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Article

Using a Physics Experiment in a Lecture Setting to Engage Biology Students with the Concepts of Poiseuille's Law

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Biology students enrolled in a typical undergraduate physiology course encounter Poiseuille's law, a physics equation that describes the properties governing the flow of blood through the circulation. According to the equation, a small change in vessel radius has an exponential effect on resistance, resulting in a larger than expected change in blood flow. To help engage students in this important concept, we performed a physics experiment as a lecture demonstration to mimic the original research by the 19th-century French scientist. We tested its impact as a research project and found that students who viewed the demonstration reacted very positively and showed an immediate increase in test performance, while the control group was able to independently "catch up" at the fourth week posttest. We further examined whether students' math skills mapped to learning gains. The students with lower math scores who viewed the demonstration had slightly more improvement in test performance than those students who did not view the demonstration. Our data suggest that watching a lecture demonstration may be of even greater benefit to biology students with lower math achievement.

INTRODUCTION

Engaging students in difficult abstract concepts is a common problem in upper-division science lecture courses, particularly when the concepts employ mathematical equations (Pepper *et al.*, 2012). Equations are encountered frequently in physiology course work and are used to help explain how the body functions. One such well-known physics equation is Poiseuille's law, which describes the mechanical properties governing the flow of blood through the circulation. While more than 150 yr old, Poiseuille's law is still important today and appears in the cardiovascular chapter of virtually every undergraduate physiology textbook. The basic mathematical formula is usually accompanied by pages of lengthy explanations and diagrams. Also known as the Hagen-Poiseuille formula, the concepts of Poiseuille's law have been highlighted by educators as important for understanding the cardiovascular system (O'Connell, 1998; Badeer, 2001; Carroll, 2001; Rehfuss, 2004; Clifford, 2011). The American Physiological Society places Poiseuille's law as one of its current major medical physiology curricular objectives and recommends that health professions students be able to explain and calculate changes in resistance using the law (Carroll *et al.*, 2012). Understanding its basic principles are part of a medical student's basic science competency, according to the joint Association of American Medical Colleges and Howard Hughes Medical Institute committee report entitled *Scientific Foundations for Future Physicians* (AAMC-HHMI, 2009).

Poiseuille's equation is a simple algebraic expression[1] that defines the inverse relationship between the radius of a tube and its resistance to fluid flow. According to the equation, a small increase in tube or vessel radius causes an exponentially large decrease in resistance to the fourth power, thus resulting in an unexpectedly large increase in fluid flow rate. This nonlinear relationship between radius and resistance is not necessarily "intuitive" and was based on the original experimental data on small glass tubes obtained by Poiseuille,

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[1]Poiseuille's law describes the physical forces that drive blood flow through a vessel. It is often written simply as: Flow = $\Delta P/R$, where ΔP is the pressure gradient along the vessel and R is the resistance to flow. The resistance term is defined as $8L\eta/\pi r^4$, where L is tube length, r is inner radius, and η is fluid viscosity.

with earlier and later contributions by other 18th- and 19th-century European scientists and engineers (Badeer and Synolakis, 1989; Sutera and Skalak, 1993; Parker, 2009). In spite of the importance of Poiseuille's law, students have difficulty understanding the physics and mathematics underlying it, and teaching it remains a challenge to both physics and physiology instructors (Carroll, 2001; Fairman *et al.*, 2003; Kamela, 2007; Clifford, 2011). One author duly noted that cardiovascular resistance and Poiseuille's law are areas in which students become confused and struggle for full comprehension (Carroll, 2001), and this certainly describes our own experiences in the physiology classroom.

One approach to teaching abstract concepts in biology is through active-learning strategies designed to improve student engagement (Carvalho, 2009; Goldberg and Ingram, 2011). There is no single method of active learning, although one way is to provide lecture demonstrations and objects that make the content more meaningful (Huck *et al.*, 1985; Di Stefano, 1995; Crouch *et al.*, 2004; Morgan *et al.*, 2007; Krontiris-Litowitz 2008; O'Dowd and Aguilar-Roca, 2009). When properly used, a highly effective lecture demonstration can be a part of any science curriculum, enliven the lecture atmosphere, and provide unique, three-dimensional learning experiences. Physics teaching journals are filled with creative and wonderful ideas for lecture demonstrations, many using simple materials (Camino and Gangui, 2012; Corpuz and Rebello, 2012; Graf, 2012; Isik and Yurumezoglu, 2012; Jumper, 2012; Organtini, 2012; Torigoe, 2012). There are far fewer published examples of demonstrations of physics principles in a physiology course, even though many relevant physics topics are presented (e.g., effects of gravity, friction, electrical potentials, fluid dynamics, respiratory mechanics, wall tension, musculoskeletal levers). Furthermore, demonstrations might be especially helpful to many students who find it difficult to transfer their knowledge of physics to physiology (West, 2008; Plomer *et al.*, 2010) and may help students integrate overlapping concepts in these two science disciplines.

To help students become more actively engaged in Poiseuille's law, we created a new lecture demonstration for the human physiology course using a physics experiment that perhaps roughly resembles Poiseuille's research in his Paris laboratory in the late 1830s. The demonstration was an interactive inquiry-based activity and was not simply designed to entertain. Our approach was similar to those using physics demonstrations to stimulate questioning and build scientific skills (Gross, 2002; Sokoloff and Thornton, 2004; Wenning, 2011; Stafford, 2012). Our demonstration included data collection and application of knowledge to enhance constructivist elements of active learning (Andrews *et al.*, 2011). The design also incorporated practical constraints, inexpensive materials, easy visibility in the lecture hall, and a restricted time allotment of 10 min to collect and analyze the experimental data with the students. Our demonstration also touched upon the history of science in fluid dynamics[2] as a way of contextualizing the demonstration and included a brief discussion of Poiseuille and his original research apparatus.

Although many science instructors have used lecture demonstrations, one does not necessarily know the effect on performance or which students in the class are most likely to benefit. Because Poiseuille's law is an algebraic equation with fractions and exponents, students with a solid understanding of algebra would have a learning advantage. We proposed that students' pre-existing math skills would map to the outcome assessments and learning gains. Math ability is clearly a general predictor of performance in science course work, including physics and biology (Sadler and Tai, 2007; Pepper *et al.*, 2012). For this reason, we asked students to complete an algebra skill test and math course survey. We also included an open-ended question in our assessment tools to try and discern differences between students' computational skills and conceptual understanding.

