alike (6) and that students can facilitate the learning of student peers in meaningful ways (7, 8). In the context of a medical education, the capacity to successfully develop clinical reasoning skills is greatly facilitated by mastery of systems physiology (9) and the adoption of appropriate mental models for understanding (10). Work over several decades is consistent; learning to master complex and uncertain knowledge and using it to solve problems and test new evidence requires purposeful practice with well-designed activities and staff who, to quote West, “may guide, direct, or stimulate the student; but do[es] not push, pull or carry” (2).

RELEVANT PHYSIOLOGY

The oral rehydration activity was developed first for the veterinary science students, as a replacement for two gut bath experiments that were part of the gastrointestinal physiology teaching in their first year of study. It was felt by teaching staff that gut bath experiments focused attention on details of smooth muscle regulation and did not cultivate a wider appreciation of interdependence of physiological systems.

We choose diarrhea because it is an important clinical problem for any clinician and its effects can be seen in cardiovascular, respiratory, and renal physiology, making it an excellent vehicle to illustrate the interconnectedness of these body systems. Fundamentally, diarrhea is a disorder of fluid and electrolytes resulting from an imbalance of secretion and absorption in the GI tract that sustains an abnormally high fluid loss in the feces (11). When prolonged or extreme, the excessive water loss in diarrhea can result in a clinical crisis and understanding this process is important in the context of choosing appropriate clinical actions.

MATERIALS AND METHODS

The inquiry activity is focused on a workbook (see Supplementary files at https://doi.org/10.6084/m9.figshare.1413589.v1) containing data from studies published between 1967 and 2009 (12–20). Students are each provided with a copy of the workbook and work in groups of three or four. Before the inquiry activity all students complete a prepractical quiz composed of questions that probe the students’ ability to recall and apply relevant material from cellular physiology as well as cardiorespiratory and renal physiology and hence encourage engagement with support materials that provide a foundation of knowledge on which to build during the inquiry. Meaningful engagement with support materials and the prepractical quiz should enable students to appreciate the links between the knowledge they have acquired throughout their first year of undergraduate study. Within 5 days of the activity, students also complete a postpractical quiz composed of questions that aim to consolidate students’ understanding of the impact of diarrhea on the different body systems already mentioned. The pre- and postpractical quizzes do not carry summative credit but are individually badged as “must pass” which in the UK means a score of 50% or higher.

The workbook consists of 15 figures and tables, taken from 5 journal articles and 2 textbooks. The figures are ordered so that learning from the early figures is useful in the interpretation of the later figures and, as a whole, the figures highlight the physiological challenges precipitated by diarrhea and the evidence supporting the development of oral rehydration solutions (ORS) that are hyperosmotic (21). The first four figures in the workbook are reproduced from a single article (16) and highlight the impact of diarrhea on blood volume, lactate, pH, and osmolarity. For each of these four figures in the workbook and for several others, the groups are instructed to “Describe and explain the changes you see here.” Over the years we have learned to make an example of the first figure. We give the groups 3 min to discuss and come to a consensus about how to describe and explain the first figure (Fig. 1).

Typically, a group volunteers a description and explanation that is close to ideal. Regardless, staff are at pains to stress that the description of any figure should take account of the axes; in Fig. 1 in the workbook these are percent change (in the positive direction) and time in hours, so groups are expected to describe an increase in both packed cell volume and plasma protein concentration that is more or less linear over the 60 h of available data. The key factor for a relevant explanation is the short period of time which rules out meaningful increase in the number of red cells or plasma protein. Thus the most reasonable explanation is a reduction in plasma volume so that a similar volume of cells [cell volume will change in proportion to any change in osmolarity (22)] and a similar quantity of plasma protein is distributed in a smaller volume of plasma. The key outcome
at this stage is that the teams connect their explanation to the physiological significance, in this case a relatively large contraction of blood volume, hypovolemia. This is important because hypovolemia resulting from hemorrhage is the focus of a separate physiology demonstration that makes use of our human patient simulator teaching resource (23) and making this connection helps students appreciate both the consequences of volume contraction on cardiovascular function and the primary aim for any treatment.

