Design Project on
CONTROLLED-RELEASE DRUG DELIVERY DEVICES:
Implementation, Management, and Learning Experiences

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Over the years, the engineering application of transport phenomena has contributed to research advances in various biomedical and pharmaceutical technologies. Transport processes are important factors in the design and operation of biomedical devices used for sensing, diagnosing, or imaging purposes, as well as applications including drug and gene delivery, biological signal transduction, and tissue engineering. Drug delivery is an emerging field in which chemical engineers have had a major impact, particularly for controlled delivery of pharmaceutical drugs to specific target sites. It has been projected that the demand for drug delivery systems in the United States will expand more than 10% annually to $132 billion in 2012.[1] Growth opportunities for drug delivery systems extend into all therapeutic classes of pharmaceuticals and encompass a wide range of compounds and formulations.

Considerable attention has been devoted to the design and development of drug delivery systems as evidenced by the exponential increase in the number of books, review articles, and research papers published. These drug delivery devices offer definite advantages over conventional modes of delivery, which include: i) reduce systematic toxicity by providing localized delivery; ii) provide precise timing in delivery; iii) protect drugs from *in vivo* metabolism, thus achieving higher drug stability, longer therapeutic effect, and lower dosing frequency; iv) enhance delivery of poorly soluble drugs; and v) increase in cost-effectiveness. In the development of these drug delivery devices, mathematical modeling of the release process is important since it establishes the mechanism(s) of drug release and provides more general guidelines for the development of other systems.[2] Undeniably, many successful controlled-release drug delivery devices have been developed as a result of an almost arbitrary selection of components, configurations, and geometries.[2]

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This paper describes the introduction of a drug delivery project in a mass transfer course. Farrell and Hesketh[3] have similarly explored the drug delivery field in the freshman curriculum and in a senior-level elective. The authors reported an experiment that involved drug release from a lozenge formulation, and the students were required to determine the drug concentration as a function of time, evaluate the drug dissolution rate, and compare between experimental and model data. Besides drug delivery, there are also other interesting daily-life examples that have been reported by various authors to illustrate the concepts of heat and mass transfer, which include i) processing of ice cream,[4] ii) cooling of a cup of coffee,[5] iii) cooking of potatoes,[6, 7] iv) drying of a bath towel,[8] and v) microwave drying.[9] Mass transfer phenomenon may also be illustrated via simple experiments to determine liquid[10] or vapor[11-13] diffusion coefficients, or via complex equipment to evaluate oxygen transfer in a bioreactor[14] or diffusion across a membrane.[15, 16]

The main objective of this drug delivery project is to show how the principles of mass transfer are employed in pharmaceutical applications. The project first focuses on introducing students to various fabrication techniques of drug delivery devices, before they proceed with vigorous mathematical modeling of these devices of various geometries. Mathematical modeling of drug release provides insights concerning device shape and size on the effect of the release of drug. As a conclusion, the students can deal with a specific area of interest on controlled release in the open-ended component of the project.

PROJECT DESCRIPTION

The aim of the project is to introduce students to the most important, cutting-edge technologies used in the fabrication of drug delivery systems and provide a practical exercise in the design of these delivery devices using MATLAB® software. The project was initiated as a compulsory component of the undergraduate course CN2125 Heat and Mass Transfer in the Spring semester 2009 at the Department of Chemical and Biomolecular Engineering, National University of Singapore. The cohort had a class size of 246 students (divided into 41 teams, six students per team) and the project constituted a weighting factor of 20% in the course grading.

The project consists of three main sections. For the first section, the teams are required to conduct a review of the research literature on the subject of polymeric micro- and nano-particle fabrication and summarize recent developments on a particular chosen technique. Table 1 shows a description of the various particle fabrication techniques.[17-22]

For the second section, the teams are required to perform vigorous mass transfer calculations for the design of controlled-release drug delivery devices using MATLAB®. Each team is assigned with a specific drug and a corresponding diffusion coefficient. Table 2 shows a list of the assigned drugs for the various teams. In this section, the teams will have to model and simulate for an idealized delivery device with the following assumptions:

- *The drug is uniformly distributed within the delivery device with an initial concentration of 30 mg/cm^3.*

TABLE 1
Brief Description of Various Techniques for the Fabrication Of Polymeric Micro- and Nano-Particles

