AC 2010-624: THE ARTIFICIAL KIDNEY: INVESTIGATING CURRENT DIALYSIS METHODS AS A FRESHMAN DESIGN PROJECT

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Abstract

A new project based freshman engineering course has been developed at Villanova University to introduce students to the different engineering disciplines. The goal of this paper is to evaluate the effectiveness of using an artificial kidney design project in this course. The kidney is the human body's organ of purification, removing waste from blood on a daily basis. When a person's kidneys fail it is necessary for them to have outpatient dialysis at a minimum of three days a week to clear the blood of wastes and excess fluids. Students were taught basic biology and engineering principles which they used to design their own filtering device. The effectiveness of this course at introducing freshman students to engineering concepts and retaining their enthusiasm for engineering was evaluated using a pre/post course survey, student quiz performance and final student design reports (both oral and written). Overall, the instructors found the course to be effective at improving student understanding of engineering fundamentals and increasing their enthusiasm for engineering. Recommendations for improvement focus largely on the specific language of the project description that was handed out to the students.

Introduction

Freshman engineering programs vary greatly at different universities and are constantly a topic of debate for educators seeking to inspire, excite and educate the next generation of engineers. The demand from industry is to provide engineers that are not only technically competent, but that can thrive in a group environment and lead a team to design a better product. The challenge for educators then, is to introduce more design within socially relevant contexts into their curriculum starting at the freshman level without decreasing student retention. The dilemma is in introducing design problems, which are open-ended, with more than one solution, to freshman[1]. Most freshman still learn by acquiring knowledge from the teacher, assuming that all knowledge is a collection of facts that are right or wrong[2]. Therefore asking them to achieve the next leaving of learning that is required of engineering design is not an easy task.

Felder and Silverman in their paper "Learning and Teaching Styles in Engineering Education" nicely laid out the need for a teaching style that benefits the majority of engineering students involves some hands-on and reflective activity, not just lecture[3]. Active learning, especially problem based learning, has been shown effective at increasing student interest in courses, and improving their retention of information [1, 3-7]. Problem based learning also can work as an excellent opportunity to teach students the professional skills industry requires of them (teamwork, leadership, effective communication-written and oral)[6]. Taking these studies into consideration, the challenge to create a design experience within the freshman program should be an active, "hands-on", group effort. Similar freshman project based courses have been attempted and found that projects that included design elements were the most effective at teaching communication and teamwork skills[4].

The new freshman program that was developed at Villanova University desired to upgrade the current problem-based learning strategy by adding more relevant social context to the designs. The new freshman introduction to engineering sequence devised was divided into four sessions over two semesters. Each session was half a semester, with the first being a common introduction for all students. The topics covered in the first seven weeks were engineering mathematics; units, dimensions and conversions; the engineering design process; estimating and problem solving; engineering software packages; and an introduction to basic engineering principles[8]. The students then had the choice of one of six different mini-projects for the second half of the fall semester. The six mini-projects available to students to choose from then were desired to be multidisciplinary, socially relevant, and challenging enough to engineering concepts without scaring students away from engineering. The projects offered were: Robotics with Matlab & Lego NXT, Analytical & Experimental Evaluation of a SMARTBEAM, Application of Acoustic Technologies, Fuel Cell Electric Car, Artificial Kidney: Improving the Current Dialysis System, Aerodynamics of Vehicles. The goal of these projects was to excite the students about engineering, provide an understanding of what engineers do, and give a basic understanding of the level of independent learning and professionalism expected of an engineering student. At the beginning of the second semester, the students had a choice of a second mini-project (from the same six offered in the fall), after which they are to select their major within engineering and enter a final session that is major specific. The goal of this paper is to evaluate the effectiveness of one of these mini-projects, specifically the Artificial Kidney, at increasing student design ability, professional skills, understanding of engineering disciplines, and excitement for bioengineering.

