IN RECENT YEARS, the importance of inquiry-based learning has been recognized in helping students to understand and retain material better as well as to improve their performance on tests. National Science Education Standards (14), the National Science Foundation (15), the American Association for the Advancement of Science (1), and the Illinois State Board of Education (8) recommend and support inquiry-based learning for students. Inquiry-based laboratory components have also been successfully implemented in college undergraduate physiology curriculum (3, 5) and biology curriculum (12) to increase student learning. Biomedical engineers learned physiology better and reduced their memorization load when team-based learning and inquiry-based research methods were used (2).

Students in high schools are novices to scientific inquiry despite increased inquiry-based activities in elementary and middle school curricula. For example, Indian Prairie District 204 (9) emphasizes biology as an investigative process based on inquiry. The district (located in Illinois) places emphasis on creating hypotheses by studying the facts and devising an explanation for them. The Falk Elementary School curriculum (13) states the following: “All aspects of the curriculum stress student inquiry, critical and creative thinking, and the ability to become independent, lifelong learners.”

My school, the Illinois Mathematics and Science Academy (IMSA), is a state-funded residential 3-yr school (grades 10-12) for students from all over the state of Illinois who are academically talented in mathematics and science. IMSA is considered a “teaching and learning laboratory” that serves educators and students in Illinois through innovative instructional programs that foster imagination and inquiry (7). Students at IMSA often struggle with being away from their parents and having to be responsible for their own learning. In addition, the distractions of residential life sometimes keep them awake late, which results in their being tired for classes, irrespective of whether it is a 7:30 AM class or 2:15 PM class. In my own experience, students do much better if they are physically moving and are responsible for their own work. I surveyed my students and, based on their comments, such as “we like designing our own experiments, it helps us understand better” and “it is so much easier to do something than to listen to someone talking,” I gradually changed my curriculum in my Physiology and Disease (PAD) classes to be completely inquiry-based. Students design all the laboratory experiments in my course, using available resources. The objective of this study was to observe quantitatively whether allowing high school students to take responsibility for designing their own laboratory experiments raised their test scores.

METHODS

Context of the study. The PAD course is a one-semester Biology elective available to juniors and seniors. The prerequisite for this class is a sophomore core biology course called Scientific Inquiries in Biology. PAD classes meet twice a week for 95 min. In general, material is discussed for 20–30 min followed by small-group discussions and later a large-group class discussion. In almost every class, students participate in a hands-on laboratory experience to help them better understand the material discussed in class earlier.

I have taught this class for 5 yr and have always insisted on student interactions to promote better understanding. I conduct a survey at the end of each semester looking for suggestions to improve the course from the students, and some comments I received set me thinking. Students enjoyed the course in general but had a hard time understanding some of the concepts and suggested more laboratories for this purpose. IMSA’s emphasis on inquiry-based learning gave me the idea of making ALL the labs in my course student designed, which I implemented in fall 2008. Thus far, I had only allowed them to design
one or two laboratories and usually gave the students direction on the rest.

The data shown here were gathered from students during my 5 yr of teaching this course beginning fall 2006.

All test questions were formulated and graded by me, as the sole teacher in charge of this course at the school.

**Organization of the activities.** Students were divided into small groups of 3–4 students/group and given the task of designing an experiment for each of the laboratories shown in Table 4. Once the students decided upon their experiment, they asked for resources to perform their experiment. Students could ask for any resources they needed, as long as they were easily and quickly available in the classroom. Students then conducted their experiments and collected data. Later, they wrote individual laboratory reports on their laboratory experience, making conclusions based on evidence.

Students were offered the opportunity of turning in weekly reports where they were encouraged to transfer their understanding in answering simple questions covering the week’s class material. Students were not given a grade for these weekly submissions but were encouraged to turn them in for my feedback. The course was structured such that there were more student-centered experiments during the first quarter of each semester and more teacher-centered experiments during the second quarter of each semester.

Since the PAD course is a one-semester course, the average percent weekly report submissions from the first and second half (quarters 1 and 2) of both semesters of each academic year covering five sections (100 students) were studied over the 5 yr that this course has been offered. Yearly differences between the first and second half of each academic year covering five sections (100 students) were studied over a period of 4 academic years (2006/2007–2009/2010), but not in 2008/2009.