OVERVIEW OF THE EXPERIMENT

We examined the relative effectiveness of an in-class demonstration for learning about Poiseuille's law, a physics principle described by a simple algebraic equation. Nearly all students in the physiology course had already completed at least one semester each of college calculus and physics. At the time of the demonstration, students had already received a didactic lecture the previous class period from their regular instructor on Poiseuille's law, which we felt was necessary in order for students to begin their learning of this difficult concept. The lecture included PowerPoint diagrams from a standard physiology text describing the determinants of blood flow and vascular resistance and the full Poiseuille's formula. Student participants were randomly assigned to one of two groups for the remainder of the study; the experimental group (EXP) would view the demonstration, and the control group (CON) would not. Our study design was similar to other published educational research projects in physiology (Sturges *et al.*, 2009; Anderson *et al.*, 2011).

Although education research studies differ in whether or not a control group is necessary, we felt that a control group would contribute to an understanding of the impact of the intervention (i.e., the demonstration). We hypothesized that students who viewed the demonstration would perform better on assessment questions that involved conceptual learning, plus they would have longer retention. We were also interested in knowing whether students' math backgrounds and abilities would map to performance gains on the physiology material.

METHODS

Participants

Students were recruited from a one-semester undergraduate human physiology course for biology majors (Biology 612) at San Francisco State University (SFSU), a large and diverse

[2]The experiments of Dr. Jean Poiseuille, a French physician in Paris, and the subsequent development of the final equation make a fascinating story and serve as a wonderful illustration of the workings of science in the 18th and 19th centuries in Europe (Sutera and Skalak, 1993; Parker, 2009). There were early contributions by George Stokes of the famous Navier-Stokes equation and Daniel Bernoulli. Although the Poiseuille equation is usually credited to Dr. Poiseuille, the equation was probably derived simultaneously by a German hydraulics engineer named Gotthilf Hagen (hence the equation is often referred to as the Hagen-Poiseuille formula), and the viscosity term was added by another scientist, Eduard Hagenbach, yielding the equation we know today.

multicultural public institution. Most students in this course have junior or senior class standing. Prerequisite courses for physiology consist of two semesters of introductory biology, two semesters of chemistry (including one semester of organic chemistry), and one semester of introductory physics with its own prerequisite of one semester of calculus. The physics course content at our university varies depending on the instructor, but usually covers some aspects of static fluids (i.e., pressure, density, buoyancy). Also, fluid flow rates in response to pressure differences are discussed, but without math calculations or much detail. There is generally no explicit discussion of Poiseuille's law or its concepts, which involve resistance and radius (W. Man, personal communication). The study involved students enrolled in physiology in the Spring 2011 or Fall 2011 semester. The course was taught by a different instructor each semester. A test–retest study viewed the performance of a third class of students enrolled in Spring 2013.

Demonstration Materials

The materials used for the demonstration we created are shown in the images of Figure 1. The main materials consisted of a large 5-gal. plastic paint bucket (see Figure 1A) and approximately 3 m each of three different sizes of tubing (i.e., clear Tygon B-44-3 beverage tubing of 1/16-in. wall thickness purchased from amazon.com). Tube diameters and inner radii '*r*' were as follows: 1/8-in. tubing (r = 1.5 mm), 1/4-in. tubing (r = 3 mm) and 1/2-in. tubing (r = 6 mm). The two smaller tubes were used for the actual experiment, and the largest tube was shown for the hypothetical prediction only (see Figure 1B). The ends of the two tubes were taped to the inside bottom surface of the bucket with duct tape in order to secure them (see Figure 1C). The collection ends of the tubes were prepared by attaching a wooden chopstick with duct tape to the side of each tube such that the stick extended exactly 5 cm beyond the tube end. This was done in order to ensure that each tube end was at the exact same height above its collecting pan (Figure 1B, inset) to minimize errors in flow rate due to varying hydrostatic pressure.

Other materials included two 500-ml glass graduated cylinders to measure collection volumes and a paper model of a graduated cylinder 2.04 m high, a timer, red food coloring, a 9.5-l bucket, and two wide-mouth plastic collection containers ~25 cm in diameter and 5 cm deep.

During our design process, we tested a number of variables affecting flow rate that we needed to optimize for our brief demonstration in order to avoid turbulence and inaccuracies. For example, we varied the height of water in the bucket (from 13 to 20 cm, resulting in an optimal 15 cm of water), and the height and size of different collecting containers. For the final demonstration, the collection containers and bucket were all placed on the table. Doubling the radius consistently produced a 12-fold increase in collection volume (Poiseuille's law predicts 16-fold) but required a very long collection time and slow fluid velocity. Instead, we decided to use a short 1-min collection time that resulted in only a 10-fold increase in flow rate, but would require a shorter attention span on the part of students and allow sufficiently large collecting volumes for visualization.

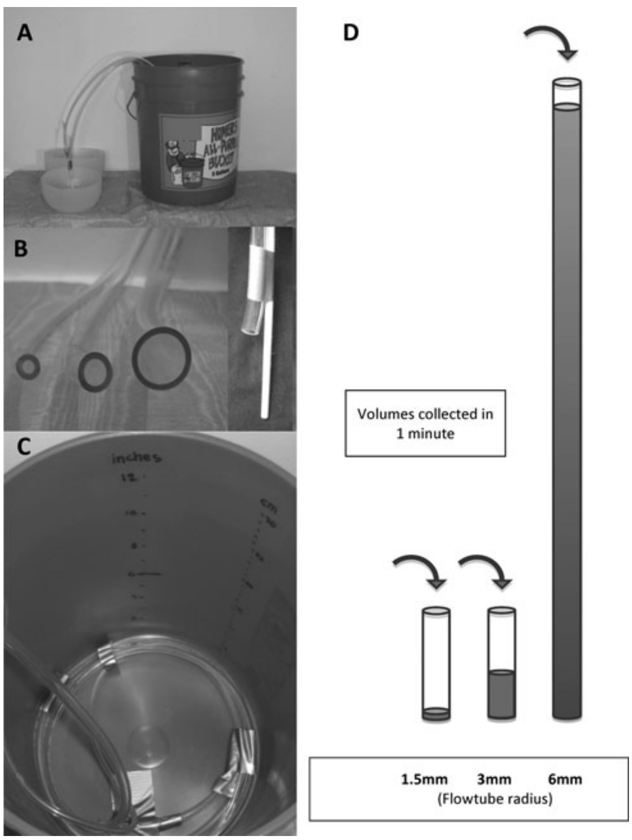

Figure 1. (A) Demonstration setup consists of a bucket, collecting containers, chopsticks at the end of the tubing, and colored water. (B) Tubing in three different inner radii; the widest tube was used for the hypothetical prediction. (C) Tubing was coiled and taped to the bottom of bucket. (D) The collection containers received volumes of roughly 40, 400, and 4000 ml each (the last measurement is only hypothetical, and was done mathematically, not as part of the experiment).