The Artificial Kidney Project

Project Objective

The kidney is the human body's organ of purification, removing waste from our blood on a daily basis. When a person's kidneys fail it is necessary for them to have outpatient dialysis at a minimum of three days a week to clear the blood of wastes and excess fluids. This process is tiring and time consuming for the patient, and an easier, at-home, or implantable artificial kidney would be desired. The goal of this project is for students to use basic engineering principles to model and study the current system and design a model filtering device. The project objectives were as follows:

- Introduction to bioengineering and design in a medical context
- Improve understanding of different engineering disciplines
- Introduce engineering concepts - balance equations (mass and energy balances), Fick's Law , Darcy's Law, Hagen-Poiseuille
- Improve data collection and experimental skills
- Introduce students to engineering and medical ethics
- Build student teamwork skills – conflict resolution, communication, time management
- Improve both written and oral communication skills of the students

Course Overview

The course met two days per week for seven week for 75 minutes each class. For ten of the classes, the time was divided into a "lecture" and "lab" portion. The "lecture" was to introduce the basic principles necessary for design, while the "lab" was to introduce the different hands-on experimental equipment necessary to test the design. The lecture was designed to be interactive by the incorporation of "clickers" from Turning Technologies[9] with power point presentations and online resources. The "clickers" allowed students to interact by answering questions and proving a graph of the response giving the instructor instant feedback to their understanding. Each lecture was followed by a lab activity that was designed to utilize the information just taught in order to increase comprehension. The lecture was kept to around 30 minutes to allow enough time for the lab. The topics covered in the classes are summarized in table 1. The remaining four classes were design days (for the students to work on their design project) and a final day for oral presentations on their design.

Lesson	Lecture	Lab
1	Intro to Bioengineering & Kidney Function	Group Selection
2	History of Dialysis & Current Dialysis Methods	Practice using peristaltic pumps, measure flow rates
3	Fluid Flow Concepts Conservation of Mass, Hagen-Poiseuille, Darcy's Law	Use a "y" connector in pumps to show conservation of mass
4	Fluid Flow Concepts – Pressure changes	Use manometers to measure pressure at different flow rates, tubing sizes
5	Solute Flow- Diffusion Fick's Law	Learn how to use conductivity meter , make salt solutions
6	Solute Flow- Convection	Make standards curve for conductivity meter
7	Biomaterial Considerations Sterilization	Visit Materials Characterization lab to see SEM, AFM, and mechanical testing devices
8	Transient Systems- Organ Systems	Work on MathCAD – learn how to use a basic solve block
9	Regulatory/Ethical Issues with Biomedical Device Design	Begin project design
10	Newer Artificial Kidney Designs Professionalism	Project design time

Table 1. Overview of the topics covered in the Artificial Kidney Project. Each topic was divided into a lecture style instruction and a hands-on laboratory experience.

Kidney & Dialysis Background (Classes 1 & 2)

The students were first introduced to the concept of the artificial kidney with a lecture on the physiology of a normal functioning kidney. Its structure and function were discussed, with emphasis placed on the kidney's role as a filtering device. An in depth look was also taken at the main components of the kidney; the nephron, glomerulus, proximal tube, and loop of Henle. An example of a valuable on-line resource used was flash animation to demonstrate the functions of the kidney[10]. The students were able to follow a protein or waste molecule as it underwent the various processes in its journey through the kidney. Students then learned about acute and chronic renal failure, including the stages of each disease. The history of dialysis was discussed, starting with the 'Father of Dialysis' Thomas Graham[11, 12]. This lead to a detailed description of the current dialysis methods, peritoneal and hemodialysis. Students were provided an example kidney dialyzer currently in use to examine (*donated by Fresenius Medical Care)[13]*.

Introduction to Fluid Flow Principles (Classes 3 & 4)

In order to understand and design kidney dialysis machines, the students must have an understanding of traditional engineering principles. The function of each of the components of the kidney and thus the design of an artificial kidney have relevance to all of the major engineering disciplines; i.e. the fluid dynamics principles used to determine flow through the system, the mass transfer principles to correct chemical as well as charge imbalances across a semi-permeable membrane, and the material science principles used to determine material strength of the artificial kidney. Thus, an introduction into practical fluid dynamic theory was necessary. Students were taught about equipment for flow delivery and basic concepts governing the fluid flow, including the principle of mass conservation and the application of Newton's second law for fluid flow. Emphasis was placed on two important flow patterns that are of direct relevance to the design of an Artificial Kidney Device, Hagen-Poiseulle flow for pressure-driven fluid flow through a tube and Darcy flow for pressure-driven fluid flow across a porous membrane. These examples helped the students establish some basic concepts of fluid mechanics which was crucial for their group project. They were also taught techniques for pressure and flow rate measurement. The students learn that the same principles they previously would have only associated with a combustion engine, are also applicable to the design of artificial organs. Additionally, students are given early exposure to topics they would normally only see in the third year of the college's curriculum. This exposure is crucial in adding another dynamic to the student's education that will help them understand and apply their early math and chemistry courses.

