GUIDED DEVELOPMENT OF INDEPENDENT INQUIRY IN AN ANATOMY/PHYSIOLOGY LABORATORY

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Student-originated projects are increasingly utilized in the biology laboratory as a means of engaging students and revitalizing the laboratory experience by allowing them one to two weeks to collect data on a manipulated variable of their choice by use of an introduced technique. Such experiments fail as good models of investigative learning when they place more emphasis on novel ideas than on hypothesis testing, experimental design, statistical rigor, or use of the primary literature. In addition, students get used to the routine and tend to design the same type of simplistic experiments in each course unless challenged. Laboratories in a Comparative Anatomy and Physiology course at the University of St. Thomas were reorganized to encourage the development of investigative skills in a stepwise fashion throughout the semester. Initial labs concentrated on experimental design and statistical analysis, then use of the primary literature in interpretation of the data was emphasized, and finally, students were asked to design their experiments and analyze their data on the basis of models from the primary literature.

ADV PHYSIOL EDUC 27: 230–240, 2003; 10.1152/advan.00002.2003.

Key words: inquiry-based laboratory; physiology laboratory; student-originated project

In the past decade, science educators have begun to put more emphasis on the process of "doing science" with problem-based learning activities in the classroom and independent investigations in the laboratory (1, 4–7, 9, 11, 13–16). This approach encourages students to be active learners who are more fully engaged in their classes and who are modeling how science is done while they are learning (see examples in Refs. 8, 10, and 11). Almost by definition, the laboratory experience *should* be an active learning environment, but the learning aspect may be reduced when students faithfully follow the steps in an instructor-designed lab exercise without understanding or wondering why they are doing what they are asked to do. Incorporating discovery-based activities into the laboratory not only mimics more accurately the real work that scientists do but initiates the development of independent, critical, and analytical thinking and research skills that we expect of college graduates (1, 4, 7, 16).

At the University of St. Thomas (St. Paul, MN), we have incorporated student-designed projects into all levels of the undergraduate biology curriculum, where they are referred to commonly as DYO (design-your-own) projects. Once students learn the routine of the DYO type of biology laboratory experience (as early as first semester freshman year; see Ref. 1), the learning potential of this unique experience tends to become diluted as students progress in the curriculum and the DYO experience becomes "old hat." Unless sufficiently motivated or encouraged, students tend to perform DYO projects in each of their biology courses at about the same level of sophistication as in their introductory core course. In this report, I describe how a reorganization of the course content of intermediate level Comparative Vertebrate Anatomy and Vertebrate Physiology courses at the University of St. Thomas has facilitated the use of inquiry-based activities in the laboratory and enhanced acquisition of research skills by the students beyond their initial DYO experience.

INTEGRATED ANATOMY AND PHYSIOLOGY LABORATORIES

With the assistance of an Instrumentation and Laboratory Improvement (ILI) grant from the National Science Foundation awarded in 1996, my colleague Dwight Nelson, a neurobiologist, and I redesigned our two intermediate-level majors' courses, Comparative Vertebrate Anatomy and Vertebrate Physiology, combining them into a two-semester, nonsequenced, fully integrated curriculum. The primary motivation for this reorganization was to avoid the redundancy of topics we found in teaching functional morphology in Comparative Anatomy and the morphological basis of physiology in Vertebrate Physiology, often to the same pool of students in successive semesters. After reorganization, one semester ("Brains and Brawn") now focuses on skeletal, muscular, nervous, sensory, and endocrine systems and integrates the evolution of vertebrates and embryonic development with the comparative anatomy and physiology of the five major systems. The other semester ("Blood and Guts") focuses on cardiovascular, respiratory, renal, and digestive systems, integrating the evolutionary history, development, histology, comparative anatomy, and physiological functions of those four organ systems, with some review of nerve and endocrine function at the beginning of the semester. Teaching only four to five organ systems in a semester-long course means that we can go into much greater depth, using case studies or discussions of primary-literature articles in the classroom. It also means that we have approximately one month of labs in each unit, sufficient time to develop laboratory exercises around a single theme for each unit. It also allows time for student-originated projects, which enhances the active learning component of the lab (see Table 1 for course schedule).