Fabrication Technique	Description	Reference
Emulsion-based methods	• These methods involve solvent extraction or evaporation from the emulsion containing the polymer. • The emulsion consists of the dispersed organic phase (polymer solution) and the continuous phase (usually an aqueous phase).	[17]
Nanoprecipitation	• It is based on the interfacial deposition of the polymer, followed by displacement of a semi-polar solvent miscible with water from a lipophilic solution.	[18]
Spray-freezing into liquid	• It is a novel cryogenic atomization technology for forming drug-encapsulated microparticles. • It involves spraying the liquid formulation directly into the cryogenic liquid, which results in rapid freezing of the atomized droplets and formation of microparticles. • The frozen particles are collected and lyophilized.	[19]
Spray drying	• The drug is dissolved or dispersed in an organic solution of the polymer which is then nebulized in a hot-air flow. • The solvent is evaporated and dried microparticles are recovered.	[20]
Electro-hydrodynamic atomization (EHDA)	• It is suitable for the preparation of nearly monodispersed microparticles from a solution, containing dissolved polymer and drug, by using an applied electric field.	[21]
Supercritical anti-solvent (SAS)	• The drug is dissolved in an organic solvent and the solution is injected into supercritical carbon dioxide. • The supercritical fluid, due to its high diffusivity, rapidly extracts the solvent and results in precipitating the microparticles.	[22]

- *Once the device is injected or implanted within the human body, it begins to release the drug by a diffusion-limited process with a constant diffusion coefficient.*
- *The resistance to film mass transfer of the drug through the liquid boundary layer surrounding the delivery device surface to the bulk fluid is negligible.*
- *The drug is immediately consumed or swept away once it reaches the bulk solution so that in essence the surrounding fluid is an infinite sink.*
- *The shape and size of the delivery device do not change during the drug-release process.*

The project statement requires the delivery device to have at least 20% of the drug being released to the body within one week. Four geometries of the delivery device made of polymer A have been proposed, which include: i) a sphere with a radius of 3 μm, ii) a cylindrical tablet with a radius of 3 μm and a height of 6 μm, iii) a cylindrical fiber with a radius of 3 μm, and iv) a rectangular cuboid with a length, width, and height of 6, 6, and 7 μm, respectively. The following tasks are assigned:

a. Plot the drug-release profile for a duration of one week for the different geometries.

b. Determine the geometries appropriate for this particular application.

c. Plot the drug concentration profile for the different geometries at a time of i) one week, ii) two weeks, and iii) four weeks.

d. Discuss the differences in the profiles exhibited by the different geometries.

Next, it is proposed that the drug is to be encapsulated in a cylindrical tablet of radius 1 μm and height 2 μm made of polymer B (composition and physical properties to be determined by the individual project teams). It has the same initial concentration as the previous part, 30 mg/cm^3. From its drug release profile, it is found that 40% of the drug is released to the body within one week. The following questions are asked:

a. Determine the diffusion coefficient of the drug in polymer B.

b. What is the drug concentration at the center of the device?

The third section forms the open-ended component of the project in which the teams have the flexibility to qualitatively or quantitatively discuss related controlled-release concepts or ideas gained from the first and second sections of the project. In particular, they can deal in-depth with specific areas of interest, which include but are not limited to: i) the discussion of the limitations of the developed model and its practicability under nonidealized conditions or applications, and ii) the model fitting of experimental drug-release data of the assigned drug obtained from the literature using nonlinear regression, followed by the comparison between model and experimental results. These are some of the suggested topics the teams can undertake. The last section is meant to provide a linkage or coupling of the knowledge gained from the earlier two sections of the project.

SOLUTION

The solution presented here is for the second section of the report. Based on the assumptions described earlier, we can write Fick's second law of diffusion with the associated initial and boundary conditions for a symmetrical drug delivery device as follows:

$$\frac{\partial C}{\partial t} = D\nabla^2 C \qquad (1)$$

Initial condition: $C=C_0=30$ mg/cm^3

Boundary conditions: $C=C_s=0$ (at the surface of the device)

$\nabla C = 0$ (at the centerline symmetry of the device)

where C is the drug concentration, t is the time, D is the drug diffusion coefficient, C_0 is the initial drug concentration, and C_s is the surface drug concentration. The analytical solutions for Fick's second law of diffusion with the described boundary conditions for various simple geometries are readily available in the literature and can be expressed in terms of either infinite summation series or error functions.[23, 24] The solutions in the form of infinite summation series needed for the calculation of drug concentration and release profiles for various geometries are summarized in Table 3.

