Team-Based Learning Enhances Long-Term Retention and Critical Thinking in an Undergraduate Microbial Physiology Course

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Abstract

We used team-based learning to improve comprehension and critical thinking of students in an undergraduate microbial metabolism-physiology course. The course used well-known bacterial pathways to highlight themes of energy conservation and biodegradation. Prior to the introduction of team-based learning, student recall of this information was poor and students had difficulty extrapolating information to new organisms. Initially, individual and group quizzes were added to promote problem-solving and critical-thinking skills. This significantly improved student attitudes about the amount of information they learned and whether the instructor promoted critical thinking. However, retention of the material as judged by final examination scores was still poor. In the next year, two challenging projects were added to the course to complement the above themes: (i) postulating a pathway for the metabolism of a substrate by a bacterium, and (ii) modifying the current model for anaerobic sulfate reduction by incorporating recent genetic information. The inclusion of the team projects significantly improved final examination scores compared to the previous year without team projects. Overall, team-based learning with challenging projects improved the students' comprehension and retention of information, critical thinking, and attitudes about the course and focused student-instructor interactions on learning rather than grades.

Article

Teaching microbial physiology can be challenging because it is easy to overwhelm students with information. Microorganisms metabolize a number of compounds as carbon and/or energy sources and use diverse pathways and modes of energy conservation. In addition, an enormous amount of information has accumulated on microbial metabolism. However, such information is critically needed if the students are to understand how microorganisms function.

What are the ways in which instructors can respond to this challenge? The traditional approach of teaching microbial physiology as a lecture course is efficient in that it allows the teacher to present a large amount of information to many students. The downside of this approach is that it fosters passive learning where students expect to be told what to learn and how to learn it (31). Students do not develop the skills or the interest to learn on their own, and enthusiasm for the course is low. It is also counterproductive, given what we know about how students learn and what the mission of a university is. It is clear that learning styles of students in science classes are diverse (5, 6, 12, 22). Thus, at best, the lecture format reaches only a select group of students. The mission of a university should be to introduce students to research and inspire in them the passion for discovery (16). Finally, there is the temptation to cover as much material as possible in a lecture, but this often comes at the expense of in-depth understanding of key concepts such that students have difficulty applying these concepts in new contexts (1). These points raise the question of how we can change our mode of instruction so that students acquire the information base they need, but they also engage in the genuine inquiry that is at the heart of the scientific process.

A number of studies indicate that active learning, especially the use of small group activities, improves student performance and enthusiasm in diverse college courses (2-7, 9, 18, 19, 21, 31, 37). Several recent papers examine the value of small groups for teaching microbiology. Suchman et al. (31) found that small group activities were effective in an introductory microbiology course if the activities had well-defined and obtainable goals and clearly articulated guidelines. Cooperative learning activities increased student interest in research in microbiology (5) and the inclusion of collaborative learning and other activities improved the final grades of students in an introductory microbiology course for allied health students (19). Trempy et al. (32) found that cooperative learning where students work interdependently on well-defined tasks resulted in high retention of key concepts and high student satisfaction in a microbiology course that included both science, mathematics, engineering, and technology (SMET) majors and non-SMET majors.

These reports on the use of small groups indicate some clear benefits from small groups in comparison with a primary reliance on lecturing. However, there may be additional benefits in a more structured, intense use of small groups, as represented in team-based learning. During the academic years from 2000 to 2002, we restructured the microbial physiology course to include an increasing number of team-learning activities. In this article, we describe the changes that we made from year to year and the impact of these changes on student learning, student attitudes, and student-instructor interactions.

TEAM-BASED LEARNING: AN OVERVIEW

Team-based learning is a special, in-depth approach to the use of small groups in teaching. It calls for restructuring a course in a way that facilitates the development of newly formed groups into teams and then engages those teams with challenging, complex learning tasks (14). There are three general approaches to the use of small groups that are well identified in the literature on college teaching: cooperative learning, problem-based learning, and team-based learning. In general, cooperative learning advocates the use of small groups as a specific activity that is inserted into an existing course structure that otherwise remains more or less undisturbed (21, 25, 29). In contrast, problem-based learning calls for a significant restructuring of the design of a course such that groups of students are presented with a problem before they have studied all the relevant concepts (13, 36), i. e., "The problem comes first." Team-based learning falls in between these two approaches. In team-based learning, the course does need to be structured in a special way to support the development of groups into teams. But, unlike problem-based learning, students in team-based learning courses acquire the needed information and concepts first, often by the traditional lecture-based format, and then engage as teams in various application exercises.