**RESULTS**

Table 1 shows the summary of two-way ANOVA for independent samples (Vassar statistics) comparing the percent mean weekly report submissions by quarter from 2006 to 2010. The interaction value of 0.0123 suggests lack of consistency among the academic years studied. This difference is also shown in Fig. 1, which shows the weekly percent report submissions for the first quarter of each semester to be consistently higher than the second quarter for the years of 2006/2007, 2007/2008, and 2009/2010, but not in 2008/2009. Figure 1 also shows a significant difference between quarters 1 and 2 ($P = 0.0002$) and between the academic years of 2006/2007–2009/2010 ($P < 0.0001$). Four hundred students were studied over a period of 4 academic years beginning 2006/2007. Quarters 1 and 2 refer to the first and second halves of each semester. The course was structured such that there were more student-centered experiments during the first quarter of each semester and more teacher-centered experiments during the second. Since the PAD course is a one-semester course, the average percent weekly submissions from the first and second halves of each semester (~75–90 min) on the same laboratories. It is important to note here that all the students were given equal opportunity to learn through inquiry and participate in discussion for the concepts covered in class; only the laboratories were either student centered or teacher centered.

At the end of the semester, score percentages of those test questions that specifically tested student transfer in the four unit tests were analyzed for both sections using two-way ANOVA. Table 5 shows examples of some student transfer questions.

### Table 1. Summary of the results of two-way ANOVA for independent samples comparing mean percent weekly report submissions by quarter from 2006 to 2010

<table>
<thead>
<tr>
<th>Groups for Which Mean Percent Weekly Report Submissions were Compared</th>
<th>Degrees of Freedom</th>
<th>Error degrees of freedom = 48.</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarters 1 and 2 of each semester</td>
<td>1</td>
<td>16.4 (F Value)</td>
<td>0.0002</td>
</tr>
<tr>
<td>Interaction</td>
<td>3</td>
<td>4.03</td>
<td>0.0123</td>
</tr>
</tbody>
</table>

Quarters 1 and 2 refer to the first and second quarters of each semester.

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**Fig. 1.** Comparison of mean percent weekly report submissions by quarter from 2006 to 2010. Quarters 1 and 2 refer to the first and second halves of each semester. Since the Physiology and Disease (PAD) course is a one-semester course, the average percent weekly report submissions from the first and second halves of both semesters of each academic year covering 5 sections (~100 students) were studied over a period of 4 academic years (2006/2007–2009/2010). Weekly reports refer to optional reports that helped student transfer of understanding. The course was structured such that there were more student-centered experiments during the first quarter of each semester and more teacher-centered experiments during the second quarter. There was a significant increase in the first quarter compared with the second quarter ($\star$) for the years of 2006/2007, 2007/2008, and 2009/2010, but not in 2008/2009. The mean weekly report submission percentages for the first quarter (more student-centered experiments) were highest during 2009/2010. Second quarter submission (more teacher-centered experiments) increased in 2008/2009, and this increase was maintained fairly consistently in 2009/2010 as well.

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1 All data were analyzed using two-way ANOVA for independent samples using Vassar statistics (http://faculty.vassar.edu/lowry/VassarStats.html) (16). In addition, graphs were made using Microsoft Excel.
both semesters of each academic year covering 5 sections (100 students) were studied over a period of 4 academic years (2006/2007–2009/2010). The mean weekly report submission percentages for the first quarter (more student-centered experiments) was highest during 2009/2010 and the second quarter (more teacher-centered experiments) showed an increase in 2008/2009, which was maintained fairly consistently in 2009/2010 as well.

Table 2 shows the summary of two-way ANOVA for independent samples (Vassar statistics) comparing the percent total test score before and after implementation of inquiry in fall 2008 from the academic years of 2006/2007–2009/2010. The interaction $P$ value of $<0.0001$ suggests a lack of consistency across the tests studied. Figure 2 shows the significant difference between total test score percentages before and after inquiry ($P = 0.0125$) and between tests ($P < 0.0001$). Inquiry refers to an increase in student-centered experiments; all experiments were gradually changed from teacher centered to student centered. Figure 2 also shows a clear increase in total student test score percentages after inquiry compared with before inquiry for tests 1, 3, and 4, with test 4 having the greatest increase. However, the total test score percentages for test 2 were slightly higher before inquiry compared with after inquiry. Score percentages were lowest for test 3 and highest for test 4.