A diffusion coefficient of 2.50×10^{-15} cm^2/s will be used to illustrate the following sample calculation. By using the expressions presented in Table 3, it is possible to obtain the drug concentration and release profiles for the four geometries

TABLE 2
Different Types of Drugs Assigned to the Teams

No.	Drug
1	Mitomycin C
2	5-Fluorouracil
3	5-Fluorouridine
4	Goserelin acetate
5	Leuprolide acetate
6	Adriamycin
7	Dopamine
8	Dexamethasone
9	Nerve growth factor
10	Bovine serum albumin

TABLE 3

Analytical solutions of Fick's second law of diffusion for various geometries under the described initial and boundary conditions. The symbols used include the following: r is the radial position; x, y, and z are the x, y, and z positions, respectively; J_0 and J_1 are the first kind Bessel function of order zero and one, respectively; $\alpha_n R$ is the nth root of the first kind Bessel function of order zero; M_t is the amount of drug released in time t; M_∞ is the amount of drug released after infinite time.

Geometry	Drug Concentration	Drug Release
Sphere (radius = R)	$\frac{C-C_s}{C_0-C_s}=-\frac{2R}{\pi r}\sum_{n=1}^{\infty}\frac{(-1)^n}{n}\sin\left(\frac{n\pi r}{R}\right)\exp\left(-\frac{n^2\pi^2 Dt}{R^2}\right)$	$\frac{M_t}{M_\infty}=1-\frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-\frac{n^2\pi^2 Dt}{R^2}\right)$
Cylindrical Tablet (radius = R & height = 2Z)	$\frac{C-C_s}{C_0-C_s}=\frac{2}{R}\sum_{n=1}^{\infty}\frac{J_0(\alpha_n r)}{\alpha_n J_1(\alpha_n R)}\exp\left(-\alpha_n^2 Dt\right)$ $\times\frac{4}{\pi}\sum_{p=0}^{\infty}\frac{(-1)^p}{2p+1}\cos\left[\frac{(2p+1)\pi z}{2Z}\right]\exp\left[-\frac{(2p+1)^2\pi^2 Dt}{4Z^2}\right]$	$\frac{M_t}{M_\infty}=1-\sum_{n=1}^{\infty}\frac{4}{\alpha_n^2 R^2}\exp\left(-\alpha_n^2 Dt\right)$ $\times\frac{8}{\pi^2}\sum_{p=0}^{\infty}\frac{1}{(2p+1)^2}\exp\left[-\frac{(2p+1)^2\pi^2 Dt}{4Z^2}\right]$
Cylindrical Fiber (radius = R)	$\frac{C-C_s}{C_0-C_s}=\frac{2}{R}\sum_{n=1}^{\infty}\frac{J_0(\alpha_n r)}{\alpha_n J_1(\alpha_n R)}\exp\left(-\alpha_n^2 Dt\right)$	$\frac{M_t}{M_\infty}=1-\sum_{n=1}^{\infty}\frac{4}{\alpha_n^2 R^2}\exp\left(-\alpha_n^2 Dt\right)$
Cuboid (length = 2a, width = 2b & height = 2c)	$\frac{C-C_s}{C_0-C_s}=\frac{64}{\pi^3}\sum_{m=0}^{\infty}\frac{(-1)^m}{2m+1}\cos\left[\frac{(2m+1)\pi x}{2a}\right]\exp\left[-\frac{(2m+1)^2\pi^2 Dt}{4a^2}\right]$ $\times\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}\cos\left[\frac{(2n+1)\pi y}{2b}\right]\exp\left[-\frac{(2n+1)^2\pi^2 Dt}{4b^2}\right]$ $\times\sum_{p=0}^{\infty}\frac{(-1)^p}{2p+1}\cos\left[\frac{(2p+1)\pi z}{2c}\right]\exp\left[-\frac{(2p+1)^2\pi^2 Dt}{4c^2}\right]$	$\frac{M_t}{M_\infty}=1-\frac{512}{\pi^6}\sum_{m=0}^{\infty}\frac{1}{(2m+1)^2}\exp\left[-\frac{(2m+1)^2\pi^2 Dt}{4a^2}\right]$ $\times\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\frac{(2n+1)^2\pi^2 Dt}{4b^2}\right]$ $\times\sum_{p=0}^{\infty}\frac{1}{(2p+1)^2}\exp\left[-\frac{(2p+1)^2\pi^2 Dt}{4c^2}\right]$