In addition, there are a few other more specific differences that distinguish team-based learning from the other two approaches. In team-based learning, individual members of the team are not assigned roles. The team contains five to eight members, is kept intact for the entire academic term, works primarily during class time, and is given frequent and prompt feedback on its work. Unlike problem-based learning, team-based learning does not require the use of tutors to guide the work of individual groups. Finally, the team is given tasks that require the team to make a decision or solve a problem—not a lengthy paper to write. (For more specifics on how team-based learning works see: http://www.ou.edu/ipd/teambasedlearning.html). In team-based learning, the students become motivated to do the work necessary for high-quality learning, develop a thorough understanding of the content, learn how to solve very complex problems, and learn the value of teamwork when confronted with difficult problems (14, 24). In general, it promotes a learning-centered culture in the course.

How does it work? Team-based learning sets up a sequence of learning activities that consists of three phases. First is the **preparation phase** where students acquire introductory information from lectures, readings, etc. and are tested on this information to ensure accountability. Students take a test on this content individually and then immediately retake the same test as a group. Both tests are graded and both count as part of the course grade. This is followed by "corrective" instruction from the instructor as needed. Second is the **application phase** where the teams are given increasingly challenging problems on which to work. These are practice problems, i.e., they are assessed but they do not count as part of the course grade. The teams work on these problems during class and the instructor leads a discussion of their responses. This provides immediate feedback on the quality of their responses. Finally, there is the **assessment phase** where the teams are given challenging projects on which to work that will form part of their grade.

Making teamwork a central part of the course requires changes in the way assessments take place. There must be both individual and group accountability. Graded teamwork should constitute a significant portion of the course grade, e.g., 20% to 40%. In addition, individual students must be accountable for their individual preparation and for their contribution to the work of the team. This latter factor calls for peer assessment at the end of the course in which each member of a team rates the contribution of other team members. A summary score of this rating process is then included in the calculation of the final course grade for each student.

SITUATIONAL ANALYSIS

Type and purpose of course. Microbial physiology is a senior-level course required for all microbiology majors. It has three 50-minute lecture periods each week and an enrollment of 55 to 70 students. The course focuses on substrate-level and chemiosmotic mechanisms used to conserve energy in diverse bacteria and the role of microorganisms in the cycling of elements on Earth. The metabolism of different types of chemical structures is covered to illustrate the diverse approaches that microorganisms use to obtain energy, the unifying features of metabolic pathways, the mechanisms of carbon-carbon bond cleavage, and the role of coenzymes and vitamins.

Students' background. Nearly all of the students in the microbial physiology course are senior microbiology majors. A few students come from environmental science, zoology, and biochemistry. The career goal of most undergraduates is medical school or a medically-related profession. There are a few beginning graduate students, mostly from microbiology.

Problems prior to the introduction of team-based learning. Prior to 2000, the course was taught with a lecture format. A major problem was that the students felt overwhelmed with information. In addition, they believed that the course focused on memorization, and relevance of the information to future applications in their careers was lacking. The retention of essential information was also poor. Basic aspects of essential pathways were forgotten after the examination and could not be applied later in the course.

PEDAGOGICAL CHANGES MADE

In 2000, team-learning activities were introduced. First, we put students into teams and introduced weekly quizzes that were taken by individual students and then by the teams. In the years 2001 and 2002, the teams were given challenging projects on which to work.

Forming the teams. Teams were organized during the second week of the class based on the previous experience and training that the students had in microbiology and chemistry. Each team contained five to six students. Students who were seniors and had at least four microbiology courses and biochemistry stood and were placed into separate teams. Next, students who were seniors who had taken at least four microbiology courses but not biochemistry were placed into the teams formed above. Graduate students were dispersed into separate teams. This process was repeated until all students were placed into teams. Students were not allowed to switch teams once they were formed. This placement process allowed each team to have similar training and experience to other teams and specifically avoided assignment based on grade point average.

Weekly individual and team quizzes. In 2000, weekly team-learning quizzes were introduced. Each week, students individually took a short quiz with two to three multiple-choice questions that covered material discussed in lecture that week. Questions entailed calculations, problem solving, or predicting a potential outcome. For example, after discussing the structural features needed to break a carbon-carbon bond, the students were asked to choose the most appropriate chemical to use as a gasoline additive from a list of chemicals that differed in their biodegradation potentials and octane ratings. The students were given about 15 minutes to complete the quiz, with access to their reading material. After the quiz was collected, the students organized into their teams and took the same quiz. The teams were given 15 minutes to reach a consensus. During the team quiz, the instructor roamed from team to team, monitoring how the teams were approaching the problem. After turning in the team quiz, the teams simultaneously reported their answers by one member from each team raising a card with the letter of their answer to the question. This allowed the teams to compare their answers. If the teams had different answers, the reasoning behind and relative merits of each answer were discussed. If the teams could not resolve their differences, the instructor could intercede and provide corrective instruction. However, many of the questions did not have simple answers. In these cases, discussion continued to allow the students to express their thoughts completely. If the reasoning was sound and well argued, credit was given.