During the first two years I taught the reorganized Blood and Guts course, I followed a static formula in the lab portion of the course, marching through the organ systems from cardiovascular to respiratory to renal to digestive. Each unit consisted of an anatomic dissection of the organ system during the first week, introduction to a physiological technique and classical physiological recording during the second week, followed by a two-week period for student-originated projects, which culminated in either a written formal scientific report or an oral formal presentation of the project to the rest of the lab section. However, four repetitions of this highly structured format became boring, the enthusiasm for student-originated projects waned by semester's end, and I found that students were not really improving in their experimental design skills, in the sophistication of their measurements or analysis over the course of the semester, or in their ability to use the primary literature in their scientific writing. This led me to rethink how I could use the lab periods better to promote the development of the skills critical for independent research by more directly guiding the students in inquiry-based lab activity.

What were the most obvious deficiencies in their investigative laboratory skills?

- Finding appropriate primary literature on which to base their projects
- Reading and interpreting the primary literature to formulate testable hypotheses
- Posing interesting questions to investigate
- Designing experiments with some complexity and sophistication
- Gaining competence in analyzing data for a sophisticated experimental design that might utilize nested units and two-way nested ANOVA
- Thinking more deeply than the obvious statistical comparison (e.g., the mean of this treatment was greater or less than the control) to look at the underlying meaning of variability in the data or in the shape of the response curve (e.g., why is one

TABLE 1
Schedule of lecture and laboratory topics and associated objectives for the laboratory in Comparative Anatomy and Physiology II at University of St. Thomas

Week	Lecture Topic	Stage	Lab Topic	Objective for Guided Inquiry	Instructor Role
1	Nerve and endocrine physiology	*Step 1*	Statistics	Analyze sample physiological data; choose the appropriate statistical tests	Provide overview of statistical analysis and worksheet of sample problems related to physiology
2–3	Gastrointestinal physiology	*Step 1* (cont.)	Gastrointestinal tract dissections; comparative morphology	Choose appropriate experimental groups and sample sizes as a first step in experimental design to answer a question	Facilitate choices of experimental subjects that will enable students to test a hypothesis about GI structure/ function
4–6	Renal physiology	*Step 2*	Urogenital anatomy/ histology; gerbil osmoregulation experiment	Conduct higher-order data analysis; use primary literature to interpret and compare with results; write a paper in scientific format (group)	Model sophisticated experimental design; illustrate deeper levels of data and graphical analysis; demonstrate how to use primary literature in interpretation of results; provide in-depth feedback on papers
7–8, 10–11	Cardiovascular physiology	*Step 3*	Circulatory anatomy and bloodflow; ECG experiments	Use primary literature to design an experiment based on a demonstrated technique; write a paper in scientific format (individual)	Critique experimental design based on background research; encourage deeper analysis of results; assist with interpretation of results and comparison with data in the primary literature
12–14	Respiratory physiology	*Step 3* (cont.)	Metabolic rate and Pulmonary function tests; respiratory physiology experiments	Use skills from all preceding units: experimental design, data analysis, and primary literature research to conduct an original investigation; present findings at a mock research symposium	Model a research talk at a scientific meeting; assist students with experimental design and analysis as in *step 3* above

population so much more variable than another or why is a response nonlinear?)

- Writing formal scientific reports that used the primary literature appropriately in the introduction to the question and the discussion of the results

To address all of these deficiencies in just the lab portion of a course in one semester is a tall order. However, after revising the goals of each lab unit separately, I redesigned the laboratory curriculum with the goal of building skills in an incremental fashion throughout the semester, providing more structure and direction in experimental design at the beginning of the semester, but relaxing that control to give students more control toward the end of the semester.

GUIDED INQUIRY AS A MODEL FOR INVESTIGATIVE LABS

The steps involved in guiding students to achieve a more sophisticated product in their laboratory investigations are briefly described in Table 1 and discussed in detail below.

Step 1. Choosing experimental subjects and performing statistical analysis. The first lab of the semester employs a statistics exercise designed to introduce students to descriptive statistics, comparison of means, analysis of variance, and regression by use of physiological examples. Because most of the students have had some exposure to statistics in their introductory-level courses or in a statistics course, this may be largely review for some, but the use of physiological examples gives students a preview of the kinds of experiments they might think about in the future. For example, one question in the statistics exercise asks students to analyze the relationship between respiratory characteristics (tidal volume and respiratory rate) and running speed in male and female subjects. These data were obtained from student subjects in previous physiology courses. Beyond simply gaining an understanding of regression analysis in examining these responses, students also get a glimpse of what others before them have attempted in this course.