as shown in Figures 1 and 2, respectively. Here, only the drug concentration profiles for the four geometries after four weeks will be presented. From Figure 2, it becomes clear that to satisfy the therapeutic requirement of at least 20% of the drug being released to the body within one week, all four geometries can be used. The geometry that has the closest percentage release of 20% is the cylindrical fiber. The differences in the drug release profiles may be attributed to their differences in the specific surface areas. Both the sphere and the cylindrical tablet have the highest specific surface area, followed by the cuboid and then the cylindrical fiber. Both the sphere and the cylindrical tablet have the same specific surface area, thus resulting in almost the same percentage of drug being released to the body during the initial release stage.

In the next part of the question, given the information that 40% of the same drug is released to the body within one week, we need to find the diffusion coefficient of the drug in polymer B. Since it was not possible to rewrite the expression for the drug release equation explicitly to solve for the diffusion coefficient, a trial-and-error method will be used to determine the unknown. It is found that the diffusion coefficient is approximately 3.11×10^{-16} cm^2/s. The drug concentration at the center of the device is close to the initial drug concentration of 30 mg/cm^3.

PROJECT PHASES

For the heat and mass transfer course, a total of three hours of formal lecture and one hour of tutorial class had been allocated per week over 13 teaching weeks (with a recess break during week 7). For the project component, four contact sessions of one hour each were scheduled regularly during the entire phase of the project (12 weeks). The students were organized into teams of six, with two students in each team appointed as the chairperson and vice-chairperson, respectively. The following paragraphs contain more details about the activities planned for the students. The project can be roughly divided into two main phases. It should be noted that some of the tasks had to be carried out simultaneously in order to achieve proper progress.

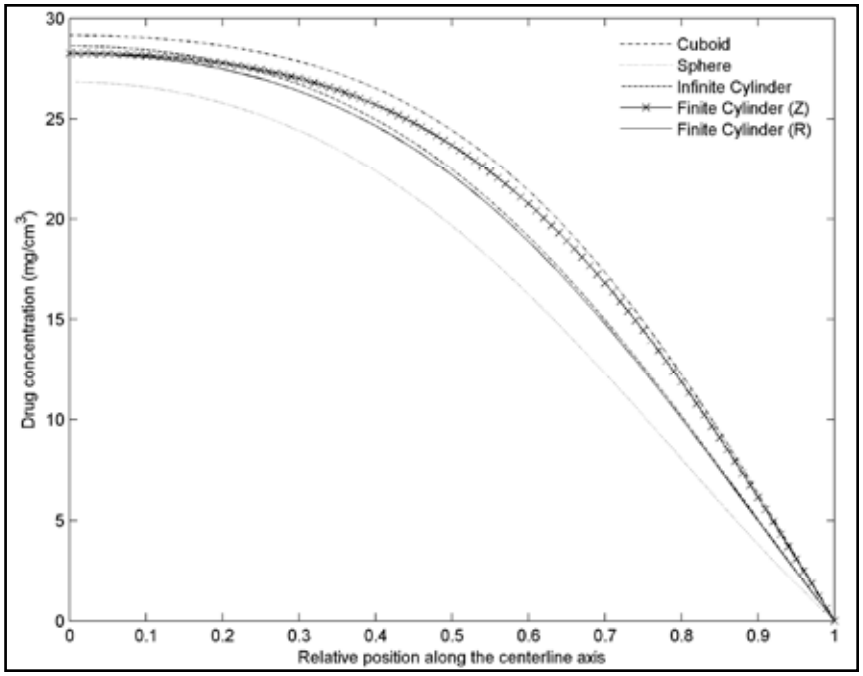

Figure 1. *Drug-concentration profiles based on diffusion coefficient of 2.50 × 10^{-15} cm^2/s for various geometries after 4 weeks. The concentration profile for the cuboid is plotted along the x direction (by setting y = z = 0). The concentration profiles for the sphere and the infinite cylinder are plotted along the radial direction. The concentration profile for the finite cylinder (Z) is plotted along the z direction (by setting r = 0). The concentration profile for the finite cylinder (R) is plotted along the radial direction (by setting z = 0).*