Basic Mass Transfer Concepts- Introduction to solute flow (Lessons 5&6)

Since the key principle to the kidney dialyzer design is to remove salts from the blood, students must first learn some basic mass transfer principles. Basic Fickian diffusion was introduced with some example problems for students to work through. Emphasis was placed on the kidney itself and how diffusion controls the movement of many salts through the nephrons. This was followed by an introduction to the concept of convective mass transfer, specifically filtration design. The concept of solute flow was essential for their design, and provided them an insight to a different application of a high-level chemical engineering concept.

Students were introduced to a "hands-on" method for analysis of solute concentrations, a critical step in designing and evaluating separation processes. Students learned how to operate a conductivity meter, and created calibration curves for their salt solutions using these meters. This experience, though simple, helps to emphasize the importance of analytical chemistry techniques in chemical and biochemical engineering. Good experimental methods and calibration curve generation are excellent skills for all engineers.

Transient Systems & Computer programs for engineering computation (Lesson 8)

The engineering concepts introduced in prior lessons were all based on steady-state systems, which are not always the case, especially for bioengineers looking at organs. The concept of transient systems was introduced by talking about organ systems within the human body and modeling those systems as black boxes. A simple compartment model was introduced, as shown in Figure 1, that helped to the higher level analysis expected of engineers as well as introduce the "human" element to the design. The model relates central nervous system (CNS), the blood, and extracellular fluid by three different black boxes[14]. The model equations were provided to them in MathCAD where they could change the rate of urea removal to find an optimal time (too fast causes large pressure build up in the cerebrospinal fluid making the patient sick, while too slow would be uncomfortable for the patient). The model also helped to familiarize students with MathCAD, which is a computational software package frequently used in the chemical engineering department at Villanova University.

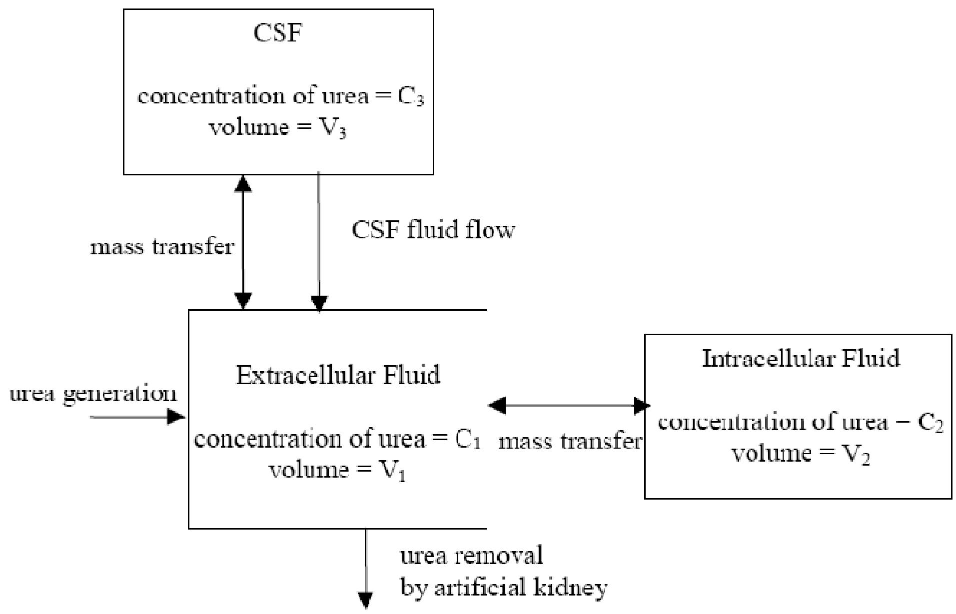


Figure 1. Three compartment model for the removal of urea. Students used this model along with a provided MathCAD sheet to optimize the time for urea removal by an artificial kidney. Adapted from [14].