During the next week of lab, we start the first unit, the digestive system. Instead of only dissecting sharks, frogs, rats, and cats just to identify organs, this lab also focuses on analyzing structural relationships between the digestive tract components (foregut, midgut, hindgut) in three types of carnivores and one herbivore. After the dissection, the rest of the lab period is devoted to learning more about gut morphology among different vertebrate groups and different feeding specializations by researching and reading primary and secondary literature sources on these subjects. The purpose of this exercise is to help students become more efficient and critical in their search for appropriate reference material. Many students are unaware of the electronic database resources available to them and automatically go only to PubMed to look for primary literature. This would obviously be a poor source of references on comparative vertebrate gut morphology, so students follow a more directed search, using a handout on literature searching that I provide, through some of the databases with which they are less or not at all familiar, e.g., BioAbstracts, FirstSearch, Agricola, ScienceDirect, Carl Uncover, etc. A secondary goal of this exercise is to help them see how they can design an experiment the following week based on what they read during lab about comparative gut structure and feeding specialization in vertebrates. During the last week of this unit, students design a test of a hypothesis based on their reading by analyzing structural components of vertebrate digestive tracts illustrated in *Comparative Physiology of the Vertebrate Digestive System* (12). In making choices of appropriate groups to compare and appropriate species to include within a group, students refine their experimental design skills. After deciding how many species and how many groups to include in their analysis, students perform the appropriate statistical comparisons (with some guidance), which reinforces the statistical analysis exercises done two weeks earlier. After graphing and tabulating their results, students give a brief presentation to the rest of the lab groups, including some background for the basis of their comparison, methods of comparison and statistical analysis, and results. This lab exercise provides a very basic introduction to the skills that I expect to be refined and developed in succeeding lab units.

Step 2. Introduction to experimental design and use of primary literature. The second lab unit, on renal physiology, investigates osmoregulation in gerbils and was initially developed around a set of core papers from the primary literature on salt and water balance in gerbils (2, 3). This lab unit is probably the most important one of the semester, because it models a more sophisticated type of investigative inquiry expected of student-designed experiments in this course (i.e., going beyond the DYO of introductory-level courses). The goals of this lab are severalfold: to introduce the type of complex experimental design students should emulate; to learn classical techniques for measuring animal water balance, quantitative electrolyte and urea analysis (and use of standard curves), and osmometry; to instruct students in animal husbandry and handling; to examine a large data set, find and choose trends to analyze statistically, and perform the appropriate statistical and graphical analyses; and to critically read, analyze, and incorporate the primary literature into formal written scientific reports.

The primary outcome of this experiment is the observation of the change in renal concentrating ability and urine composition of a desert mammal after it has drunk saline (2%) water. Although the gerbil's urine-concentrating ability is well known, there are no published studies on the changes that occur in renal function during the transition period from drinking tap to saline water. Thus the students realize that they will collect unique data in this experiment and will be able to analyze and report original unpublished results.

Before beginning the experiment, students examine the microanatomy of vertebrate kidneys by use of slides of fish, frog, bird, and mammal kidneys; they identify the components of the nephron and compare the structural differences in them between vertebrate classes. Dissections of fresh beef and gerbil kidneys convince them that the renal medullary structure of gerbils is quite different from that of a typical mammal (bovine and human). Students set up metabolic cages (e.g., Harvard Apparatus Metabolic Cage, AH 62–6707)) for urine collection from eight gerbils during the first week of lab, learn animal- handling techniques for daily weighing, and set up spreadsheets for recording daily water consumption and urine production of each gerbil. Pairs of students record these data daily over the next week and collect and freeze urine samples for later analysis.