Table 3 shows two-way ANOVA results for independent samples (Vassar statistics) comparing the percent scores on only those questions that tested student transfer in two classes in fall 2010. The interaction $P$ value of 0.328 shows that there was not a significant difference among the four tests studied. Figure 3 shows the significant difference between the student-centered and teacher-centered groups ($P = 0.012$) and also between the tests ($P < 0.0001$). Percent scores were compared because not all test questions were worth the same number of points during the time period studied. Figure 3 also shows a consistent increase in score percentages of student-centered groups for tests 1, 3, and 4 but a decrease in the student-centered group score percentages for test 2. This decrease, however, is slightly lesser in magnitude than the increases on the other tests, thus allowing for an interaction $P$ value of 0.328, and resulting in the lack of significance among the tests studied. Test 3 score percentages were the lowest and test 4 score percentages were the highest for both student-centered and teacher-centered groups.
How We Teach

Table 4. Laboratory experiments in the PAD course and schedule by unit

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The immune system: summary of slides of autoimmune diseases (week 3)</td>
</tr>
<tr>
<td>2</td>
<td>The cardiovascular system: recording changes in heart rate and blood pressure (weeks 6 and 7)</td>
</tr>
<tr>
<td>3</td>
<td>The respiratory system: recording changes in lung capacity (week 10)</td>
</tr>
<tr>
<td>4</td>
<td>The neuromuscular system: recording changes in various central and peripheral nervous system reflexes caused by different kinds of activities (week 13)</td>
</tr>
<tr>
<td>5</td>
<td>The digestive/urinary system: explaining the pathophysiology of various diseases based on experiments performed using kits in the laboratory (week 14)</td>
</tr>
</tbody>
</table>

PAD course, Physiology and Disease course. In addition to these physiology experiments, each unit also includes anatomy explorations and dissections of sheep organs, which are not shown above.

Table 4 shows laboratory experiments and the schedule by unit in the PAD course.

Table 5 shows sample student transfer questions on tests from the four unit tests in the course.

Table 6 shows student responses to questions about inquiry-based laboratories from the student-centered group. These comments were in response to specific questions on what students found good and bad about the class. Table 6 shows that students felt that their study times decreased and their grades went up by ~15–20%.

Table 7 shows the results of student surveys on the effect of the method of PAD instruction had on their performance in the other subjects they studied during the semester. The student-centered groups reported greater improvement in performance in other subjects than the teacher-centered groups. The student-centered groups also reported better study skills, decreased time studying for tests, and better performance on tests, especially the transfer questions. When asked how this kind of instruction helped their test performance, students in the student-centered group reported the following:

“It helped modify study skills and understand concepts better because we were responsible for designing labs, made study guides and discussed more. Study time decreased and we did better on later tests especially the transfer questions.”

Students in the teacher-centered group reported that this method of instruction:

“Did not really help much, we did not try to study concepts beforehand because the teacher gave us the lab procedures. We did not always make study guides, spent a lot of time memorizing, and actually did worse on later tests that involved transfer questions.”

All test questions were formulated and graded by the author, who is the sole teacher for the course at the school.

DISCUSSION

Results from this study concur with those of DiPasquale et al. (3) and Luckie et al. (4) and suggest that allowing students to shoulder responsibility for designing experiments, analyzing data, and making conclusions based on evidence has a positive effect on their learning.

Trying different methods to promote inquiry, such as those tested by Cardinal (2) and Casotti et al. (3), might further improve high school students’ understanding of physiology through inquiry, which, in turn, could help them have better attitudes toward learning and possibly be better students in college. The student surveys in this study show a definite step in this direction. Students reported decreased study time and improvement in studying for other subjects. Further research in this regard is planned by surveying the juniors’ progress into their senior year and evaluating the data gathered at that time.

Since there was a significant difference between weekly quarter submissions between the academic years of 2006/2007 and 2009/2010, we can assume that engaging students in more student-centered activities encouraged them to turn in reports more regularly than before. The significant difference between quarters 1 and 2 for these years could be because when this course was first designed laboratories in quarter 1 were student designed and laboratories in quarter 2 were teacher designed. Later, beginning fall 2008, all laboratories were converted to student centered. Both first and second quarter submissions increased over the years studied. This indicates that students were motivated enough to turn in these weekly reports despite pressure from other classes and finals during the second half of each semester. These results are similar to those of Lord et al. (11), who found that weekly quiz scores and attendance were higher for his constructivist (student centered) section compared with his traditional (teacher centered) section of students in nonmajor general biology laboratories courses in the Indiana University of Pennsylvania. The results of this study also show that report submission percentages for the first quarter (more student-centered experiments) were consistently higher than those for second quarter (more teacher-centered experiments) for all years except 2008/2009, when the submission percentages for second quarter were almost equal to those for the first quarter. This timing coincides with the conversion of all laboratories to student-centered laboratories. It is interesting to...
The PAD course helped your performance on tests anyway and never do well on what she calls transfer questions, so for me it was a pain.”