Addition of team projects. In 2001 and 2002, two team projects were added to the weekly individual and team quizzes. The mid-semester project was based on material taught during the first half of the course while the end-of-semester project used material from the last half of the course. For each project, the students received a handout that explained the problem and provided the experimental data and three to four journal papers to read. The latter were available to the students on the web or as handouts.

The mid-semester project asked students to elucidate the pathway for the metabolism of the compound and amount of ATP made based on an extensive data set. In the spring of 2001, students were given data on syntrophic propionate metabolism from a paper that was due to be published (10). The following year, the instructor created a problem by using published data on the metabolism of a compound, trans-aconitate, from one organism (17) and applying the data to metabolism of this compound by a different bacterium (8) (Fig. 1). The students had to determine whether the data were consistent with known pathways for propionate or trans-aconitate metabolism based on their readings. If not, the students had to propose a pathway or modify the existing pathway to explain the data.

The end-of-semester project focused on chemiosmotic mechanisms of energy conservation. The project asked whether the electron transport chain of sulfate-reducing bacteria that was published in the textbook (35) should be modified in light of recent papers describing properties of mutants defective in one or more of the components of the electron transport chain. In 2001, papers on mutations in cytochrome c_3 (28) and the *hmc* complex (11) were used. In 2002, a paper that described the effects of a mutation in the iron-only hydrogenase (27) was used instead of the paper on the *hmc* mutation. If a modification was needed, the students had to propose an electron transport chain that was consistent with the properties of the mutants and generated a sufficient number of protons on the outside of the cell to explain previously published molar growth yields (23).

Sequence of activities for the team project. On the Wednesday of the week that the assignment was due, each student turned in a one-page analysis of the problem. This served as the individual portion of the grade for the project and ensured individual accountability. During class, the students worked with their teams to formulate a consensus opinion. Each team was given poster paper and pens to prepare its poster. At the start of the class on Friday, each team hung its poster on the wall of the classroom. The posters did not have identifying names or numbers. During the first 20 to 30 minutes, each team reviewed the posters of the other teams. Each team then met to critique the posters. After a consensus was reached, each team placed a note on each poster indicating its rating. A green note meant that the poster explained the problem well; a yellow note meant that there was a question about the poster; and a red note meant that a major problem existed with the poster. The notes were posted simultaneously. The instructor then asked different teams to discuss the reasons for their ratings and allowed the team that prepared the poster to respond to the issues raised. At the end of class, the instructor gave a short summary of good and bad points about the posters.

After class, the instructor made his own assessment of the scientific validity of each poster and the ability of the teams to assess each other fairly. The team grade was based on how well the poster answered the problem (instructor's assessment, 80%), how well the team assessed other teams (10%), and how well the team responded to questions and critiques (10%).

METHODOLOGIES FOR ASSESSING THE EDUCATIONAL VALUE OF THE TEAM PROJECTS

The quality of the projects was the first criterion used to assess the educational value of the team projects. This assessment included: depth of analysis, inclusion of information discussed in the course, integration of material learned in other classes, and intuitive and creative deductions that the teams made themselves.

Performance on the final examination was used to measure the impact of team-learning activities on the students' retention and understanding of information. The final examinations for the years with and without group projects were prepared so that the format, coverage, and degree of difficulty were as similar as possible. On the final examination, students were asked to perform tasks including: matching redox reactions, substrate-level phosphorylation reactions, pyruvate metabolism enzymes, and anaplerotic biosynthetic reactions for different microbial metabolisms; calculating ATP yields from fermentation balances and different arrangements of electron transport components; and identifying and providing functions of several vitamins and cofactors. Analysis of variance was used to determine if a significant difference existed between the means of the final examinations in years with and without group projects (38). A Tukey test was done to determine which means were significantly different (38). The level of significance was 0.05.

Two questions on the university's student evaluation questionnaire were used to measure the student's attitudes about changes made in the course. One question asked the students to rate the amount of information that they learned in the course; the other asked the students to rate the instructor's ability to encourage critical and independent thinking. Chi-square analysis of the data was conducted to determine whether the responses to the evaluation questions were significantly different in years with and without team activities (20). Chi-square analysis was also used to determine if the proportion of individuals that received 90% or greater on the final examinations was significantly different between years with and without team projects. The level of significance was 0.05. In 2002, the students were asked to comment on the back of the student evaluation questionnaire whether the team-learning activities contributed to their learning and to provide feedback on the strengths and weaknesses of these activities.