All students perform chloride titrations and urea analyses during the second week of the unit by constructing standard curves for these two variables [chloride titration procedure after Burgess (http://www.uri.edu/ce/wq/ww/resources/09-NR%20salinity.pdf); urea kit 640-A from Sigma]. Students then analyze all 64 urine samples collected from the gerbils; they work in teams assigned either to determine urine chloride, urea, and osmolarity or to enter water consumption, urine production, and body weight changes on a final spreadsheet. When all the data have been entered into the spreadsheet, it is emailed to every student at the conclusion of the lab period. As homework in preparation for the third week of lab, students plot changes in the daily means of these variables during the transition from drinking tap water to saline; they write summary paragraphs of their observations, and read two primary articles (2, 3).

During the third week of this unit, we review the data collected the previous week and discuss significant changes observed. Using a computer and LCD projector, I open the same data set that students used for their homework assignment and review some of their results. Students easily recognize trends in the data such as increased osmolarity of gerbil urine and increased excretion of chloride after gerbil consumption of saline water (Fig. 1), and this is where they would typically stop in their analysis of the data. However, to get students to think about a deeper (i.e., more sophisticated) level of analysis needed to understand *how* gerbils concentrate their urine, I work through a more sophisticated data analysis with them. For example, I ask them to think about the contribution of urea vs. electrolytes to gerbil urine osmolarity by posing questions such as: "*How can we determine whether the observed increase in urine osmolarity following consumption of saline water is due to salt or urea excretion?*" Students suggest how to proceed to answer these questions (e.g., perform a regression analysis of urine urea and urine chloride vs. urine osmolarity), and in doing that on my computer with them watching the results of my manipulations projected on the screen, they see, using the above example, that there is a very strong (and significant) relationship between urine chloride and urine osmolarity and a surprisingly significant (although weaker) relationship between urine urea and urine osmolarity (Fig. 2). I then ask them to go back to their lecture notes and text to review the mechanism for urine concentration through antidiuretic hormone (ADH) release and ask another question about the control of urine concentration: "*How are gerbils able to excrete the excess salt consumed while staying in water balance*; *is there evidence for ADH release in gerbils drinking 2% saline for five days?*" Students can usually reiterate the physiological signs associated with ADH release without much prompting and can relate them to their data: increased urine osmolarity, increased solute concentration in the urine, decreased urine volume (although this does not happen in gerbils). As further proof of ADH release in their gerbils,

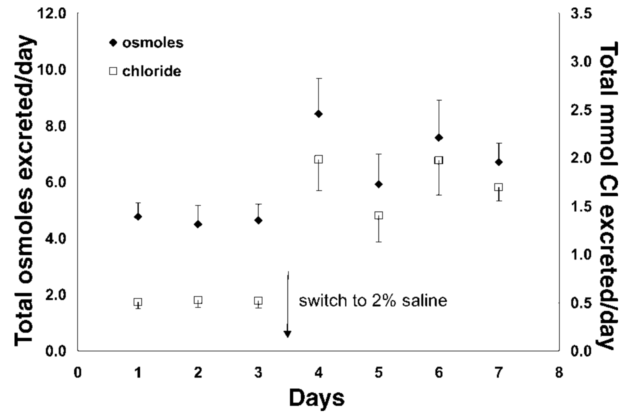

FIG. 1.
Sample data from the renal laboratory exercise on gerbil osmoregulation. Urine osmolarity and chloride excretion increased immediately after gerbils were switched from tap water to 2% saline (0.34 M) drinking water. Students are quick to see these simple trends.