Performing the Demonstration

Before the class began, we filled the bucket to a 15-cm depth of water to which 15 ml of food coloring was added to make the fluid more visible for the students. The tubes were then fully immersed in the water and inspected to make sure that they were completely filled with water and had no air bubbles that would affect flow rate. At the beginning of the class demonstration, the "scientist" co-researcher put her hands into the bucket, capped the two collection ends with her thumbs *before* taking the ends out of the water, took her hands out of the bucket, then lowered the tube ends into the collection containers, holding the chopsticks against the base of the collection container. The timed fluid collection lasted 1 min. The tube ends were then quickly capped (again with thumbs) and returned to the bucket.

In spite of our relatively crude experimental conditions in the lecture hall, we were able to achieve a very good approximation of the flow rates predicted by Poiseuille's equation. Figure 1D shows the volumes collected from two different diameters of tubing, plus the hypothetical volume expected from the widest tubing. The actual 1-min collection volumes in our experiment usually varied from 38–40 ml (for the 1.5-mm-radius tube) and 380–400 ml (3-mm-radius tube). This demonstrated a 10-fold greater amount using the larger tube with double the radius. We showed students the large

6-mm tube and asked them to hypothetically predict the result and then unfolded the 2-m-high paper cylinder with 4000-ml collection volume; this immediately elicited an exclamatory "Wow!" from the class. On the board, we graphed the data of volumes versus radii, which clearly showed the nonlinear relationship predicted by Poiseuille's law. The instructor also discussed the limitations of our setup, as compared with Poiseuille's elaborate apparatus. We pointed out that our results fell slightly short of the expected 16-fold change, because Poiseuille used much smaller glass capillary tubes and very slow fluid velocities to achieve laminar flow, and kept a constant hydrostatic pressure (Sutera and Skalak, 1993).

Test Materials and Validity

The evaluation instruments and protocol were reviewed and approved by the Institutional Review Board at SFSU (Human and Animal Subjects Committee). All student participants signed consent forms, and data were coded to maintain anonymity. All written materials (i.e., math skill test, Poiseuille's law test, demographic and attitudinal surveys) were developed for the purpose of this study by J.B. and T.C., who hold doctoral and master's degrees in physiology, respectively.

The Poiseuille's law assessment tool consisted of six questions (i.e., five multiple-choice questions and one open-ended question). To verify the content validity of this tool, the coauthors sent it to seven additional expert physiologists on the biology department faculty using SurveyMonkey (www.surveymonkey.com). These experts either teach or have taught upper-division physiology courses, and all have graduate degrees (five PhDs and two master's of science degrees). There were six out of seven respondents. Half answered all assessment questions correctly, and the remaining half missed only one question, with each expert missing a different one. Experts were also prompted to comment whether each question was scientifically accurate, understandable, and answerable by a student who had completed a physiology course. All experts indicated that all questions were scientifically accurate and understandable (with minor suggestions from three experts to enhance understandability of two questions). Five experts felt that all questions could be answered by students who completed a physiology course. One expert raised a concern that two questions did not test for students' understanding, but relied on memorization, although we had already attempted to address this type of concern by including an open-ended written question. We did not adjust the instrument or analyses because the expert consensus was positive overall. Also, at no point in the study were answers provided to students; this allowed us to perform repeated measures using the same instrument. Test–retest reliability (repeatability) was determined with a randomized group of students in the same course in Spring 2013; they were given the Poiseuille test twice, 10 min apart, during a single class period. This was the normal time frame for the pretest 2 to posttest interval (i.e., before and after the demonstration). There was no talking or intervention in between the tests. Out of $n = 49$ students who completed both tests, 15 had improved scores on the second test and nine had lower scores. The overall students' mean scores had a modest 3.3% improvement on the second test, which is an acceptable index of repeatability. The internal reliability of the test was also analyzed by comparing the changes in examinees over time. For mean scores from pretest 2 to posttest value (before and after the demonstration), the Pearson product r was 0.758, which indicates a fairly high test reliability (Crocker and Algina, 1986).

The math assessment tool consisted of six objective questions that included questions on exponents and fractions. Three questions concerned inequalities ("Fill in greater than/equal to/less than"), two questions involved solving a formula ("Solve the formula for the variable '*r*' and circle the correct answer"), and one fill-in question required students to solve the equation for *x* and write the answer. The tool was derived from similar questions found in algebra textbooks and was discussed with a college math education expert. The test–retest scores for students enrolled in Spring 2013 showed only 1.6% improvement in the math retest, indicating a high test repeatability.

A demographic survey was given once and contained background questions on gender, grade point average (GPA), and major. We also asked students to check off boxes to indicate the highest level of math they had completed and the number of semesters of biology, chemistry, and physics they had passed. All survey data were self-reported.

In addition, students in the EXP group filled out a post-demonstration attitudinal instrument consisting of five short statements with a modified Likert scale (strongly agree, agree, neutral, disagree, strongly disagree).