RESULTS

The first change made was the introduction of the group quizzes in 2000. This change made the class more energetic, and the students enjoyed the opportunity to engage in meaningful discussions with each other about the subject material. However, their final examination scores indicated that their retention of the content was poor. Therefore, a further change was made, namely the addition of the team projects.

Outcome of team projects. The analysis of the team-learning projects showed that the students performed at a high level. The mid-semester project asked the students to elucidate the pathway for the metabolism of the compound and amount of ATP made based on an extensive data set. The project on syntrophic propionate metabolism in 2001 was especially challenging. It required the analysis of data using various ^{14}C-labeled and ^{13}C-position-labeled substrates relative to the literature on known pathways for propionate metabolism (10). All of the teams (*n* = 12) correctly deduced that a new pathway for propionate metabolism was required. Surprisingly, three-fourths of the teams had creative solutions to the problem, including the formation of a six-carbon intermediate, a novel cyclic intermediate, or a novel alpha-oxidation mechanism that completely accounted for the data. Their answers showed that these teams successfully applied lecture information on the reactivity of CoA substrates and the mechanisms of biotin- and cofactor B_{12}-mediated reactions.

In 2002, the mid-semester project involved the analysis of data on enzyme activities and intermediates detected during growth with glutamate and trans-aconitate by a rumen bacterium (Fig. 1, Fig. 2A). Again, all 12 of the teams correctly deduced that a modification of the original pathway (assumed to be that discussed in (8)) was required. Ten teams completely accounted for the enzymes and intermediates detected and the intricacies of labeling patterns of acetate with the different substrates. This was not a trivial accomplishment since the students had to understand that citrate, one of the possible intermediates, is prochiral (i.e., a compound that lacks an asymmetrical carbon atom but has the potential to react in an asymmetrical manner). Neither the lectures nor the text discussed the question of prochirality. When questioned about this information, the students responded that they used information from their organic chemistry or biochemistry courses to help solve the problem.

The end-of-semester project involved a study of the electron transport chain for dissimilatory sulfate reduction (33) (Fig. 2B). For both years, all of the teams (*n* = 12 for each year) correctly deduced that the respiratory chain in the text needed modification. Many of the groups used creative approaches to explain the phenotypes of the mutants, for example the inclusion of branching points or different domains on some components such as the *hmc* complex that had different affinities for redox carriers. Thus, they understood how to use genetic information to solve physiological problems. Clearly, the analysis of the team projects showed that the students were able to (i) interpret extensive experimental data sets and recent discoveries in the literature correctly, (ii) integrate and apply information they obtained in other courses, and (iii) use their creativity to solve physiological problems.

Effect of team projects on retention and understanding of information. Student performance on the final examination was used to measure the effectiveness of the team projects in improving the retention and understanding of information. The data from 2000 were used as the control since this is the year when weekly group quizzes were first introduced. In the subsequent two years (2001 and 2002), the course was taught in an identical manner as in 2000 (i.e., same text, nearly identical coverage of topics, and the use of weekly quizzes), except that the two team projects discussed above were added. The average on the final examination in 2000 was 133.4 ± 28.9 (Table 1), and many of the students in 2000 scored below 70% (Fig. 3). After the inclusion of the group project, there was a significant improvement in the performance on the final examination (Table 1). Analysis of variance and Tukey test showed that the mean scores for the final examination for the two years with team projects (2001 and 2002) were not significantly different from each other, but were significantly higher than the mean for the year without the team project (2000). Chi-square analysis showed that the proportion of students that had 90% or greater on the final was not significantly different. This argues that the final examination had a similar degree of difficulty in each of the three years. The main change that occurred in the grade distribution was that fewer individuals scored below 70% and more individuals scored between 70% and 90% in the two years with a team project compared to the year without the team project (Fig. 3).

Student attitudes concerning team activities. Student evaluations were conducted in the second to last week of the course as required by university policy. Two questions on the student evaluation form were used to measure the students' attitudes about changes made in the course. One question asked the students to rate the amount of information that they learned in the course; the other asked the students to rate the instructor's ability to encourage critical and independent thinking. The responses from 1999 were used as the control since this is the year before any group activity was introduced (weekly team quizzes or team projects). Figure 4 shows that a greater number of students in 2000, 2001, and 2002 thought that they learned more and that the instructor's ability to encourage critical and independent thinking was improved when team-learning activities (weekly group quizzes and group projects) were included compared to 1999, the year without team learning activities. These differences were statistically significant by chi-square analysis.