Biomaterial and Biomedical Design Issues (Lessons 7, 9&10)

In order to design effectively as an engineer, one must always keep the context in mind. The context critical to a bioengineer is the human body itself, so students were introduced to the concept of biocompatibility. Students were also taught briefly about methods to test for biocompatibility and ideas of how to improve biocompatibility were also discussed. Several methods of sterilization were reviewed, including steam, electron beam and gamma irradiation. Regulatory and ethical issues, such as FDA compliance, and how to distribute the limited supply of dialysis centers to appropriate patients were also discussed. Students were then introduced to ideas for the future of kidney dialysis. Specifically, the AWAK, or Automatic Wearable Artificial Kidney was discussed. This revolutionary technologically allows the dialysis patient to have continuous dialysis treatment while performing their everyday activities. This excited the student's interest about projects they could potentially work on in their near future.

The Design Project

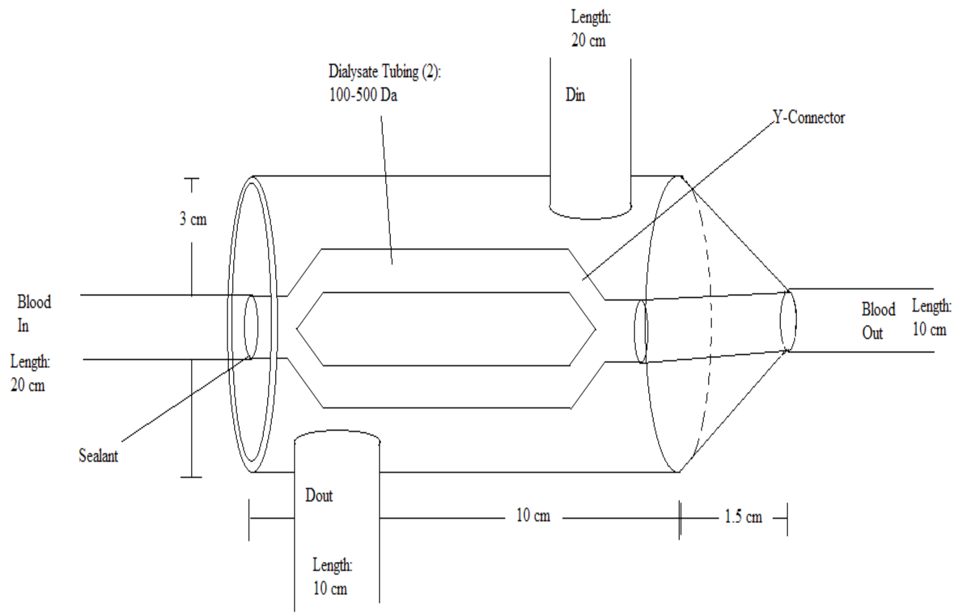
The students are able to apply their newly gained engineering theory and organ physiology to participate in hands-on experiments throughout the course. Early on, they were exposed to a simple pumping system in which they could take pressure and flow measurements, and apply their newly acquired fluid dynamics knowledge. Throughout the course, the students gained valuable group work and laboratory experience when they analyzed and designed their own kidney-dialysis systems. The project given to the students was in three parts, as follows:

1. *Students will design and build their own dialysis circuit, with the goal of maximizing removal of salt from the blood (Kg/s) while removing < 5% of the liquid/water in in-coming blood. As part of your design description choose: the membrane pore size and the number of filter tubes. (i.e. you may choose to split the flow of the blood solution into more than one tube in the dialysis filter)*

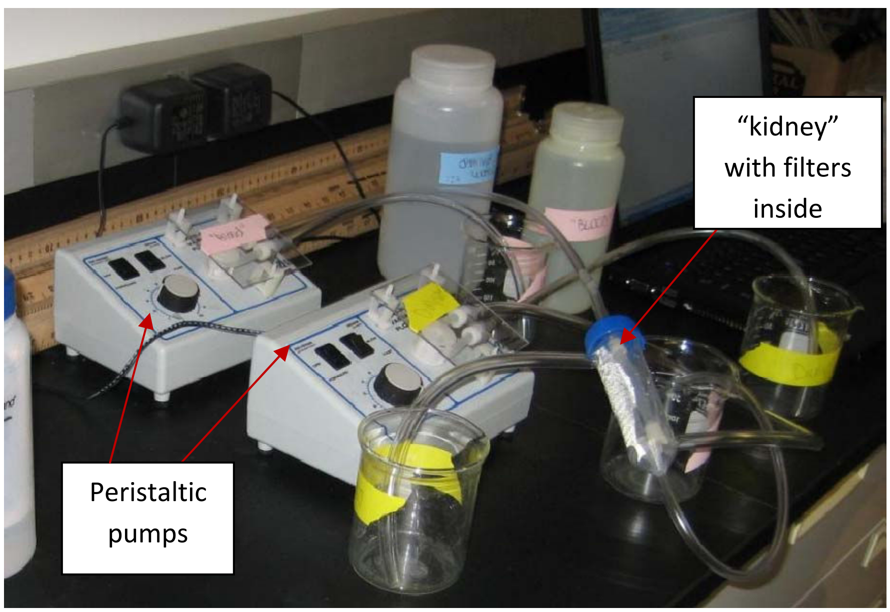
2. *The students will use MathCAD worksheet to run the simulation and recommend an optimum flow of blood through the dialysis unit for YOUR patient (each group will be given a different patient "weight"). Justify your recommendation with data, graphs and text etc in the report and in your presentation.*