Study Protocol and Data Collection

The timeline flowchart for the experimental research design is shown in Figure 2. Throughout the study, *pre* refers to any item or activity occurring prior to the demonstration; *post* refers to any item administered after the demonstration. The main part of the study took place during three consecutive class days. On the first day of assessment, the researchers came to class and distributed the three types of materials to all students: demographic survey, math assessment, and the Poiseuille's law assessment (i.e., pretest 1). In the next class period, students attended a traditional cardiovascular physiology lecture presented by their regular instructor, which included Poiseuille's law and cardiovascular resistance. In the third and subsequent class period, all students first took the Poiseuille's law assessment again (i.e., pretest 2). Following pretest 2, the CON group was excused from class and the EXP group stayed to watch the 10-min demonstration. Immediately following the demonstration or roughly 10-min later, the EXP group took the Poiseuille's law assessment for the third time (i.e., posttest) and completed the attitudinal survey. In our study design, we did not assign the CON group a different intervention.

One month later, as part of their regular class midterm exam, all students in the class answered one of the Poiseuille's law assessment questions in order to ascertain their long-term retention of the material. We were only able to insert a single question on this test with the instructors' permission due to the length of the exam; we selected question 4 from our Poiseuille assessment, because it was the most specific question and contained both computational and conceptual aspects. This assessment question is referred to as the 1-mo (delayed) posttest.

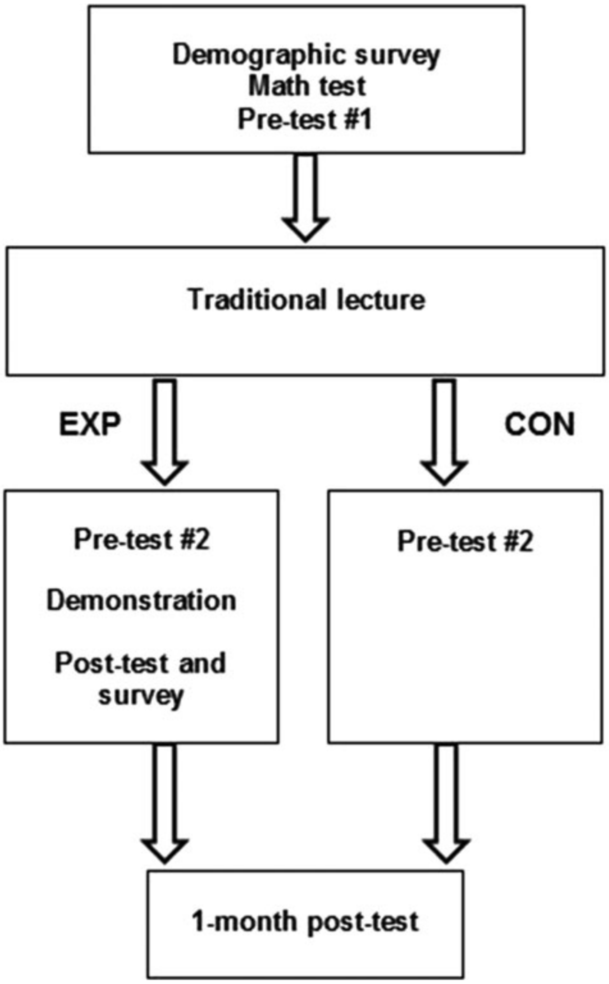

Figure 2. Experimental protocol to assess the impact of a physics demonstration on students' understanding of Poiseuille's law. Tests and surveys for the EXP and CON groups differed only on the third day of the study (i.e., demonstration day).

Interrater Reliability. The open-ended question (i.e., question 6) required a scoring rubric that was constructed by one author (T.C.), who read all responses and created initial scoring categories. To prevent intentional bias of pre/post data analyses, T.C. coded all tests with a random number identifier so that the two scorers (J.L.B. and W.C.) would not know whether they were scoring a pretest or posttest. Scorers first analyzed 50 tests and obtained 80% agreement on some or all tests; they then remodified and negotiated the rubric to reach at least 90% full agreement on all categories and rankings. Each written response was coded as either mentioning a category (1 point) or not (0 points). A total point score was not calculated, as it did not represent answer quality. Three additional scoring categories were added to capture data on "blank," "irrelevant," or "incorrect" student answers, yielding a final total of eight rubric categories (letters A–H). A total of 338 pretests and posttests were scored and discussed to reach 98% interrater agreement on all categories. Four tests were scored with partial agreement, and rankings were combined, and only two rankings (one 1 EXP and one CON) were eliminated for lack of agreement. A third scorer, a physiology expert, graded every 10th test ($n = 30$), which gave 96% full or partial agreement, further confirming strong interrater reliability.

Analyses

The assessment data were entered into an Excel spreadsheet (Microsoft Office 2010, Redmond, WA) and later input to SPSS Statistics version 20, 2011 (IBM Corp.) for further statistical tests. The two semesters of student data were combined after we determined their demographic results were similar. Multiple-choice questions were individually scored as either correct (1 point) or incorrect (0 points). Pretest and posttest Poiseuille's assessment scores were compared both within the groups and across the two groups in order to evaluate the effectiveness of each procedure using paired and unpaired *t* tests. We used a repeated-measures design, although students in the CON group did not view the demonstration intervention and were not given the Poiseuille assessment test (posttest) a third time. Mean ± SEM was computed; significance was determined at $p < 0.05$. For determining the influence of math skills on test performance, an analysis of covariance (ANCOVA) with time as the within-subjects factor and test scores as the dependent variable was conducted, although all test requirements were not fully met due to the lack of control posttest data. A test for nonparallelism, with a partial *F* test for equality of covariate slopes, was also performed (Kleinbaum *et al*., 1988). A small random variation in the data was used to reduce point overlap.

RESULTS

Demographic Analysis

There were 154 responses collected from the human physiology (Biology 612) course, which had a combined total enrollment of 156 students during Fall and Spring, 2011, yielding a 98.7% response rate of those enrolled at the fourth week census date. Nineteen student responses were not tallied, either because the informed consent form was unsigned or the complete set of assessment tools was not turned in by the student. Therefore, the data from a total of 135 participants were analyzed for this study (135/154 or 88% of respondents).

For all demographic parameters surveyed (i.e., gender, major, GPA, prerequisite courses completed), there were no significant differences between the EXP group ($n = 68$ students) and the CON group ($n = 67$ students), as compared by unpaired *t* tests. The overall gender composition was 61% female and 39% male. Approximately 89% of the students were majoring in biological sciences, and 74% of the students had never taken a formal physiology course before. Self-reported GPA varied, with the majority declaring grades of B or better (54% reported GPA 3.1 and above, 37% between 2.6 and 3.0, and 9% below 2.6). Roughly nine out of 10 students (91%) had already completed two semesters of physics; 78% had taken one or more semesters of college calculus, and an additional 7% reported having taken advanced math beyond calculus. Thus, 85% of the students in the study had already taken a course in college calculus.