In 2002, the students provided written comments during the evaluation process on whether the team-learning activities were beneficial. Of the 53 evaluations received, one did not have any written comments; three evaluations had negative comments about the course or instructor, but not specifically about the team activities; and six had positive comments about the class and/or instructor, but not specifically about the team activities. The overwhelming majority of responses (43 responses or 81%) had favorable comments about the class, the instructor, and the team activities. Nine students commented that the team activities provided practice, brought things together, and helped in preparing for exams. One of the students commented that the weekly quizzes showed where his/her thinking went wrong and allowed for correction of the problem.

Six students commented that team activities improved their ability to learn on their own, understand real world problems, and apply concepts. Four students liked the interaction provided by team activities; they learned from each other or learned by doing rather than listening. Seven students commented that the team activities contributed to critical and free thinking. One student thought that the team activities integrated all of the information from all courses that the student had taken in 3 1/2 years at the university.

DISCUSSION

While many active-learning activities have been developed to improve college science instruction, the limited analysis of the data makes it difficult to assess the effectiveness of some approaches (2, 3, 6, 7, 18). We used three criteria to assess the effectiveness of the team-based learning approach to microbial physiology. First, we asked whether the teams accomplished significant learning tasks indicative of the formation of high performance learning teams. The outcome of the team projects showed that significant learning occurred. All teams correctly deduced that new pathways or modifications of pathways were needed based on their analysis of the experimental data relative to what was known in the literature. Almost all teams proposed scientifically sound pathways to explain very complex data sets, several of which were quite creative. The students were able to transfer concepts and information they learned during this course and from other courses and apply this information in new contexts. More concisely stated, the students functioned as trained scientists. They critically analyzed and interpreted the literature in relation to new experimental data, made deductions and inferences concerning this information, and used creativity in formulating solutions.

Secondly, we asked whether the team projects improved the understanding and retention of metabolic information. The comparison of student performance on the final examination indicates that team projects significantly improved the performance of the majority of students relative to the year before team projects were instituted (Table 1). Consistent with our results, several investigators found that cooperative learning approaches using small groups improved retention and final performance in different kinds of microbiology classes (5, 6, 19, 32). However, this is not always the case. The introduction of active-learning exercises did not improve the final grades in physical chemistry classes (18). The authors noted that there was a "disconnect" between the material covered in the group activities and that covered on examinations and quizzes. This emphasizes a critical point. Group activities must be integrated into the expectations that the instructor has for student performance. We used team activities as practice for students to learn and apply difficult and important concepts emphasized throughout the class. The students then expected similar types of questions on examinations.

The final criterion was whether the students felt that the team activities were useful. As shown in Fig. 4, a significantly greater number of students thought that they learned more and that the instructor’s ability to encourage critical and independent thinking was improved when team-learning activities were included. The positive attitude indicated by the evaluation data was reinforced by the overwhelmingly positive written responses obtained at the end of this year’s course.

There are several reasons why the introduction of team projects improved performance on the final examination. Although data on the learning styles of the students that took the microbial physiology course were not obtained, the introduction of different learning activities benefits students with diverse learning styles. Group activities involve oral discussion, which is beneficial to learning by sensor feelers as defined by the Cognitive Profile Model (22). Intuitive thinkers generally do not memorize well and must understand concepts in order to figure out what they have to learn. These students have the traits that are best suited for research scientists, and team projects provide them with an ideal way to learn. Another possible explanation for the improved performance is that the numerous team activities may have provided the students with metacognitive instruction. The interactions with other team members may have allowed the student to envision how others learn and, thus, develop a better sense of how they learn. Metacognitive instruction is critical for the durability of concepts and the transfer of the concepts to new settings (15, 34). In support of this hypothesis, several students mentioned on their written comments that they enjoyed the interaction that the teams provided and learned from other students' discussions. We asked three of the best students whether they thought that the team activities were useful. These students all stated that they learned from other students and were surprised that someone always had a different approach to the problem.

While we went to great lengths to make changes in a systematic fashion in order to assess how each change in the course affected learning, there may have been additional factors that could explain our data. Differences in the student population could be an explanation for the improved performance on the final examinations in years 2001 and 2002. While the distribution of individuals that scored 90% or better on the final examination did not change during the last three years, there was a marked shift in the distribution of grades below 90% (Fig. 3). While we contend that this was due to the inclusion of team projects, it may be that the course had fewer poor students than in 2001 and 2002 compared to 2000. One could also argue that a general improvement in the instructor's ability to use this new format or other slight changes in teaching style might have contributed to the improved performance of students in 2001 and 2002. Other types of assignments rather than the team projects described here may also be effective, so long as they provide the students with the opportunity to work on challenging problems with others and give prompt and constructive feedback of their performance.