3. *Students will test their dialyzer design and record the results. The goal is still to maximize removal of salt from the blood (Kg/s) while removing < 5% of the liquid/water in in-coming blood. The groups are expected to run their dialysis circuit and provide the performance data of their device. Some changes on the design can be made based on the running conditions (flow rates etc…) to achieve better exchange rates/salt removal. Recommend the optimal operating conditions and justify your recommendation with data, (graphs and text) in your written report and oral presentation*

The students were given a mock up kidney dialysis circuit which used a salt water solution to represent blood and its particulates. The system had two variable peristaltic pumps to control the flow rates, and student were provided stop watches, graduated cylinders and monometers for taking whatever measurements they decided where necessary. The students were also provided access to the conductivity meters they had previously calibrated in order to determine salt concentrations. They varied the systems' membranes, dialysis tubes, and flow rates with the objective of maximizing the exchange rate of the salt in the system. At the same time, they were also given practical design constraints familiar to biomedical engineers. For example, they had to securely fasten all connections to prevent leakage and keep the system sterile, but be careful not to overdesign the system due to the constraint that they could only use the supplies provided (centrifuge tubes, cellulose membranes of two different molecular weight cut-offs, "y" adaptors). A sample picture of a student design is shown in Figure 2.



(A)



(B)

Figure 2. A working model of one student group's design of an artificial kidney. Picture (A) is the design drawing by student group and picture (B) is a design hooked up to the peristaltic pumps for testing.

Results

The primary goal of the course was to excite and motivate the freshman engineers in the area of bioengineering, through providing enough biology and engineering background to allow for a thoughtful group design of an artificial kidney. The student performance on three quizzes was assessed prior to evaluation of their group project presentations and reports. A secondary goal of the course was to help the freshman engineering students understand what it means to be an engineer and some of the similarities and differences between the disciplines.

Student interest in engineering and understanding of the disciplines

The students were intentionally exposed to a faculty member from two different departments. Each faculty lectured on topics most related to his/her discipline. Furthermore, the students were asked to survey the colleges engineering course list to determine which courses (in which departments) covered topics essential to kidney design such as diffusion. The following six questions were given on pre and post class quizzes to determine to what degree the students understand the role of engineers and are excited about becoming one: (where EE = electrical engineering, CHE= chemical engineering, ME= mechanical engineering)

1. In which engineering discipline do you study principles associated with flowing fluids (*EE, CHE, ME*)?
2. In which engineering major do you study principles associated with the diffusion of dissolved molecules across membranes (*EE, ME, CHE*)?
3. In which engineering discipline do you study strength of materials such as membranes and prosthetics (*CHE, EE, ME*)?
4. Does engineering help people (*1=little,2,3,4,5=very much*)
5. Are you excite about becoming an engineer (*1=little,2,3,4,5=very much*)
6. Engineers have an ethical obligation to do quality work (*1=no,2,3,4,5=always*)

With regards to the first two questions about the engineering disciplines, approximately 80% of the students indicated in the pre and post class quizzes that flowing fluids and diffusion was covered in the chemical engineering curriculum. There was a modest shift in class response for question three, with the percentage of students associating strength of materials with mechanical engineering changing from 47% pre-class to 64% post-class. There was a small but interesting and consistent shift in responses to questions 4 and 6, in that the average scores for both questions changed from approximately 4.9/5.0 to 5.0/5.0. The instructors were encouraged by the results to question 5, presented in Figure 3.