Throughout the exercise, students are encouraged to look for overall trends and not to be overly fixated on individual data points that might be displaced from what is otherwise a trend.

In the second figure in the workbook (Fig. 2), limb temperature is stable at ~37°C but begins to decrease after the indicated start of diarrhea. A steeper (more rapid) fall in temperature is observed for the feotloc which is distal to the hock. Students are apt to become fixated on the last data point for core (rectal) temperature which shows a sharp fall. In such cases we advise application of the “thumb” test. This involves hiding the offending data point with a thumb and looking at the remaining points. This does tend to help but often there is no satisfactory explanation in the article. One might imagine that some of the animals are very sick and normal homeostatic variables are beginning to fall out of active control. A normal level of metabolism will eventually be unsustainable and both metabolic rate and body temperature will begin to fall.

Figures 3 and 4 in the workbook (see Supplementary files at https://doi.org/10.6084/m9.figshare.14113589.v1) highlight changes in lactate, plasma osmolarity and pH. Together, the first four figures in the workbook highlight the key disturbances associated with diarrhea, in particular a contraction of blood volume and evidence of peripheral vasoconstriction, the absence of a change in osmolarity (Table 1), a fall in both plasma and intracellular pH and an increase in lactate. The increase in lactate merits comment. The literature suggests that diarrhea is associated with increases in both D- and L-lactate though the proportions vary. D-lactate is indicative of microbial fermentation whereas L-lactate could derive from both mammalian and microbial metabolism (24). The key point for students to work towards is to equate the temperature changes in Fig. 2 in the workbook with baroreceptor reflex driven peripheral vasoconstriction. Students will already have worked through the cascade of effects starting with hypovolemia, reduced central venous pressure, reduced end diastolic volume, cardiac output and arterial pressure, and so vasoconstriction and raised heart rate are easily rationalized. The short-term solution, that most teams quickly identify, is anaerobic glycolysis that has lactate as an end product. By this point in the activity, with the encouragement of the teaching staff, teams are actively sharing and discussing ideas and explanations, and our observations are consistent with reports showing peer learning to be a highly effective model for learning (8).

Figures 5–10 in the workbook (see Supplementary files at https://doi.org/10.6084/m9.figshare.14113589.v1) were taken from a study (18) that compares the efficacy of three different oral rehydration solution (ORS) formulations in the treatment of diarrhea in calves inoculated with the same strain of *Escherichia coli*. The table that appears as the fifth figure in the workbook (see Supplementary files at https://doi.org/10.6084/m9.figshare.14113589.v1) provides the teams with the composition of each of the three commercial formulations and importantly includes the composition of cow’s milk, from Constable et al. (12). In this part of the exercise, the learning aims changes from identifying the physiological challenges (hypovolemia and acidosis) to evaluating research that compares the effectiveness of three rather different formulations of ORS in correcting plasma sodium concentration, blood plasma and extracellular volumes, and blood pH. Figure 3 is reproduced from Curran et al. (13) and serves to remind the students that water is absorbed from the gut as a consequence of the prior and coupled absorption of solutes, principally sodium together with either glucose or specific amino acids (25).

This fundamental observation of sodium-coupled solute transport is the foundation of oral rehydration therapy (ORT) and so the point made is that drinking water (or milk...
in the case of these calves) alone is a poor strategy to rehy-
drate and restore electrolyte balance after diarrhea.

The next section of the workbook focusses on the factors
that appear to determine whether an animal rises to the
physiological challenge of fluid loss due to diarrhea and sur-
vives, or not. The key data are reproduced from a study (14)
in which calves were inoculated with an enterotoxic strain of
E. coli to induce diarrhea. Daily blood samples were taken,
but the animals were untreated and unfed, although access
to water is not specified. The data were analyzed after the
animals had been divided between outcomes of die and sur-
vive. This article raises important moral and ethical ques-
tions, given that the animals are not recruited after chance
infection but rather deliberately infected, and some students
do question how veterinarians could take samples but other-
wise make no intervention. The key panels that appear in
the student workbook are reproduced here (Fig. 4).