“I loved the labs. This course has so many labs and they are all interactive. I had to keep moving all the time, it was hard because it was a 7.55 am class, but the labs woke me up and they were a lot of fun, especially because she let us decide what we wanted to do. We had to know what we were testing, and this helped me study for the tests and do better. Knowing what I did on the labs meant less time studying them. That works! Plus, I started doing better on tests, my grade went up by a letter grade.”

“The labs were the best part of this course. I liked that we were always required to do physical activity and that we could relate what we tested in the lab to what we do in real life. This helped me understand the material better. I also found that I was studying PAD for less time than before, and that freed up time for other subjects. If I did not have to decide what to do in these labs, I think I would have just memorized the concepts and done worse on the tests than I actually did. My test grades went up about 20%. I love this class!”

“We had so many hands-on inquiry based experiences in this class. I liked that we were allowed to decide what we were testing and that we could relate everything to our body. It helped me understand the organ systems better and I did about 20% better on the later tests.”

“I prefer lecture based classes and therefore did not like the fact that we were always being asked to do inquiry based stuff in labs. I get how that is supposed to make you learn better but it was too much work and I did not do it. However when I noticed that my friends were doing better on tests because they were designing the labs because they remembered things better, I wished I had taken the time to do so as well, I would have gotten a better grade than I did.”

Note that second quarter submission percentages did not match those of first quarter in 2009/2010, but this could be due to any number of factors, including the fact that most of the students enrolled in the year 2008/09 were juniors, who are more motivated to try new things, and those enrolled in 2009/2010 were mostly second-semester seniors, who are less motivated to turn reports in on time. More research in this regard for future PAD classes might throw some light on this indiscrery.

This study also showed a significant difference between total test score percentages before and after implementation of entirely student-centered labs in fall 2008 compared with previous years (2006/2007 and 2007/2008). During the 2 yr in between, all laboratories were slowly converted from teacher centered to student centered. This implementation of inquiry-based, student-centered teaching seems to have helped the students, as judging by their total test scores, to take more interest in studying for their tests as well as improved their understanding. These results concur with those of Catalano and Catalano (4), whose results showed a 15% increase over average when a student-centered approach to engineering education was implemented. The student surveys in this study also attest to an improvement in attitude, modified study habits, and decrease in study time in the student-centered group compared with the teacher-centered group. Grades in the student-centered group also were improved in the PAD course, and students stated that the method of instruction in the PAD course helped their performance in other subjects as well. These other subjects include some that use the more traditional format of teacher-led teaching as opposed to student-led teaching.

It is interesting to note that the results showed an increase in total test score percentages after the implementation of inquiry compared with those before inquiry for tests 1, 3, and 4 (with the greatest increase on test 4), whereas score percentages for test 2 actually showed a decrease after inquiry. This could be because test 2 was on the cardiovascular system, and, although the test contained several questions that required transfer, they were analyzed more easily compared with similar questions on other systems (tests 1, 3, and 4), probably because most students had prior experience studying the cardiovascular system in their elementary and middle schools. Further research is planned through student surveys on prior experiences with the cardiovascular system and also by studying future PAD total student test score percentages to look for explanations of the results obtained here.

In a focused effort to see how much the student-led inquiry based laboratories had helped improve student understanding, two sections of the fall 2010 PAD class were divided into two groups each. One group (teacher-centered) was led by the teacher in laboratory experiments, and the other group (student centered) designed their own laboratories. At the end of the semester, test questions that tested student transfer were pulled out of four unit tests, and score percentages were compared among the teacher-led and student-centered groups. Student-centered groups scored significantly higher, suggesting that designing their own laboratories might have improved student understanding compared with the teacher telling them what to do. Percent scores were compared because not all test questions were worth the same number of points during the time period studied. This part of the study was modeled after that of teachers.

Table 6. Student comments about inquiry-based laboratories from the student-centered groups

<table>
<thead>
<tr>
<th>Survey Subjects</th>
<th>Student-Centered Group</th>
<th>Teacher-Centered Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>The PAD course helped your performance in other science classes</td>
<td>77</td>
<td>45</td>
</tr>
<tr>
<td>The PAD course helped your performance in English, foreign language, and world studies</td>
<td>43</td>
<td>28</td>
</tr>
<tr>
<td>“A”s earned in the course from your group</td>
<td>13</td>
<td>7</td>
</tr>
</tbody>
</table>

Values are in %.