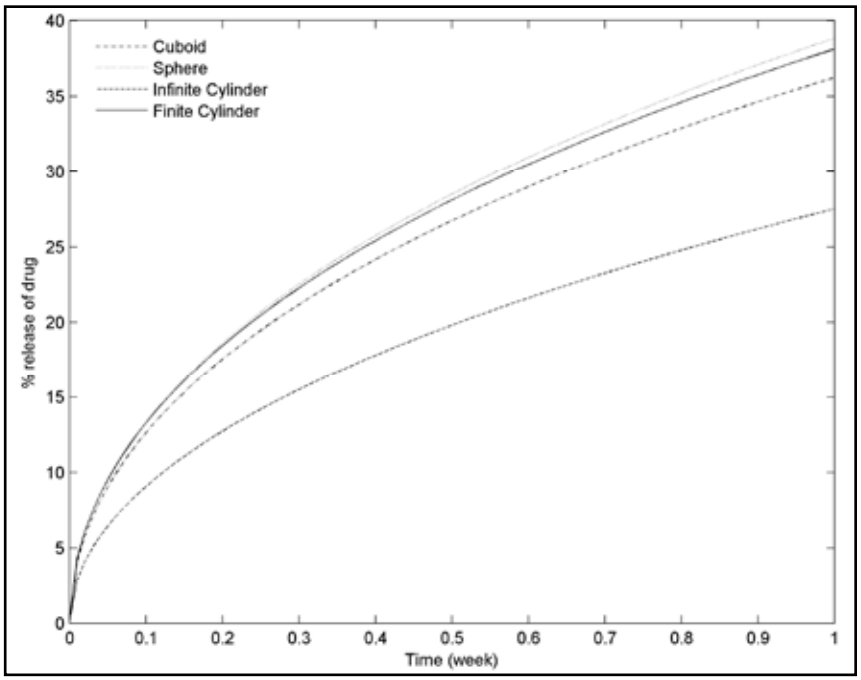

Figure 2. *Drug-release profiles based on a diffusion coefficient of 2.50 × 10^{-15} cm^2/s for various geometries for 1 week. Based on dimensions of the geometries described in problem statement, the specific surface areas for the sphere, cylindrical tablet, cuboid, and cylindrical fiber are 1, 1, 0.952, and 0.667 μm^{-1}, respectively. The corresponding percentages of drug released after 1 week are 38.8, 38.1, 36.2, and 27.5%, respectively.*

Phase One (Week 1 Through Week 9)

For the initial phase, attention was focused on the first section of the project. The first contact session scheduled during week 1 was to provide an interesting, enjoyable, and challenging overview of the numerous techniques for the fabrication of micro- and nano-particles to the students. In addition, the students were advised to view a laboratory-made video that was readily available for download from the course website. The video showcased actual experimental setups and explained principles of some of the fabrication techniques available in the current research group. Due to the difficulties in managing first-hand experience on the fabrication techniques for the large body of students, it was hoped that the video would help them understand how the particles were fabricated in the laboratory.

The teams then spent the remaining seven weeks conducting a detailed literature review on a particular fabrication technique before submitting their findings in the form of a five-page mid-term report at the end of week 8. During week 9, sharing sessions were conducted to conclude the first phase of the project. In the sessions, the teams shared their literature findings while the student facilitators provided feedback on the grading of the mid-term reports.

Phase Two (Week 5 Through Week 12)

For the second phase, attention was focused on the second and third sections of the project. Due to the curriculum structure of the course, the topic of mass transfer was covered only during the later part of the semester. Thus, an introduction of the topic to the students was essential for their project work. The second contact session scheduled during week 5 was to introduce the concept of mass transfer and focus on the physics of diffusion.

The students had fundamental backgrounds in MATLAB® programming that was covered during their first-year undergraduate course. The third contact session scheduled during week 9 was to review some of the important MATLAB® commands and syntaxes that would be used frequently in their projects. Much of the time was focused on the introduction of Bessel functions and roots that were needed for the simulation of drug concentration and release profiles for cylindrical geometries.