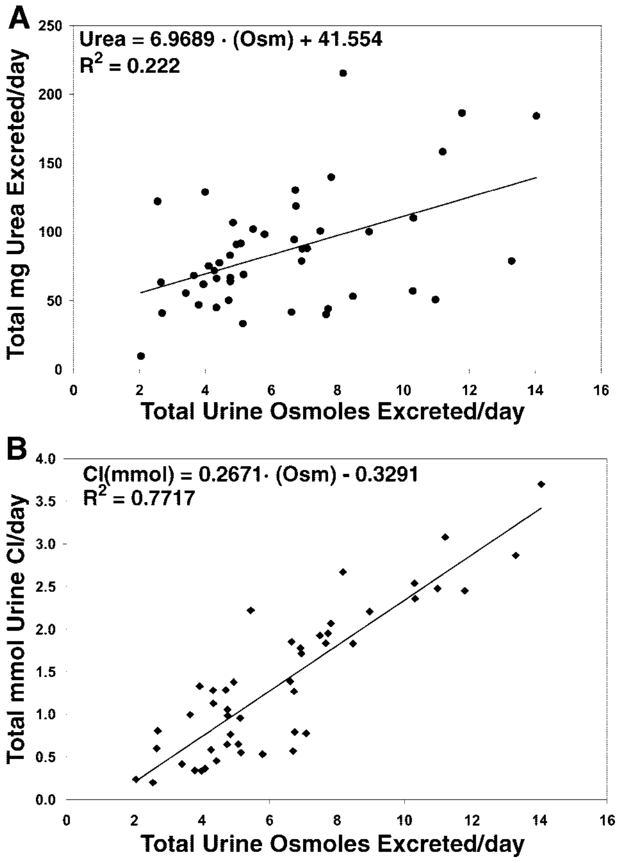

FIG. 2.

Examination of the contribution of urea (*A*) and chloride (*B*) to total urine osmolarity in gerbils drinking tap water, and 2% saline reveals a strong (and highly significant) relationship between total chloride excreted and total urine osmoles excreted and a weaker relationship between total urea excreted and total urine osmoles. Students need prompting to analyze raw data at this level.

I ask them to examine changes in urea concentration in the urine over the course of the experiment. Knowing that ADH promotes urea as well as water reabsorption in the distal collecting duct, students hypothesize that the urea concentration of the urine should be less during saline consumption than during water consumption, *if* ADH is being released then. By inspection of their data, students find that this is exactly the case and that one explanation for their observation of increased urine concentration in gerbils consuming saline water is urea recycling promoted by ADH release. This exercise models the deeper analysis of data that students should strive for in their written reports, and as a result, their written reports are less superficial and incorporate much more sophisticated treatment of the data.

This leads us to examine the data in the two primary articles they were assigned to read. I first ask students to compare their methods and their results (just analyzed) with what the authors did and what they found. By examining tables and figures from the papers with their own data, students learn that their measurements of water consumption, urine production, urine osmolarity, and chloride content are quite similar to those reported in Tables 1 and 2 of the Donaldson and Edwards paper (2) for gerbils drinking 2% saline. The intent here is to model the practice of using the primary literature for corroboration and comparison. To answer the question of whether gerbils drinking 2% saline (0.34 M) secrete ADH to concentrate their urine, I direct students to Table 2 of the Edwards and Peters paper (3), which shows that gerbils drinking 0.25 M saline store increased amounts of neurohormones in the posterior pituitary, indicative of synthesis but not release of ADH, whereas gerbils drinking higher concentrations of saline (0.5–1.0 M) exhibit reduced neurohormone content of the posterior pituitary, suggestive of ADH release. I leave it up to the students to conclude whether the gerbils in their study (drinking saline whose molarity is between the two solutions tested in the Edwards and Peters study) show evidence of ADH secretion or not.

The next task in the analysis of primary literature is to have students list examples of how the authors themselves used primary literature in their discussion to support, explain, or contradict their results. I then ask students to give me examples of statements in the two articles that would support, explain, or contradict the results of the class experiment. This exercise is intended to demonstrate to students how to "use" the primary literature to explain an effect observed in their own study. Usually there are a lot of "a-hah"s during this part of the exercise.

The final task for this lab period is to have students practice writing a paragraph of their discussion incorporating these references as comparison data for their own results. I critique each group's writing during the lab period to help them think carefully about the formal scientific report they will submit as a group the following week. I provide them with a detailed handout that describes what should be included in each section of a scientific physiology paper and an exhaustive list of important writing tips to check off before they submit the report (Table 2). Giving them just the written directions for organization of a scientific report proved to be inadequate during the first two years that I taught the course. Adding the checklist (recently) ensured that students paid attention to the directions and proofed their papers more critically before turning them in, thus achieving a better product.