From the instructor's viewpoint, team-learning activities, particularly the team projects, changed class dynamics. Previous to the introduction of team activities, the most common interaction that the instructor had with students concerned grading of examinations or explaining how to answer questions found on old examinations that were available in test files on campus. After the introduction of team projects, students would discuss their ideas about the projects. Discussions on prochirality and whether a six-carbon compound can form a ring are notable examples. At times, students would discuss nuances of the weekly quiz when the instructor was having coffee or lunch at the cafeteria. The dynamics changed from one focused on grades and grading to one focused on scientific concepts and process.

Creating assignments that challenge even the best students is critical for the development of team interaction and function. It is important to impress upon the students that there is not a specific or single correct answer. This allows the students to use their own creativity in exploring solutions. It may not always be possible to obtain new data sets for such assignments. However, applying existing data in a new context, e.g., to a different organism or environmental setting, should allow the instructor to generate different assignments each year. Another approach is to develop projects in an area of microbial physiology that is undergoing rapid change. One then asks the students to analyze this new information in context of what is already known to determine if modified or completely new models are needed.

For weekly quizzes, it is important to use open-ended questions that still require a simple yes or no answer. This forces the students to make a specific choice and to justify their reasoning with their team members and with other teams. Each team then has a vested interest in defending its answer in order to obtain credit. As an example, after discussing the role of hydrogen production and utilization in anaerobic environments, the students were asked whether they would fund a proposal to develop mutants of clostridia that lack hydrogenases in order to overproduce 1, 3-propanediol, an important intermediate in the chemical industry.

Team projects provide an excellent way to engage students in exploring the fundamental and unifying concepts and processes of science. They also emphasize the evolving process of scientific thought and inquiry. This is often difficult to do in a microbial physiology class where the impression of the field is that all of the pathways have been worked out. Team-based learning is an excellent format to introduce students to research, since these projects are very similar to the types of problems that investigators tackle when describing the metabolism of a new organism or compound. Lastly, the team projects provide a powerful learning tool to teach students about microbial diversity. Once the posters are hung and the teams realize that there are multiple explanations and approaches for metabolism of the compound, they have been provided with a very powerful hands-on example of microbial diversity. The use of team projects and team-based learning requires the teacher to work at learning how to properly implement this novel way of teaching. However, it is clear that this way of teaching has a powerful impact on student learning.

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Figure 1

1. Products produced from *trans*-aconitate:
1 *trans*-aconitic acid → 1.8 acetic acid + 0.1 butyric acid + 2 CO_2 + 0.9 H_2

2. Molar growth yield:
~ 8 g (dry weight) per mole aconitic acid

3. Metabolism of position-labeled substrates:

> No incorporation of radioactivity was detected in acetate or butyrate when [5-^{14}C]-glutamate was used. Radioactivity was detected in carboxyl group of acetate with a specific activity of acetate one-half of the specific activity of [5-^{14}C]-*trans*-aconitate.

4. Enzyme activities detected in cell-free extracts of strain AO:

Cell-free extract	**Enzyme activity (µmol/min/mg protein)**	
	Glutamate-grown cells	***trans*-aconitate-grown cells**
Citrate lyase	0.3	0.4
Oxaloacetate decarboxylase	0.5	0.5
Pyruvate:ferredoxin oxidoreductase	ND[a]	0.1
Hydrogenase	0.3	0.8
Glutamate dehydrogenase	34.0	20.0
Glutaconate CoA transferase	2.0	2.2
Glutaconyl-CoA decarboxylase	3.0	0.2

[a] ND, not detected.

5. Intermediates detected during the metabolism of 25 mM glutamate or *trans*-aconitic acid by cell-free extracts of strain AO:

Compound detected	**Glutamate (mM)**	***trans*-aconitate (mM)**
Citrate	ND	8.5
cis-aconitate	ND	0.9
Oxaloacetate	ND	1.6

Pyruvate	ND	0.5
2-oxoglutarate	0.7	ND
Glutaconate	0.55	ND

6. Required readings: The texts listed in references 8, 26, and 30.

FIG. 1. Example of a team project used in the physiology class: the metabolism of *trans*-aconitic acid by a rumen bacterium.