Table 7. Surveys on the effect of instruction in the PAD course on other subjects studied

<table>
<thead>
<tr>
<th>Survey Subjects</th>
<th>Student-Centered Group</th>
<th>Teacher-Centered Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>The PAD course helped your performance in other science classes</td>
<td>77</td>
<td>45</td>
</tr>
<tr>
<td>The PAD course helped your performance in English, foreign language, and world studies</td>
<td>43</td>
<td>28</td>
</tr>
<tr>
<td>“A”s earned in the course from your group</td>
<td>13</td>
<td>7</td>
</tr>
</tbody>
</table>

Values are in %.
Lord et al. (11) except that instead of using entire sections, the sections were divided into half. Also, that study used entire quiz scores, whereas the present study focused on transfer questions only. The results of this study also showed a consistent increase in score percentages of transfer questions for the student-centered groups for tests 1, 3, and 4 but a decrease in the student-centered group score percentages for test 2. This decrease, however, was slightly lesser in magnitude than the increases on the other tests. This is an interesting observation in light of the similar trend of decreased total test score percentages for test 2, as discussed above. Further research on correlation between transfer question score percentages and total test score percentages for test 2 is planned, using student scores from the next few semesters, and this, combined with student surveys on previous experience with the cardiovascular system, might promote a better understanding of why students did not benefit from this unit to the same extent that they did with other units. This might, in turn, inspire new and improved ideas of betterment, based on inquiry and student-centered experiences, that would enable students to improve their understanding of the cardiovascular system.

The reasoning behind this study was to observe if inquiry-based, student-centered teaching helped students do better on tests and understand material better. All students had an equal opportunity for discussion and inquiry-based learning for material covered in class; only the design of the laboratories was either student or teacher centered. At the end of the semester, based on verbal student comments, the teacher-centered group felt that they “had been cheated out of learning how to study” and that “their other classmates in the student-centered group had an unfair advantage.” Of the 20% As in the course, 13% came from the student-centered groups and 7% from the teacher-centered groups. These findings suggest that student-centered learning may be beneficial to students not only in the class in question but also in other classes with more traditional methods of study. More research is also suggested to follow the study habits and improvement (or not) of these students in other classes in the next 2 yr.

Although both groups were given equal opportunity to “learn how to study” through weekly report submissions that required students to apply their understanding to answer the formative questions, and both groups were also given the opportunity to make observations and discuss concepts with their team members, only the student-centered groups were required to do the latter. The teacher-centered groups had the option of discussion but preferred not to do so since they did not have to. My observations of the two sections showed that the student-centered groups were always enthusiastic and eager to learn, showing more interest than their counterparts, but the teacher-centered groups often appeared bored and preferred not to do any extra work. Student-centered groups were required to use prior knowledge and experience to learn new concepts and, therefore, were always engaged, even at 7:55 AM, whereas the teacher-centered groups were not. Future interviews and focus groups with students to discuss their attitudes toward learning are planned for next year.

The small SE in the analyses could be accounted for by the fact that students had very similar score percentages in the same group, especially if they did not know the correct answer to the transfer questions. It is encouraging that the results of this study concurred with other studies (4, 10) that demonstrated a raise in student test scores in college undergraduate courses. The results of this project will be used to further improve student test performance by creating more opportunities for inquiry-based learning and by implementing new technology-driven means to this end.

Work is being presently done to combine student data from the 5 yr that I have taught this course into a common website that would be available to students for more meaningful analyses. Although the focus this semester was more on student performance than the results of their experiments, I hope to have enough data in the next few years to correlate their laboratory results with their test scores and surveys on understanding of the material. In this regard, the successful student investigations model of FitzPatrick and Campisi (6) in exercise physiology is very encouraging. It is interesting to note that high school students can also benefit from the same kinds of inquiry-based techniques that undergraduates do. I am planning to follow up this study by including each year’s outcomes to expand my database. I will also continue collecting feedback from students on the best ways to help them study while continuing to give them feedback on the formative reports that require transfer. To explore the possibility of incorporating new and recent research experiments into my PAD course, I have also started collaborating with college professors and other professionals who are doing physiology research in their laboratories. Through these methods, I hope to help students improve not only their performance on tests but also learn leadership and analytical skills through inquiry-based thinking, which will serve them well in their undergraduate and graduate courses in college.

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DISCLOSURES

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

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