The utility of the data from the study of calves that sur-
vived or died is that there is sometimes much to learn from
the differences between animals whose physiology can com-
promise for a given disturbance, and who go on to survive,
and those that die and so may be expected to exhibit a failure
of compensation.

In Fig. 4, top left, the levels of urea and potassium are
markedly elevated in the calves that die. Rising urea clearly
signals a relative failure of renal function. The rise is potas-
sium is less diagnostic of renal failure, but it is clearly quite
different from the response of the animals that survive.
Similarly, the bicarbonate and PCO2 levels differ between
the groups. Along with these data are reproduced the first of two
textbook figures that provide a framework for understanding
the distinction between respiratory and metabolic acidosis
and the homeostatic changes in ventilation that might be
anticipated (Fig. 5).

The final series of figures in the workbook are taken from
a study of the changes in renin, aldosterone and arginine-va-
sopressin during diarrhea in calves (19). These figures are
provided along with an explanation of their meaning, but
with more time for the activity (currently 3 h), it would be
preferable for students to associate the challenges (dehydra-
tion and acidosis) with changes in hormone levels.

The final task the students complete during the activity is
to write a holistic summary of what they have learned to-
gether. The following text is provided to help the teams
understand the scope and focus of their summary:

“Write a brief summary of what you understand of the
effects of diarrhea (dehydration and acidosis). In par-
ticular, you should explain what charts and Tables 1
through 15 (pages 3–7) collectively tell you about the
impact that diarrhea has on the body water and its dis-
tribution, on the cardiovascular system, on renal
function and on acid-base balance.

You should conclude by summarizing the cellular
absorptive mechanism(s) that underpin the use of
ORT and explain the rationale for the relatively high
of glucose and potassium.”

This summary is the main and final focus of the teaching
staff as all teams must use this text as notes as they work to-
together to explain their learning to staff before leaving the ses-
sion. It is instructive how easily gaps in knowledge and
misunderstandings can be identified from a short discussion
of such a summary. Within 1 wk of the activity students must
individually complete an online postlaboratory quiz that
requires an understanding of the physiology gained from the
activity.

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**Table 1. Summary of the principal classifications of dehydration in the context of diarrhea in calves**

| Isotonic     | Blood Sodium (Normal Range: 130–150 Mmol/L) | Osmolarity (Normal Range: 275–295 mosmol/L) | Cause (in Context of Young Calves) |
|--------------|-------------------------------------------|-------------------------------------------|-----------------------------------|
| Hyponatremic | Low                                        | Low                                       | Greater loss of sodium than water. Typically seen when isotonic dehydration is followed by drinking large volumes of low sodium fluids (water, milk). |
| Hypernatremic| High                                       | High                                      | Disproportionate loss of water over salts. Can be caused by osmotic diarrhea but also sweating and panting. Not typical for diarrhea in calves. |

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**Figure 3.** Reproduced from Curran et al. (13) showing that the transport of alanine (from the luminal surface) was augmented in the presence of extracellular sodium. Similar studies using the same inverted sac preparation provided evidence for sodium-coupled transport of some amino acids and glucose.
RESULTS

The ORT activity has been a part of the first-year veterinary curriculum for ten years and its value been recognized by students, “The practical on oral rehydration practical was useful for integrating information and understanding” (Student feedback, 2018) and by staff who act as demonstrators. In 2018–19, 150 first-year veterinary students completed the exercise (75 in each 3-h session) with guidance from four staff.

Students complete two online quizzes, one before and one after their laboratory work. These quizzes do not carry any marks but are regarded as “must pass” tests and these pre and postlaboratory quizzes have completion rates close to 100%. The questions used are either multiple choice format, typically with one correct option, or else require numeric responses. Questions in the prelaboratory quiz are designed to encourage students to consider the structure and function of the gastrointestinal tract, the distribution of body water, and key electrolyte levels; examples are shown in Fig. 6.