Office and phone consultations were announced at the start of week 5, mainly to provide technical assistance for the project. Weekly office consultations of one hour each were conducted on week 5 and from week 8 through week 12. Apart from the official consultation hours, the teams could request further meetings or follow-up meetings with the student facilitators whenever necessary.

When the project phase reached week 12, there had been numerous e-mails and office enquiries related to mass transfer concepts and MATLAB® troubleshooting. These questions were clarified and shared during the last contact session scheduled during week 12. This was done so that the rest of the teams would benefit from the answers. The teams submitted their 20-page final reports at the end of week 12.

ROLES OF MANAGERS AND STUDENT FACILITATORS

The project was administered by two managers and two student facilitators. The managers were the course lecturers and their main roles were to oversee the overall project management, supervise the teams, and advise the student facilitators. The managers conducted the first contact session and introduced various techniques for the fabrication of micro- and nano-particles. They were also in charge of maintaining the course website. In particular, the website was updated regularly with important project announcements, essential contact session materials, relevant project references, and most importantly an up-to-date compilation of frequently asked questions based on the e-mail enquiries sent by various teams. The compilation of the frequently asked questions provided several benefits to the overall project management, which include: i) to ensure the information was available and communicated to every team, ii) to allow the teams to learn based on the problems or questions raised by others, and iii) to lighten the e-mail load of the management team by minimizing the need to answer similar questions raised by different teams.

Small sharing sessions were also led by the managers, together with the student facilitators, after the teams had submitted their mid-term reports. Those teams that focused on the same area of fabrication technique were grouped in the same sharing session. In each session, the teams shared their literature findings and any enquiries they had about the fabrication techniques. In addition, the student facilitators provided feedback on the grading of the mid-term reports. In doing so, a two-way exchange of knowledge between the students and the management team was possible.

The main role of the student facilitators was to conduct the remaining three contact sessions with the relevant teaching materials needed for the project. Moreover, they had expertise in MATLAB® programming and were able to provide technical assistance to the teams. The office and e-mail consultations were also handled by the student facilitators. At the end of the project phase when the final reports had been submitted, all of the managers and student facilitators participated in grading the reports and in finalizing the overall marking for the project.

PROJECT ASSESSMENT

The project constituted 20% of the overall assessment of the course, with the rest composed of assignments, quizzes, and final examination. For the first section on the review of research literature, reports were graded based on the comprehensiveness of the review, the ability to integrate information from multiple sources, and the validity of the various points raised.

For the second section, the reports were graded based on the ability to explain the methodology and justify the assumptions and the choice of equations, the accuracy of the solutions, and the discussion of the simulation results. A good discussion should include explanations for the differences in drug concentration and release profiles for the various geometries in terms of their specific surface areas.

The final section was an open-ended component and there was no fixed set of grading criteria. Instead, the reports were graded based on the innovative linkage or coupling of the earlier two sections of the project and the ability to justify those claims. In one particular report, the team recommended a particular fabrication technique for the encapsulation of the assigned drug, with the consideration of factors such as: i) the operating conditions of the fabrication process (*e.g.*, temperature and pH); ii) the properties of the drug (*e.g.*, solubility, hydrophobicity, and stability); and iii) the typical drug-release rates and thus, the therapeutic window of the target drug. The selection of an appropriate fabrication technique was important since some of the conditions would sometimes result in the loss of biological activity of the drug being encapsulated. In another report, the team used the skills gained from the second section of the project to model several experimental results based on the assigned drug and the selected fabrication technique from the literature. Given the published drug release profiles, the team was able to estimate the corresponding diffusion coefficient of the encapsulated drug. The two projects listed here are some of the best reports and serve as outstanding examples.

OUTCOMES/RESULTS

Most of the teams were capable of providing detailed discussions and integrating information from multiple sources for their literature reviews. It was commendable as the students were only in their second undergraduate year and did not have prior experience in the research area. For the design calculations, many teams found them to be particularly challenging and had difficulty developing the necessary MATLAB® codes. Although the students had prior experience in MATLAB® programming, the translation of a descriptive problem statement into a working MATLAB® code was not a skill in which they were proficient. In the design calculations, some of the common errors made included the use of wrong equations, incorrect units, and insufficient terms in the summation series to reach convergence. In addition, a few teams could not determine the correct Bessel roots. Some of them had MATLAB® codes that produced repeated Bessel roots, thus resulting in incorrect drug concentration and release profiles for the cylindrical geometries.