<u>Figure 2 A and B.</u>

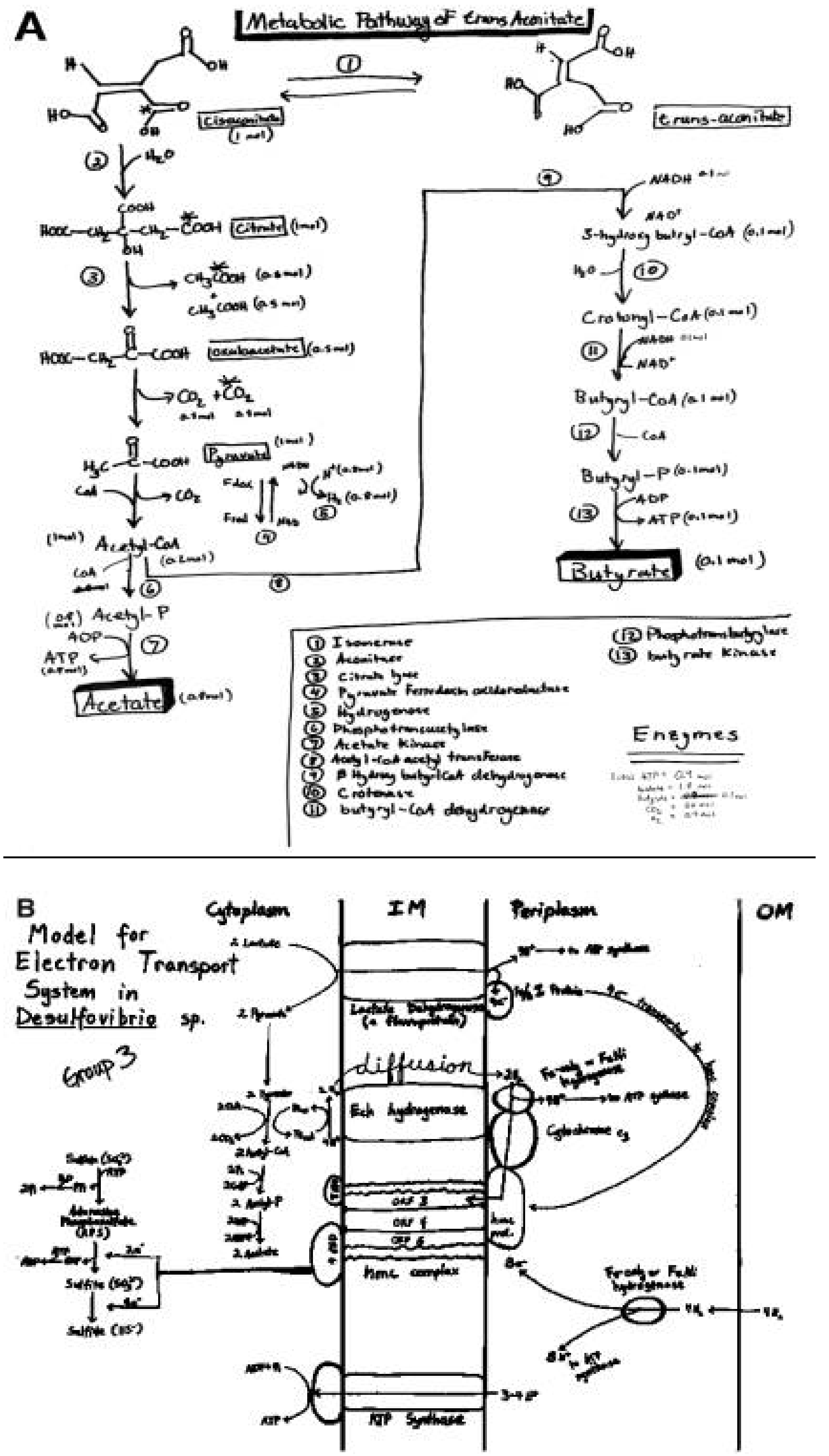

FIG. 2. Examples of posters prepared by different groups in 2002. (A) *Trans*-aconitate project. (B) Sulfate reduction project.

Figure 3.