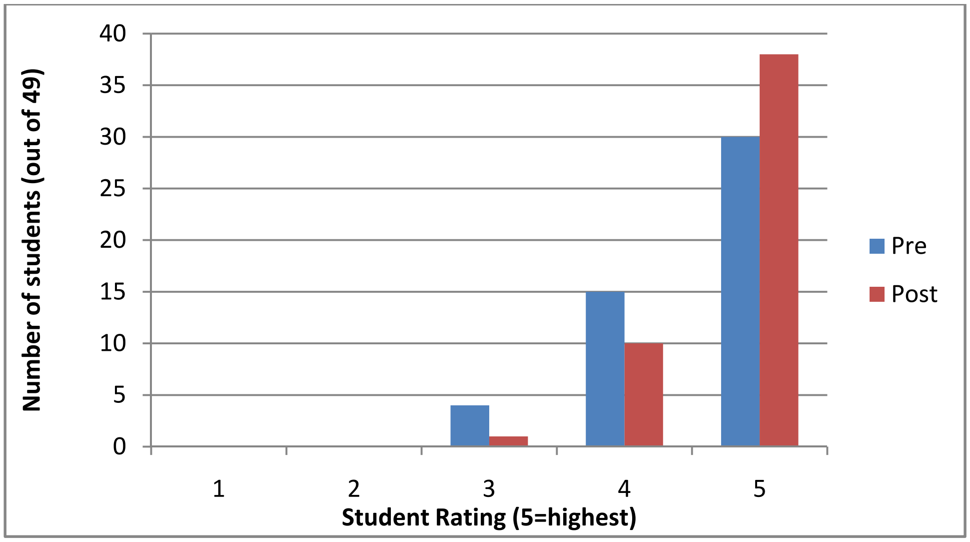


Figure 3: Results from the pre and post survey class survey of student's excitement level for engineering (1 little, 5 very much)

Figure 3 indicates a definite increase in the number of students that excited about being an engineer. Eight of the nineteen students that responded with a 3 or 4 score on their pre-class questionnaire changed their score to a 5 on the post-class questionnaire. With 38 of the 49 freshman ranked their level of excitement towards engineering as 5 out of 5, and the average post-class score increasing from that of the pre-class value, it is concluded that the rigor and seriousness of the project and the lectures did not cause the students to lose interest in engineering. Through the course, the student interest level increased.

Student understanding of biological information necessary for design project

The students understanding of the structure and function of the natural and artificial kidney was primarily assessed on quiz # 3, a challenging 45 minute and 45 question closed book quiz. The average quiz grade was a very high 88%, indicating good understanding of the biology concepts covered in the class. The following three questions were given on pre and post class quizzes to determine to what degree the biology material had been learned during this course as opposed to previous (i.e. AP Biology) courses

1. The disease caused by renal failure is (*cancer, arthritis, uremia*)
2. The (*renal vein, renal artery, ureter*) delivers blood to the kidney. Small toxin molecules pass are filtered out of the kidney and flow to the bladder through the (*renal vein, renal artery, ureter*).
3. The primary function of Artificial Kidneys performing hemodyalysis is to remove (*glucose, salts, urea*) from the (*urine, blood, lymph nodes*). Water may be intentionally removed from the patient also during hemodialysis as well (*True, False*).

For all three questions, the post class average scores (Question 1 – 100%, Question 2 – 92% and Question 3 – 94%) were higher than the pre-class scores (Question 1 – 88%, Question 2 – 70% and Question 3 – 65%.

Student understanding of engineering concepts necessary for design project

The students understanding of the engineering associated with the artificial kidney was primarily assessed on quizzes # 1 and 2; two open book 30 minute quizzes containing multiple choice questions on concepts and calculations. The calculations involved use of the conservation of mass principle for flowing fluids, as well as D'Arcy's law for pressure driven flow and Fick's law for diffusive solute movement across a membrane. The average quiz grades were both quite good (Quiz 1 – 81%, and Quiz 2 – 85%), indicating good understanding of the engineering concepts and equations covered in class. The following three questions were given on pre and post class quizzes to determine to what degree the engineering concepts had been learned during this course as opposed to previous (i.e. Physics) courses:

1. If blood is flowing through into this bifurcation at 4 liter per minute and into one of the legs at 2.3 liters per minute, then what is the flow rate of blood entering the other leg (*2.3 liters per minute, 2 liters per minute, 1.7 liters per minute*)?
2. Is the blood pressure as it exits the heart likely to be (*greater, lower, the same*) as compared to the pressure when it enters the legs?
3. Arteries such as the aorta branch into smaller blood vessels called capillaries whose walls act like membranes – being permeable to nutrients such as glucose that your body's cells and tissues need to function properly. *Explain* how the concentration of glucose in the blood and the thickness of the capillary walls affect the rate at which glucose enters the tissue surrounding a capillary.