The renal lab unit represents a definite incremental increase in the complexity of several aspects of the laboratory experience. Although the experimental design is established for them, students are responsible for setting up spreadsheets for collection of data and for choosing the variables they will analyze and write up in their formal report. They have about the same degree of independence that they had in the first lab unit, but the experiment itself is considerably more complex, and they have more choice of what to analyze, how they will analyze it, and what physiological parameters they want to emphasize in their report (e.g., water balance, salt balance, urea vs. chloride excretion). Reliance on incorporation of primary literature is greater, and the expectation for creative and coherent analysis is raised considerably from the first lab unit. Student groups have the opportunity to rewrite their lab report to their (grade) satisfaction, and I provide as many constructive comments about their writing as I can. The point of this exercise is to learn how to write scientifically so that they can apply what they have learned when they write individual reports.

Step 3. Putting the pieces together: promoting sophisticated student-designed experiments. The third lab unit focuses on the cardiovascular system and introduces techniques for recording human electrocardiogram (ECG), pulse, and blood pressure. After a comparative look at circulatory anatomy and blood flow pathways in the shark, frog, and cat during the first lab, students learn how to set up and record their ECG and finger pulse by using PowerLab and Chart software during the second lab. Students examine several aspects of the ECG waveform, the relationship of ECG to pulse, changes in ECG intervals (e.g.,

TABLE 2
Checklist of format and content expectations for formal scientific papers in Comparative Anatomy and Physiology II at University of St. Thomas

Title
1. Is the title clear and informative?

Abstract
2. Is there background information leading up to a statement of the problem?
3. Are some significant results presented?
4. Is the experimental method described briefly?
5. Is there a statement of a conclusion?

Introduction
6. Is there sufficient background information to understand the significance of the problem?
7. Is the problem, question, or hypothesis clearly stated?

Methods
8. Is the experimental procedure clearly described? Could an individual not familiar with the lab understand the procedure?
9. Is the experimental design appropriate?

Results
10. Are the results described in a narrative fashion?
11. Is there excessive concentration on reporting of statistics without general description?
12. Are the results presented in a clear and logical fashion (general to specific)
13. Are the figures and tables referred to correctly?
14. Are appropriate statistical tests performed?
15. Are statistical results interpreted correctly?

Figures and tables
16. Are figures and tables numbered correctly?
17. Do figure and table legends accurately reflect their content?
18. Are data in figures graphed correctly with appropriate axes, labeling, etc.?
19. Are data in figures and tables redundant or unnecessary?

Discussion
20. Does the discussion show analysis, interpretation, and comparison of data collected?
21. Is there an explicit statement supporting or refuting the hypothesis?
22. Are there citations of primary work that support the comparisons of this study with the work of others?
23. Is there explanation of mechanism of action or function that helps the reader understand the results obtained?
24. Does the discussion draw conclusions from the data analyzed?

Literature cited
25. Is literature cited appropriately throughout the report?
26. Are there at least five references, three of which are primary literature?
27. Are the references cited in the proper format?

Overall
28. Is the writing clear, concise, and logical?
29. Are proper grammar and spelling used?
30. Is the report informative and easy to read?

TABLE 3
Comparison of topics of student-originated investigations in Comparative Anatomy and Physiology II at University of St. Thomas before (1999–2000) and after (2001–2002) development of the guided inquiry approach

1999–2000	2001–2002
Cardiovascular experiments	
Effect of smoking on heart rate and blood pressure in college males	Effect of vagal maneuvers on heart rate and QT intervals in healthy subjects
Daily rhythms of heart rate and blood pressure in college students	Effects of different types of music on PR and QT intervals of the ECG
Respiratory experiments	
Metabolic response of goldfish to temperature	Metabolic responses of juvenile gerbils raised in different photoperiods to cold-temperature stress
Gender differences in vital capacity and tidal volume	Effect of gender on heart rate, oxygen consumption, and oxygen pulse of college students while treadmill running
Recovery of heart rate and tidal volume following strenuous running in college males	Effect of exercise intensity on respiratory rate, tidal volume, and alveolar minute volume of male athletes vs. nonathletes

QT interval) with body position, exercise, and breath holding to answer some basic questions about cardiac physiology and as technique background for the experiment they will design and conduct over the following two weeks.