Impact of Traditional Lecture on Student Performance

Prior to the regular instructor's lecture, students' knowledge of Poiseuille's law and cardiovascular resistance was low (pretest 1), as seen in Figure 3. The actual mean ± SEM score on pretest 1 was 3.03 ± 0.13 (EXP) and 2.79 ± 0.13 (CON),

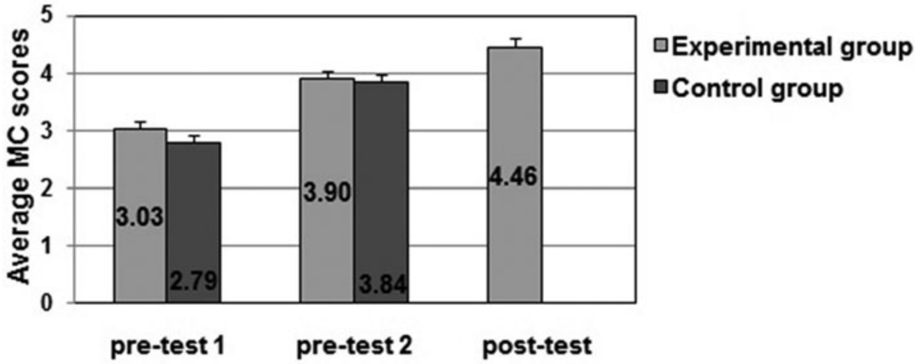

Figure 3. Student performance on the Poiseuille assessment tool. (Note: The CON group did not view the demonstration and was not given the posttest.) As seen in the figure, student scores in both groups improved after the lecture, and the EXP group had additional improvement after viewing the demonstration. Mean ± SEM scores are given. All three tests had the same five identical multiple-choice questions (5 points).

out of a maximum 5 points possible. After the lecture on cardiovascular material, which covered Poiseuille's law, the student scores improved, as seen on the pretest 2 data (3.90 ± 0.13 [EXP] vs. 3.84 ± 0.13 [CON]). Therefore, both groups showed significant increases compared with pretest 1 data (+37.6% [CON] and +28.7% [EXP]). There were no significant differences between the mean scores for the two groups (EXP and CON) for either pretest 1 or pretest 2 data using unpaired *t* tests ($p < 0.05$). Thus, prior to the start time of the demonstration, the two groups were similar in their assessment scores.

Immediate Impact of the Demonstration on Student Performance and Engagement

After viewing the 10-min demonstration, the EXP group immediately took the posttest and showed a further 14.4% increase in performance, as evidenced by the posttest results (4.46 ± 0.12 for EXP). As mentioned earlier, the students in the matched CON group were excused from the demonstration and did not take the posttest. For the EXP group, student test scores had increased at each stage of testing (post > pretest 2 > pretest 1), and the paired *t* tests at each stage were highly significant ($p < 10^{-6}$). By comparison, the test–retest reliability measure showed only 3.3% increase without intervention (see *Methods*). This suggests that performance gains observed were likely influenced by the demonstration experience, and not retesting alone.

Interestingly, the demonstration seems to have had a greater impact on certain assessment questions. Much of the performance gain was due to improved performance on question 4, as seen in Figure 4. The proportion of students with correct answers doubled (mean score increased from 0.48 to 0.9; pretest 2 to posttest). In general, correct answers to questions that were more technical and less conceptual (questions 2, 4, and 5) showed significant increases in scores ($p < 0.05$) for pretest 1, pretest 2, and posttests. On the other hand, questions 1 and 3 were more conceptual or intuitive. For question 1, there was no significant change from pretest 1 to pretest 2 or pretest 2 to posttest; for question 3 there was no significant change from pretest 2 to posttest. Contrary to our expectations, the data suggest that the demonstration may have helped students to gain more technical details about Poiseuille's law, with no obvious advantage for conceptual understanding.

Student engagement level was judged to be high during the demonstration, based on several indicators. One co-researcher (J.B.) was in the room to directly observe the students, and noted their emotional engagement: rapt attention to the experiment, eyes directed toward the "scientist" performing the demonstration, intent listening, and minimal note-taking behavior. Consistent with these observations, student attitude data revealed that the overwhelming majority held strongly positive feelings about the demonstration, with 90% being "very interested" or "interested," 9% "neutral," 1% "somewhat interested," and no one checking "not interested." Also, 94% strongly agreed or agreed that the demonstration helped them become "more aware of the importance of Poiseuille's law in cardiovascular physiology," and 96% agreed or strongly agreed with the statement "I would like to have more demonstration activities in this class."

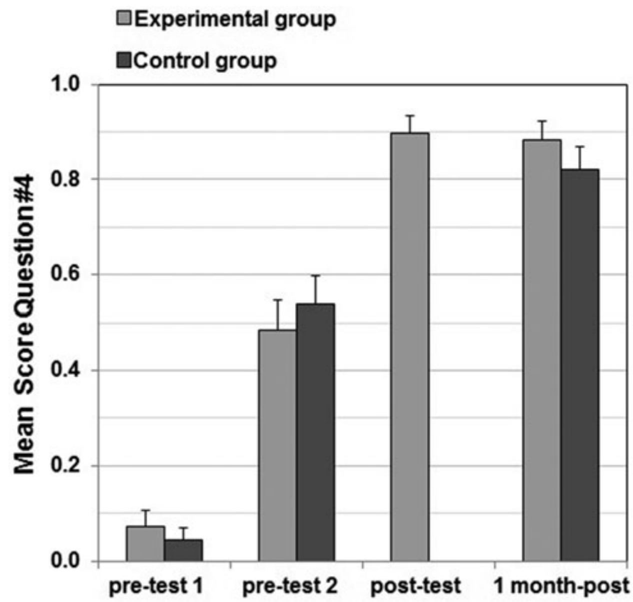

Figure 4. Mean scores for question 4 from the Poiseuille assessment tool. Answers were scored as either correct (1 point) or incorrect (0 points). There is a significant increase in the proportion of students with correct answers for both EXP and CON groups from pretest 1 to pretest 2 and pretest 2 to 1-mo posttest. After the demonstration, the EXP group scores increased (i.e., from pretest 2 to posttest), with no additional significant change at the 1-mo posttest. A statistical comparison of the EXP and CON groups shows no significant differences between their test scores on pretest 1, pretest 2, and 1-mo posttests. (Note: CON group did not view the demonstration and did not take the posttest.) Mean ± SEM scores are given.