The most significant improvement in the students engineering capabilities and understanding occurred with regards to utilizing the conservation of mass. For problem 1 above, approximately 50% of the students answered correctly on the pre-class quiz, however approximately 80% answered correctly on the post-class quiz. Unfortunately there was little improvement in performance on questions 2 and 3 above, with approximately half of the class not grasping the idea that fluid flows from high to low pressure and solutes diffuse from high to low concentration. It appears that freshman are capable of understanding the engineering concepts and using the equations for calculation; however their ability to use and integrate these principles to answer a question about a complex biological system seems limited (see design performance section).

Design project performance

The students were assigned a group project that allowed them to design an artificial kidney given basic laboratory supplies, and optimize an artificial kidney performance through use of a MathCAD program. Consistent with the instructor's expectations, a grading rubric (0=F, 4=A) was devised (Table 2).

Mathcad project	
1	Was the effect of dialysis flowrate on CSF pressure AND urea removal explored through the mathcad simulation, with an optimal operating condition recommended
Design	
2	Evaluate the design: creativity, reference to designs in use today, enough surface area, good choice or membrane MW cutoff, location of ports and direction of flow
Experimental Procedure	
3	Measured correct samples (feed, retentate and dialysate) for conductivity, and used this data to estimate salt concentrations from a standard curve or online info
4	Measured correct samples (feed, retentate and dialysate) for flowrate
5	Data for concentration, flow (and pressure) was believable/convincing with trends making sense or data points being repeated to show low variability
6	A few/enough conditions (i.e. flowrates) were evaluated to see a trend wrt to salt or water loss through the membrane and recommend an optimum operating condition
Analysis	
7	Noted the conservation of mass concept and and correctly used it to calculate the amount (kg/s) of salt passing through the membrane
8	Effectively refered to D'arcy's law, Fick's law and/or Hagen-Poiseulle equation when explaining the effects of flow and membrane geometry etc.. on the rate of salt passing through the membrane
9	Quality of recommendation of the optimum operating conditions (<u>specific</u> flowrate(s)/conditions recommended, recommended condition makes sense, recommended condition was a natural outcome of the data they collected..) for maximizing salt permeation AND meeting the < 5% water loss requirement
10	Were any suggestions made on how to improve the initial design
11	Did the students allude to any medical issues such as the importance of sterility

Table 2. Instructor's grading rubric for the final design reports (oral and written). All questions were evaluated on a scale of 0 – 4 (4 being exceptional, 2 average and 0 no evidence of this question addressed).

The group performance was based on combined evaluations of the report and presentation by the two faculty members teaching the class. The average project grade resulted from compilation of the scores on the evaluation rubric (Table 2). None of the groups effectively explained their results and design choices using the engineering concepts covered in class. Only a few of the groups even mentioned the equations or concept at all. The best group indicated their intention to promote salt movement across the membrane via Fick's law, but did not elaborate on how to maximize concentration differences. None of the groups tried to explain at all how pressure differences across the membrane might be altered to effect water or salt loss across the membrane. None of the groups presented salt concentrations, by referring to a concentration versus conductivity standard curve (that was derived earlier in the semester during class). Only two of the 12 groups conceived designs that allowed for additional membrane surface area, to enhance salt permeation. Very few of the groups sample from all possible locations, to check on water and salt mass balances. Finally, little mention of the biology and medical issues, such as the importance of sterile operations and (in the case of the Mathcad assignment) dialysis time, was found in the reports or the presentations. It is for these reasons that no A grades were given for the project. The project grade distribution is provided in Figure 4, and was considerably lower than the quiz grades.