The great value of the prelaboratory tests is that it encourages a level of preparatory work on the part of the students. Students do not always appreciate this at the time, as is clear from this feedback comment:

“We all grumbled about having to do the pre-pracs to start with, but I do get a lot more out of the practicals because of the extra bit of prep.”

The postlaboratory questions can revisit these same topics but also test the students’ ability to integrate between organ systems, for example to connect the acidosis, resulting from bicarbonate loss and lactate build-up from anaerobic metabolism, with hyperventilation. Examples of the postlaboratory questions are provided in Fig. 7.

Marks for the quizzes for the most recent academic session were 83.4% (range 50 to 100%, n = 149) and 80.4% (range 50 to 100%, n = 148) for the pre- and postlaboratory quizzes, respectively. Students require an average laboratory practical mark of 50% or better to pass the practical element of the physiology course.

Marks are a relatively dull measure of anything, but meaningful engagement is hard to measure, despite being obvious to any observer. For staff, the purposeful buzz in
the workshop is indicative of engagement and is echoed in this note received from a student shortly after one of the sessions:

“I thought the session was incredibly useful, as it not only brought some clinical relevance to what we were learning about it also encouraged us to discuss our interpretations with friends, which seems to help people learn more effectively. With regard to it being too long, I don’t think this is necessarily the case, although we were exhausted when we’d finished, I found it more rewarding than anything else to have completed it!” (Student email, 2012).

This observation is discussed in the context of what constitutes active learning.

## DISCUSSION

We began with a goal to develop a gastrointestinal focused exercise for veterinary students that would help integrate knowledge and skills. To develop clinical reasoning skills, we aimed to create something superior to a typical organ bath experiment, or a crude computer simulation of radio-isotope studies of solute transport. This quest eventually led to the inquiry exercise outlined here. We were fortunate to have trained veterinarian colleagues whose experience and intuition suggested that this approach would be fruitful and who actively contributed to its development. Subsequently, we have found support from argument and experimental evidence. For example, West, writing in 1966, suggests that “... it will be appropriate to place greater emphasis on helping the student to develop an ability to gather and evaluate evidence.” West’s reasoning relied on observation of trends he felt made the instillation of a capacity to learn imperative. To summarize his points:

- There was already too much medical knowledge to be learned.
- Knowledge that emerges during a career is as yet unknown (so cannot be taught).
- Much of what is taught is not learned.

- There is some error in what is currently taught.
- Some of what is taught will become obsolete.
- Specialization will render some learning irrelevant.
- A large part of what is learned is forgotten, save for a residue.

The oral rehydration activity qualifies as an inquiry activity (27), a form of “active” learning shown to have benefits over mere instruction of the concepts, mechanisms and facts (28–30). It is reasonable to ask what it is about active learning that makes it effective. In his review, Prince (31) identifies two key factors, activity of the learner(s) and engagement in the process of learning. It is important to understand that “activity” must have purpose and value, as Prince points out, “activities must be designed around important learning outcomes and promote thoughtful engagement on the part of the student” (31).

Thoughtful and active engagement in a learning activity is obvious and easily recognized but hard to measure, and so proxies such as examination outcomes or retention rates are often used (4). We occasionally seek qualitative feedback from students by asking them to write comments under headings such as “good” or “for improvement.” Students tend to write comments such as:

- “Very good at helping me understand and figuring out how things work and link together. Nevertheless, full-on! My brain hurts!”
- “It was hard to grasp some concepts and took us a long time to complete the booklet but ultimately it was really helpful and made us genuinely think and understand.”

Other students are more critical and request more teaching by staff:

- “Recorded explanations on *Blackboard* [our virtual learning environment].
- “Maybe provide a sheet of material for revision with all links and processes.”
- “Would be helpful for an answer sheet to be released post-practical.”
- “A little more guidance in the form of notes.”
- “After the session provide us with a mind map that shows how all the processes link.”