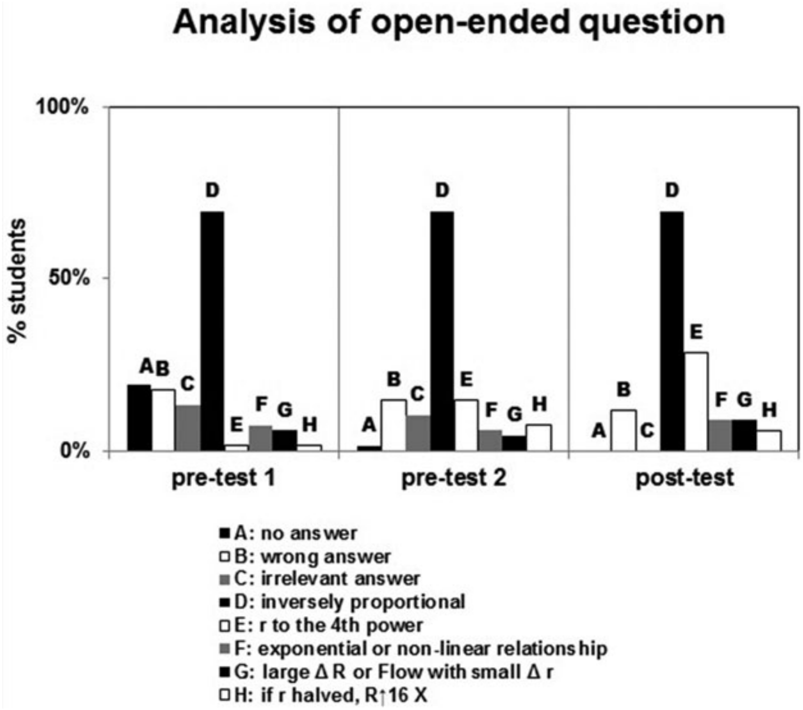

Figure 5. Analysis of the open-ended question for the EXP group. (A) Answers differed after the lecture (i.e., from pretest 1 to pretest 2 tests) for both groups (CON group not shown). After the demonstration (i.e., from pretest 2 to posttests), the EXP group shifted further away from no answer or irrelevant answers (left side of each set) toward more detailed and technical answers (right side). (See the text for discussion.)

Long-Term Retention

Four weeks following the demonstration, the instructor placed one specific question from the Poiseuille's law test (question 4) on the course midterm exam. We used the student responses to determine retention of details concerning Poiseuille's law. Question 4 reads as follows: A decrease in vessel radius from 10 mm DOWN to 5 mm will increase the resistance to blood flow by how much? a) 4 times; b) 6 times; c) 8 times; d) 16 times. The correct answer is d. [According to Poiseuille's law, when the radius is reduced by one-half, the resistance increases 16-fold. To use the equation: $1/(^1/_2)^4 = 16$]. The first time that question 4 was given on pretest 1, fewer than 10% of the students chose the correct answer (0.07 or 7% of the EXP students; 0.04 or 4% of the CON students). After the didactic lecture, roughly half of the students chose the correct answer (0.49 and 0.54 for EXP and CON on pretest 2 results, respectively), so there were substantial gains. After the demonstration, the EXP group further increased their scores (0.90 for EXP) indicating nine out of 10 students put the correct answer, nearly doubling their score after the 10-min demonstration. By the time of the 1-mo posttest, there was no significant change for the EXP group, which already had high scores at posttest; however, the CON group had greatly increased their scores (0.88 vs. 0.82 for EXP and CON, respectively) since the time of their pretest 2. Thus, at the 1-mo posttest, students who had not seen the demonstration were able to "catch up" to those who had seen it.

Analysis of Open-Ended Question

Students were also given the opportunity to explain Poiseuille's law using the open-ended written question. The text of the question was as follows: "In one or two sentences, explain what the quantitative relationship is between vascular radius and vascular resistance."

We focused our scoring analysis on the EXP group because each student had answered the open-ended question a total of three times (pretest 1, pretest 2, and posttest), including before and after the lecture and the demonstration. At the time of the first pretest, many students either gave no answer (19.4%), an irrelevant answer (13.4%), or a wrong answer (17.9%). After the demonstration, there were *zero* students with no or irrelevant answers, and wrong answers had decreased to 11.9%. The majority (70%) of students with correct answers wrote that *radius and resistance are inversely proportional*, and the number of students with this answer remained consistent throughout the study. As seen in Figure 5, the more technical answers are placed toward the right side of each data set, and these answers showed an overall increase during the study. For instance, there was an overall increase from pretest 1 to posttest for answers stating *a large change in resistance occurs with small changes in radius* (G and H combined), suggesting that students understood that the relationship was more than a simple inverse one. There was also an increase in the use of the terms "nonlinear" or "exponential" (E and F combined). In summary, there was an overall shift toward more technical, quantitative, and detailed answers after the lecture, and this trend continued to grow after the demonstration.

Comparisons between Math Scores and Test Scores for Poiseuille's Law Question

The overall mean math scores of students in the two groups (EXP and CON) were similar and not significantly different using an unpaired *t* test. The raw mean scores on the 6-point math test were 4.54 ± 0.14 (EXP) and 4.28 ± 0.16 (CON) for the two groups.