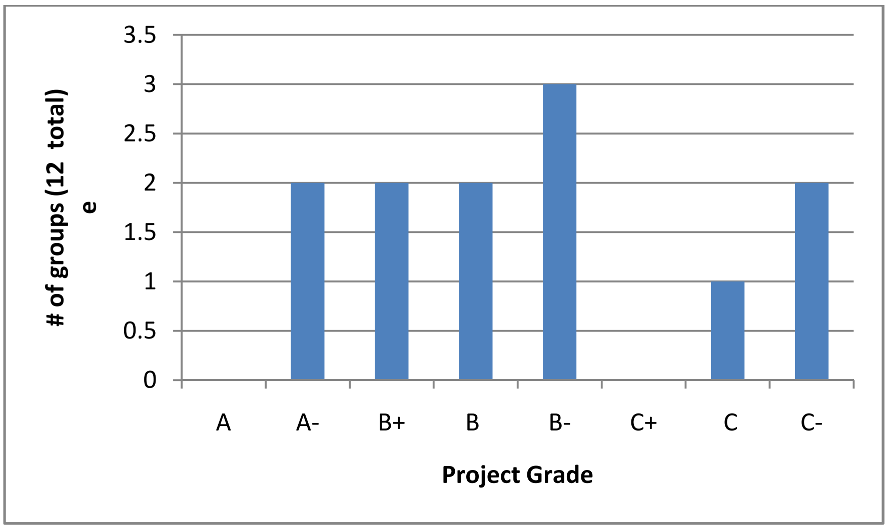


Figure 4.Grade distribution for the artificial kidney design project.

Discussion

Overall the course instructors found that the students were capable of good comprehension of sophomore and junior level engineering concepts (i.e. pressure driven flow and diffusion) as evidenced by quiz performances. The students also exhibited excellent comprehension of biology and medical concepts (i.e. kidney structure and function) as evidenced by quiz performances. The course instructors take this as a positive result, that the course was designed at a technical level that was challenging, but not unachievable for freshman engineers. The most promising result was that despite lectures that involved reasonable levels of mathematical and engineering rigor, student still exhibited a high level of interest in engineering after the course, as evidenced by the post course survey.

In evaluating the student projects, the instructors found that the students demonstrated reasonably thoughtful laboratory performances, where experiments were repeated and improved when data did not make sense. However, there was considerable room for improvement with regards to the quality of analysis and presentation provided by the students in their final project reports. This was primarily due to a lack of creativity exhibited on the project design (most student chose the easiest design to construct, not necessarily the best design), not estimating salt concentrations from a standard curve (so mass balance calculations could be made) and not referring to the equations and/or theory from class when explaining designs in either their oral or written design reports. Some of this can be attributed to their age and experience level[15], however some can be attributed to a project description that could have been more specific with more guidance provided. In future courses, the instructors may opt to provide the students with some or their entire grading rubric so that the expectations are clearer.

The ability of the course to switch from lecture to lab within a 75 minute time-frame was somewhat "rushed" in the first round of this course. This was a problem because the "lecture" and "lab" portions were hosted in two different classrooms. Switching this to one classroom capable of lab and lecture would ease this difficulty. The assistance of an undergraduate teaching assistant was also extremely beneficial in the laboratory component. The instructors believe that now that the course is outlined it could be taught by one instructor with the assistance of one or two undergraduate teaching assistants for the laboratory portion. This would allow a more sustainable staffing solution for the college.

Possible improvements to the course could be to guide the students more on their projects. Specifically, the students should be told to use their standard curve to estimate salt concentration from conductivity data, that mass balances should be conducted and the results shown in report, and to refer to equations and theory when explaining designs and data. The instructors also found within the confines of a seven week time-frame expecting freshman to complete a complex design, test it, prepare an oral and written report may have been asking too much. The project may simply be reported as a poster presentation on the final day of class. This removes the burden of public speaking from students who are not yet comfortable with this, and focuses more on the quality of the content provided in the poster presentation.

Conclusion

Student surveys illustrated the positive result of the artificial kidney project on improving their enthusiasm for engineering and increasing their understanding of different engineering disciplines. Students appeared general excited about a bioengineering based topic introduced so early in the curriculum and appreciated the more hands-on approach to the course. Quiz results indicate that the correct level of engineering "rigor" was incorporated into the projects, as the students were able to understand and apply the engineering concepts taught. The fine-details of the best implementation of this project could still be improved, but the project as a whole is recommended for the introduction of freshman engineers to biology-based engineering designs.

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