In contrast to the second unit, where students were provided with relevant primary literature, each lab group is expected to bring at least two relevant articles from the primary literature with them to lab during the third week. With this background, they use the first 15–20 minutes of lab to discuss a testable hypothesis and construct the design of their experiment; they then present a summary of what they intend to do and are critiqued by the rest of the lab section (and the instructor). After making refinements to their experimental design, they begin collecting data and then continue that data collection and analysis during the fourth week of the unit. The goal of this unit is to give them much more independence in the experimental design phase but provide feedback on their hypotheses and methods before they get too far into the experiment. The critique period allows me to help them get beyond the typical kinds of simplistic experiments that students did in previous years. For example, instead of designing an experiment that simply compares heart rate during prone vs. standing posture of three subjects, students are encouraged to think about more complex issues, e.g., recording multiple leads of the ECG and using the Chart software to construct the electrical axis during a change in posture, or correlating changes in ECG intervals with exercise duration or intensity (see examples in Table 3). They are encouraged to think critically about how many subjects they need to examine to evaluate statistical significance. By emphasizing the importance of sample size to data analysis, students utilize their time during the fourth week to analyze what they have already done to correct their technique or increase their sample size.

Each student writes his/her own formal scientific report on this experiment with the expectation that I am looking for each individual's expression of writing style, use of primary literature, data analysis, and explanation of the mechanisms underlying the results at the same or higher level than the first, group lab report. Setting this expectation is integral to improved student performance in formal scientific writing, because students can use the group lab report as a reference and refer back to the lab report checklist (Table 2) for guidance in their writing.

The last lab unit is respiratory physiology, and because we have already examined the respiratory anatomy during the cardiovascular unit, we spend the majority of the first lab meeting talking about and demonstrating techniques for measurement of respiratory performance. Again, using PowerLab and Chart software, students measure some of the classical aspects of pulmonary function (e.g., inspiratory and expiratory reserve, vital capacity, forced vital capacity, forced expiratory volume in one second) on themselves, but I also use respirometry equipment for measurement of oxygen content of air and water to demonstrate how to evaluate the metabolic rates of animals. Students can choose from a variety of subjects while learning how to use the equipment. They measure dissolved oxygen (DO) of warm and cold aerated and nonaerated water as well as dissolved oxygen of small vs. large fish, minnows vs. blue gills or frogs, by use of Hach DO kits and pocket colorimeters. They also measure oxygen consumption of male vs. female or adult vs. juvenile gerbils, mice, or other small mammals at a variety of temperatures by means of a Sable Systems oxygen analyzer and flow-through metabolic chamber. When all groups have rotated through all of the technique stations and collected data, we reconvene the entire lab class and summarize what was observed using each of the techniques. This reinforces some of the lecture material discussed earlier in the week on pulmonary physiology and introduces some concepts on metabolism that will be covered later in lecture. The goal of this lab is to demonstrate techniques, and students are then given wide latitude for experimental design and have three weeks to conduct their project on respiratory physiology. The integration of topics in lecture and laboratory becomes essential here to help students focus on a particular problem of interest and to generate ideas for study. In the past two years, students have risen to the challenge to design complex and interesting experiments with relevant bases in the primary or secondary literature (see examples in Table 3). To heighten the enthusiasm and energy for this longer project, I ask lab groups to present their results to the rest of the class in a formal oral presentation, in the form of a mock research symposium, instead of submitting another formal written report. Students welcome the change; they order refreshments, dress for the formal occasion, and design high-tech presentations using PowerPoint. I believe that the accomplishments of students, reflected by the greater sophistication of the experimental design and analysis of projects and the quality of presentations, markedly exceeded those of students from previous years. In addition, the semester-end projects were of more uniform, superior caliber compared with the uneven quality of student projects in previous classes.

CONCLUSIONS

The emphasis on incremental skill development that is reinforced and built upon with each lab unit seems a superior way to teach this lab, judging by the excellent quality of the student products compared with those of earlier years. However, in the choice to have the laboratory skill development direct the order of topics covered in lecture, some adjustments had to be made in how and when certain concepts were covered in lecture. For example, because the renal unit in lab preceded the cardiovascular unit, some aspects of cardiovascular control of fluid volume had to be introduced early. Similarly, renal control of blood pressure was omitted from the renal unit and emphasized in the cardiovascular unit instead. Acid-base balance, normally covered in the renal unit, was deferred to the respiratory physiology unit to demonstrate the integrated nature of acid-base balance by these two systems and because the emphasis in the renal unit was more strongly focused on osmoregulation than on acid-base balance. However, the case study on high-altitude physiology used in the respiratory physiology unit in lecture made the introduction of acid-base physiology more natural there. The shifting of topics was minor and actually contributed to student appreciation for integration of physiological systems that promote homeostasis.