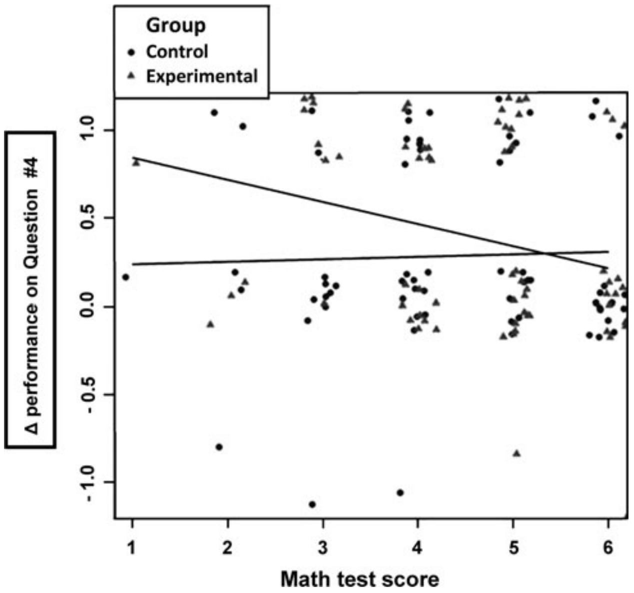

Figure 6. Comparison of student's math skills and Poiseuille's test performance. Each point represents an individual in the CON or EXP groups. The *y*-axis shows the raw difference (Δ) in an individual's scores on question 4 between pretest 2 and 1-mo delayed posttest: 0 (no change), +1 (incorrect to correct), or −1 (correct to incorrect). Regression lines show a trend in which students with lower math scores had slightly greater improvement if they viewed the demonstration (see the text for discussion). For students with higher math scores, viewing the demonstration did not make a noticeable difference.

We then compared students' individual math test performances and Poiseuille assessment scores. The analysis showed significant ($p < 0.05$) positive r (r values for pairwise correlation) between math and pretest 2 tests ($p = 0.012$, $r = 0.30$) and math and posttest ($p = 0.002$, $r = 0.37$). We also compared all individual questions on the pre and posttests with the math scores. In particular, question 4 on the math test seems to correlate most frequently with Poiseuille's law test performance as compared with the other five math questions that were asked. Interestingly, Question 4 is not the most difficult question on the math test, yet it is the most similar to Poiseuille's equation. All correlation coefficients that were statistically significant were positive ($r = 0.25$–0.48). Overall, these data suggested only a slight correlation between students' prior math knowledge and their performance scores on questions concerning Poiseuille's law.

ANCOVA revealed no significant effect of math score on the Poiseuille test performance from pretest 2 to 1-mo posttests for the CON and EXP groups combined ($F_{1131} = 1.316$, $p = 0.253$). However, a test for nonparallelism using a partial F test for equality of covariate slopes (Kleinbaum *et al.* 1988), showed that student responses were indeed slightly influenced by math score ($F_{1131} = 3.419$, $p = 0.0667$). Regression lines helped demonstrate this trend toward a math influence in the CON group (Figure 6, dark circles), as compared with the EXP (Figure 6, light diamonds) group. As seen in Figure 6, a mild trend exists in the data in which students with low math scores had a greater improvement in their performance if they viewed the demonstration, compared with those who did not view it. For students with higher math scores, the demonstration had no effect on test performance.

DISCUSSION

In this study, we describe a new lecture demonstration that can be used in a physiology course to help students understand the physical properties governing blood flow through the circulation, especially vascular resistance. Our demonstration was designed and performed in the lecture setting as a scientific experiment, using tubes or "blood vessels" of various diameters. Our aim in this study was to test the effect of this novel demonstration on student learning of Poiseuille's law, and we found that it helped or motivated students to master the physiology concepts involved.

How a Demonstration Improves Performance

As we and others have noted, a demonstration probably enhances student learning in many ways, such as motivating, applying knowledge to a new situation, or reinforcing existing knowledge. Perhaps students will uncover some of the many misconceptions they hold about the cardiovascular system (Ahopelto *et al.*, 2011).

The precise means by which our own demonstration improved student performance is not clear but the following discussion may shed light on it.

There are certain limitations to instructor-led demonstrations, including our own. Although our own students appeared emotionally engaged, we did not use specific tools to measure engagement (Fredricks *et al.*, 2011). We had encouraged students to make predictions about the outcome of the larger tubes, although we did not require students to record or discuss those predictions due to time constraints. In retrospect, learning could have been further enhanced by extending the time period for the demonstration to include more active participation (Sokoloff and Thornton, 1997; Crouch *et al.*, 2004).

As for the learning gains that we observed, we had hypothesized that students' conceptual and technical knowledge would be improved following the demonstration. On the basis of the shift in the type of answers given by students on an open-ended question, we feel that perhaps both conceptual and technical knowledge were likely improved. Yet we saw only modest gains in performance on the mean multiple-choice assessments, and many students who did not view the demonstration were able to eventually "catch up" at the time of the midterm, albeit on a single assessment question.

A demonstration provides a unique multisensorial experience, an opportunity to directly view three-dimensional objects. It is difficult to know whether our own demonstration had its greatest impact on students with certain sensory learning preferences, as we did not administer learning style questionnaires. We suspect that the lecture demonstration appealed to students with multiple learning preferences, especially those who prefer visual, auditory, and/or kinesthetic learning modalities. In our previous study with students enrolled in this same physiology course, we found that six out of 10 students preferred multiple types of learning, with nearly 70% of the class having kinesthetic or hands-on learning among their preferences (Breckler *et al.*, 2009). Others have found that multisensorial or multidimensional learning, through the use of music (Last, 2009; Courey *et al.*, 2012; Crowther, 2012;), audio podcasts (Hancock and Fornari, 2012), or video clips (Kolikant and Broza, 2011) definitely helps engage students in science or math concepts. In any case, a variety of different kinds of presentations of the same material clearly helps excite students and reinforce learning.

Students were highly enthusiastic about the demonstration. Yet there are potential criticisms of our study design that might explain the impact on performance we observed. It is certainly possible that some of the learning gains may be associated with the retesting of identical questions (Wininger, 2005; Drouin, 2010) or the "testing effect" of asking questions multiple times on the same or similar material (Karpicke and Blunt, 2011; Williams *et al*. 2011). The students in our study were not given the correct answers at any time during the study period, and our own test–retest data show a minimal increase of 3.3% in score due to retesting alone. Yet students who did not view the demonstration topic undoubtedly spoke with their peers and increased studying of the relevant material, thereby skewing the results of the CON group on the final long-term posttest. As others have pointed out, advantages of new or different methods of learning may or may not disappear over time (Pollock, 2009; Chini *et al* 2012), so any long-term effects may be equivocal.