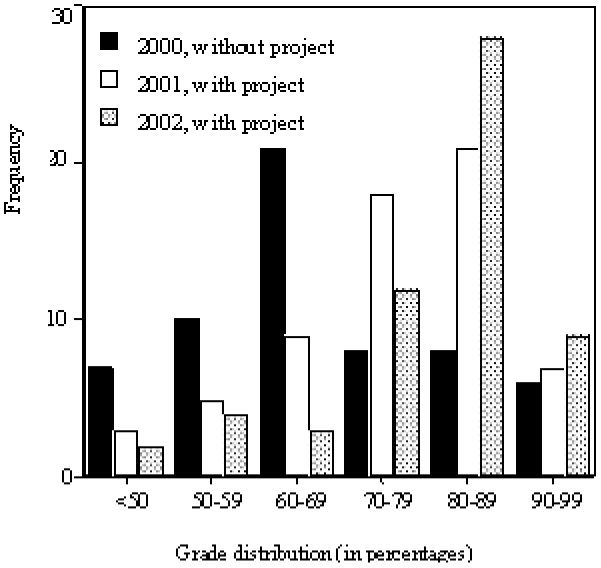

FIG. 3. Distribution of final examination grades for years with and without team projects.

Figure 4.

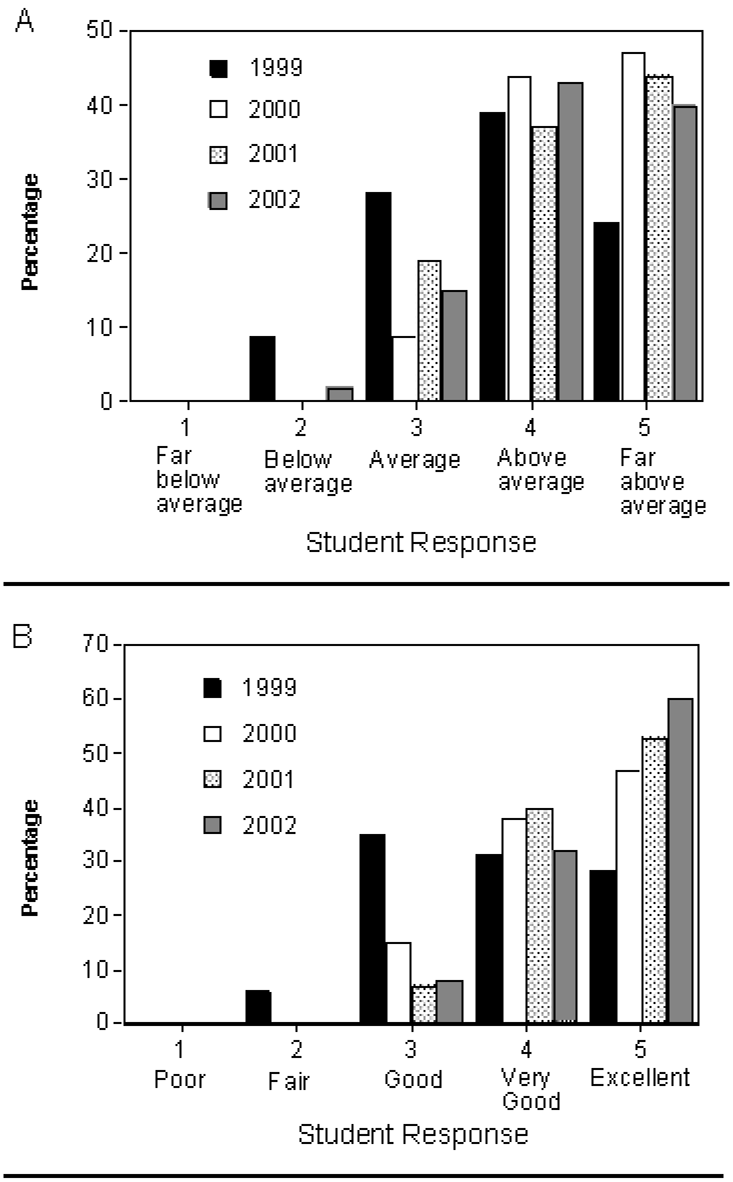

FIG. 4. Student assessment of (A) the amount they learned in the class and (B) the instructor's ability to encourage critical and independent thinking before (1999) and after (2000, 2001 and 2002) team-based learning was introduced.

TABLE 1.

Student performance on the final examination for years with and without team projects

Year	**Group project**	**Number of students**	**Mean**[a]	**Median**[a]	**95% confidence interval**
2000	No	60	133.4 ± 28.9[b]	133	126.1 – 140.7
2001	Yes	63	150.9 ± 31.2[c]	154	149.4 – 159.8
2002	Yes	58	158.7 ± 26.5[c]	165	149.4 – 159.8

[a] Final examination was worth 200 points.

[b] Analysis of variance in combination with the Tukey test showed that the mean of final for spring 2000 was significantly different from the means of finals for the other two years, $P < 0.05$.

[c] The means of the finals from 2001 and 2002 were not significantly different from each other, $P < 0.05$.