The guided approach to inquiry-based laboratories described in this report takes development of research and investigative skills a step further than the basic DYO experience. The intention of investigative (DYO) labs, especially in the introductory curriculum, is to engage students by encouraging them to “think like scientists” and get out of the practice of the rote performance of a cook mastering a recipe (4, 5, 8, 14). The guided approach to inquiry-based teaching described in this report provides more substantial support to the development of critical, analytical thinking and use of primary literature in student investigations. Without modeling the practice of science at a higher level of thinking, students continue to practice investigative science at the introductory level, even though their exposure to science content is considerably richer with each science course they take.

TABLE 4
Sample questions from the evaluation of student learning gains in physiology lab

Survey Questions	Mean Response	
	1999–2000 (n = 47)	2001–2002 (n = 52)
1. Has the lab experience in this course improved your understanding of physiological processes?	4.47 ± 0.63	4.91 ± 0.29†
2. Has the lab experience in this course stimulated your interest in physiology?	4.3 ± 0.55	4.6 ± 0.41
3. Has the lab experience in this course increased your confidence in conducting scientific investigations?	3.7 ± 0.81	4.27 ± 0.62*
4. Has the lab experience in this course helped you read and understand the primary literature?	3.75 ± 0.6	4.55 ± 0.67*
5. Has the lab experience in this course helped you analyze and statistically evaluate data?	4.1 ± 0.57	4.35 ± 0.78*
6. Has the lab experience in this course helped you understand and critically evaluate experimental design?	3.93 ± 0.75	4.6 ± 0.66†
7. Has the lab experience in this course helped you organize and present a research project orally?	4.0 ± 0.44	4.55 ± 0.81†

Reports from the 1999–2000 classes are compared with those from the 2001–2002 classes. Scores are means ± SD based on a Likert scale from 1 to 5, where 1 is a response of "not at all" and 5 is a response of "very much." *Significant differences between means 1999–2000 vs. 2001–2002 (*$P < 0.05$; †$P < 0.01$). Questions were modified from the template provided on the NISE website for Student Assessment of Learning Gains: (http://www.wcer.wisc.edu/salgains/instructor/default.asp).

Does this approach work? By subjective analysis of the product, namely the increased complexity of experimental design, sophistication of data analysis, and incorporation of primary literature in their scientific reports, YES. Student efforts were markedly improved using this approach of guided independent inquiry. This subjective assessment is supported by scores from electronic surveys of the laboratory experience that were administered at the end of the semester using the National Institute of Science Education (NISE) instrument to measure Student Assessment of Learning Gains (see http://www.wcer.wisc.edu/salgains/instructor/ for a template that can be modified to suit a particular course). Responses from 2001 and 2002 reveal that student satisfaction and learning gains associated with the laboratory portion of the course were consistently and often significantly higher than in previous years (1999–2000) of teaching this course (Table 4). For example, in answer to the question "Has the lab experience in this course improved your understanding of physiological processes," the mean evaluation score increased from 4.47 to 4.91 (on a scale from 1 = not at all to 5 = very much) between 1999–2000 and 2001–2002 ($P < 0.01$ with a two-sample *t*-test). Similarly, the lab experience was a positive contribution to increased interest in the field of physiology itself. Students from 2001–2002 classes felt more confident about their abilities as a scientist, particularly about reading and understanding the primary literature, designing experiments, and analyzing their data, than did students from 1999–2000. The investment in a structured, independent-inquiry approach to physiology education in the laboratory not only improves students' ability to do science but gives them a greater appreciation and interest in the field of physiology.

DISCLOSURES

Development of the Comparative Anatomy and Physiology I and II courses was supported by funding from National Science Foundation Institutional and Laboratory Improvement funds (DUE 96–51421) awarded to S. B. Chaplin and D. E. Nelson, and by funds from the Department of Biology at the University of St. Thomas.

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Submitted 7 February 2003; accepted in final form 3 July 2003.

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