Does Math Skill Influence Learning of Poiseuille's Law?

Initially, we were somewhat surprised that so many of our biology students still struggle with understanding and calculating basic algebraic equations, as evidenced by the math pretest results, even though 78% of our study population had completed at least one semester of calculus. Perhaps this will help raise awareness in teachers of physiology about students' basic algebra skills, beyond simply reinforcing the need for math prerequisites. This suggests that physiology pedagogy should include pertinent math reviews or opportunities for computational skills practice when introducing the quantitative relationships. It is well known that math difficulties persist into upper-division course work and clearly affect the learning of physics (Smithson and Pinkston, 1960). Moreover, students may be able to perform a required calculation, yet not necessarily understand the spatial situation (Pepper *et al*., 2012).

Our data suggest that biology students' math knowledge, especially of fractions and exponents, probably plays an important role in learning and mastering physiology concepts involving physics. Students in our study with low math computational skills were initially lowest in their assessment scores, yet they made substantial gains after lecture and further improvements after the demonstration. Other research suggests that exponents are particularly important for success in both computational and written questions. Exponents are introduced in middle school and become essential for later science course work (Porter, 1989; Elstak, 2007; Kasmer and Kim, 2012). Mastering fractions is an even longer and more complex process that may involve up to six levels of understanding (Pitta-Pantazi *et al*., 2007; Alajmi, 2012; Pantziara and Philippou, 2012). Although fractions are introduced in the United States as early as the first grade, a student's facility with them likely influences success in college physics (Pepper *et al*., 2012) and, as we showed, the related physiology concepts.

Furthermore, we found that students' math skills had a slight influence on their mastery of Poiseuille's law. Specifically, students with lower math scores who viewed the demonstration exhibited better mastery of the material than those who had not. On the other hand, students with higher math skills performed basically the same, whether or not they viewed the demonstration. Although the trend was slight, our data suggest that students with lower math scores might receive additional benefits from viewing class demonstrations, especially those that address quantitative physics concepts.

Demonstrations That Are Designed to Promote Research Experiences

The demonstration impact may be due in part to our research-based approach, as others have found (Deslauriers *et al*., 2011). The demonstration that we created was performed as an in-class science experiment. An experiment helps break up the traditional boundaries of the lecture setting and bridges the styles of lecture and laboratory teaching. The gathering and analysis of actual data gave an immediacy and relevance to its content, more closely resembling the process of science. We felt that we were able to convey more than in a didactic lecture, which, no matter how excellent, is usually a description of the principle and the accompanying mathematical equation. Creating a research-like experience has the potential to be a more exciting discovery process and is consistent with the goals of promoting a broad-based national science literacy that includes scientific thinking (National Research Council, 2003; American Association for the Advancement of Science, 2010). Our task was to accomplish it within the many constraints of a large lecture class, and we feel that we succeeded in doing that, based on the overwhelming positive survey responses by students. A carefully planned, reproducible, and well-executed demonstration can avoid some of the potential pitfalls in the classroom (Roth *et al*., 1997; Smith and Cardiaciotto, 2011). In our case, we gathered a simple raw data set and constructed a graph within the time span of only 10 min.

The Use of Demonstrations in the Physiology Lecture and Beyond

Lecture demonstrations continue to emerge as an active-learning strategy in physiology, and in this paper, we contribute to the growing list of effective demonstrations. Demonstrations have been used in other areas of physiology to illustrate abstract physics principles (Di Carlo, 2008; Anderson *et al*., 2009; Kanthakumar and Oommen, 2012). Many instructors who teach physiology tend to use other active-learning strategies, such as case studies, worksheets, small-group discussions, or computer-based exercises (Rao and DiCarlo, 2001; Dantas and Kemm, 2008; Keen-Rhinehart *et al*., 2009; Carvalho and West, 2011; Ribaric and Kordas, 2011; Ahmad *et al*., 2012). Our study reinforces the use of lecture demonstrations as an effective active-learning strategy to enhance student engagement and learning. We would like to encourage others to use demonstrations, because they can be effective, even when simple or everyday materials are employed (O'Dowd and Aguilar-Roca, 2009; Breckler and Yu, 2011; Green, 2012; Letic, 2012; Vanags *et al*., 2012).

A benefit of our demonstration is that it helps students transfer knowledge to the context of the respiratory system, a topic that often follows the cardiovascular system in a typical biology course. An instructor can bring the three tubes used in the Poiseuille experiment to redirect the focus toward airflow, rather than blood flow. Airway resistance resides primarily in the medium-sized bronchi and bronchioles, coincidentally on the order of magnitude of those used in this demonstration. By using the midsized tube as a rough example of a normal upper airway, one can explain the triggers of inflammation and/or bronchoconstriction that cause narrowing of the lumen and greater airway resistance in asthma. The prevalence of childhood asthma and links with socioeconomic status and/or environment can provide an interesting prompt for class discussion.

For undergraduate students, combating the lag in student performance in math-intensive topics will likely help retain students working toward science and science-related careers (Ceci and Williams, 2010), a national imperative in the last decade. Reaching those students with lower math achievement with creative pedagogy may have special significance for women, underrepresented minorities and first-generation college students, who make up a sizable portion of our classes and may experience motivational differences and other barriers to their academic success (Taasoobshirazi, 2007; Brown, 2010; Higgins-Opitz and Tufts, 2012). Perhaps by improving student engagement in the learning of physics and biology principles, we are also contributing to the growing list of ways to help close the achievement gap for disadvantaged students (Haak *et al*., 2011). Although we performed the demonstration for advanced biology students (i.e., juniors and seniors), introductory biology students could also benefit from deeper exposure to one of physiology's most important concepts, and it will help prepare them for upper-division physiology course work.

For students in health professions schools, revisiting physics and biology through a class demonstration might help students to make necessary multidisciplinary connections (West, 2008). Our demonstration can be used to highlight resistance variations that accompany peripheral blood flow regulation, systemic hypertension, pulmonary hypertension, asthma, and exercise. We also expect the demonstration to be adaptable for classes with either small or large numbers of students, and as a low-cost, safe experiment for the teaching laboratory.

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