Figure 5. An algorithmic cascade to recognize the hallmarks of simple (or non-mixed) acid-base disturbances that appears as Fig. 13 in the student workbook. (Reproduced with permission from Ref. 26, Fig. 10.5).
The practical was too long and not guided enough as we've not done anything like it before. Need to find some formal way of reviewing/marking it as I still have no idea about some of it and as no answers [provided], have no way of finding out.

These latter comments are typically anonymous and so we have no way to equate the nature of the comments with degree of application of the individual students.

There are distinct differences in the student's comments about the learning they are encouraged to do in preparation for laboratory sessions. Some students are highly positive:

- "Pre-practical quiz—helps because it motivates me to prepare for the practical."
- "I find the pre-practical quizzes useful as they encourage you to read the practical schedule before the practical and so you have a better understanding of what it is you are required to do."
- "As a whole I found them [quizzes] helpful as made me think through material covered in lectures and practicals."

Others were more critical (often of staff):

- "Might be good to emphasize how important the pre-lab work is so that we're fully prepared."
- "Don't like [that] it [quiz] doesn't take an average as often with the maths it would be good to go over it twice but once was only allowed."

Figure 6. Examples of typical prelaboratory questions and associated feedback.
Pre-practical quiz for ORT practical didn’t fully relate to this practical (didn’t inform us that we needed previous notes).

“Found the info interesting but didn’t feel it necessarily helped complete the practical any quicker.”

It is tempting to conclude that students who reported that they learned little were those of either failed to engage thoughtfully during the activity, or else felt their knowledge of the relevant systems was too poor or fragmented. This conclusion is supported by a comment, obtained as feedback after the activity:

“The content wasn’t entirely unexpected, but it did involve good knowledge of previous lecture series covered by other lecturers. I know that, personally, my retention of these lectures isn’t particularly high until just before exam season where I’ll go back over everything (not the best method, I know, but obviously very common amongst most people). With this in mind, trying to apply knowledge that I think may be correct but can’t quite remember for a good deal of the practical was somewhat stressful.”

The impetus for introducing the prelaboratory quizzes across all our degree courses was a desire that students would derive the best value from their time in the laboratory (32). As laboratory teaching is by far the most expensive form of student engagement, and the largest in terms of raw contact hours, staff are obliged to consider both cost and benefit. The development of inquiry activities that are designed to focus on core concepts and fundamental knowledge and that involve students working collaboratively in the same space and time (not virtual), and with the guidance of experienced staff, has been shown to be highly effective (28, 33, 34). The effort required for students to articulate their understanding has also been shown to improve learning (6). Our experience suggests that the requirement for teams to articulate what they have learned is especially valuable for staff who have the responsibility to ensure that the key learning aims have been satisfied.

While this activity was developed for veterinary students and makes use of studies published in veterinary journals, we have successfully adapted it for use in our medical curriculum (see Supplementary files at https://doi.org/10.6084/m9.figshare.14113589.v1). Moreover, it is possible to design variety of extension activities that would be useful for any student group. Students could be asked to speculate on the influence of environmental factors such as the temperature, humidity, and access to fluids as well as comorbidities such as the impact of simultaneous fluid loss from vomiting.

In conclusion, staff invest a great deal of effort in teaching but the general declining opportunity for face-to-face interaction between staff and students means that staff are less well informed about what learning is being mastered by students or the approaches the students take in their learning. This distancing between staff and students is one of the costs of the expansion of higher education although we may try to convince ourselves that online learning resources more than make up for the reduced opportunity for face-to-face discussion. Inquiry activities that engage small groups of students in a shared and collaborative challenge to make sense of observations that require consideration of multiple body systems appear to make excellent platforms for deep and meaningful learning.
DISCLOSURES

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

AUTHOR CONTRIBUTIONS

P.D.L. analyzed data; P.D.L., F.M.M., and Z.J.P. prepared figures; P.D.L. drafted manuscript; F.M.M. and Z.J.P. edited and revised manuscript; P.D.L. approved final version of manuscript.

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