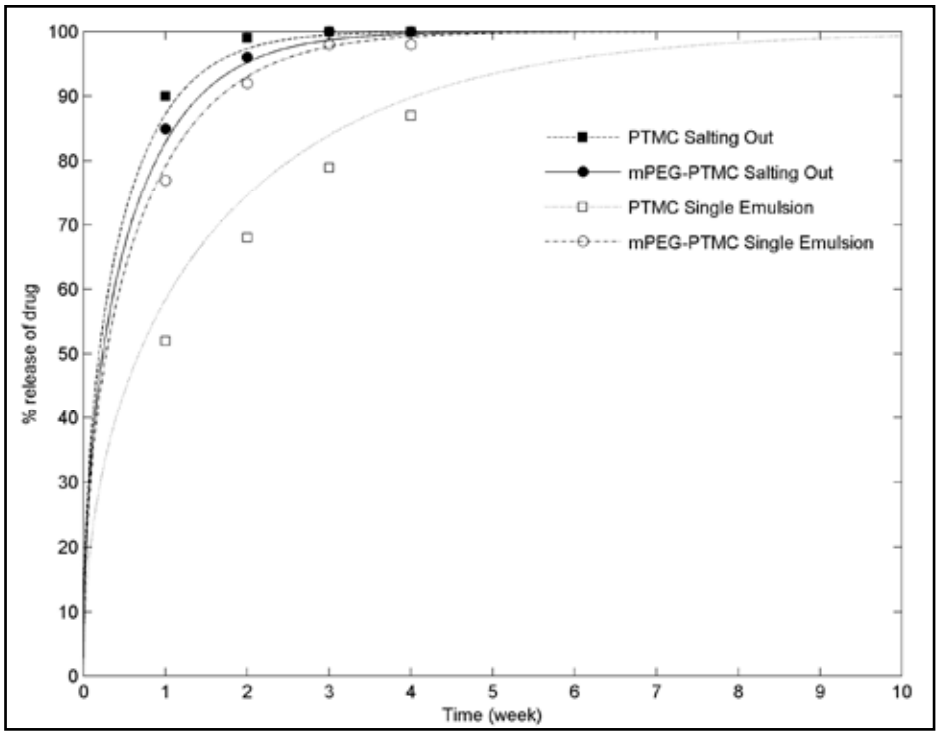

Figure 3. *Comparison between experimental and theoretical release profiles of dexamethasone from nanoparticles.[25] The profiles are obtained based on a diffusion coefficient of 22.6, 4.8, 12.7, and 4.8 × 10^{-18} cm^2/s for PTMC salting out, mPEG-PTMC salting out, PTMC single emulsion and mPEG-PTMC single emulsion, respectively. The corresponding average sizes of the nanoparticles used are 186, 95, 261, and 103 nm, respectively. The experimental drug release data for week 1, 2, 3, and 4 are estimated based on the published figure in the reference.*

Despite the difficulties faced by the teams in the MATLAB® component, most of the final reports illustrated correct trends in the drug concentration and release profiles with an acceptable degree of accuracy. Besides that, a handful of teams had written efficient MATLAB® codes that were capable of generating the required profiles in a short period of time. This certainly indicates that the contact sessions, the office and e-mail consultations, and the compilation of frequently asked questions have proven to be effective in guiding the teams in their project work.

The third section of the project turned out to be the weakest component among the teams. As it was an open-ended component, the quality of the work varied significantly among the various teams. There were some outstanding teams that were able to model experimental data by using published diffusion coefficients. An example is shown in Figure 3. While many of the teams provided innovative linkage or coupling of the knowledge gained from

the earlier two sections of the project, a handful of teams had simply discussed the fabrication techniques without considering the drugs they had been assigned.

An online survey was conducted at the end of the course to gather project feedback and suggestions. Out of a class size of 246, 106 students took part in this voluntary survey and the results are summarized in Figures 4, 5, and 6. Most of the students perceived the design project as difficult when they first read the project description. Upon completion of the project, more students felt that the level of difficulty was normal rather than difficult (Figure 4). For the various components required in this project, more than 50% of the students found those that involved MATLAB® programming to be the most challenging (Figure 5). Not surprisingly, they also found contact sessions 2 and 3, during which MATLAB® programming was illustrated, to be the most useful resource (Figure 6).

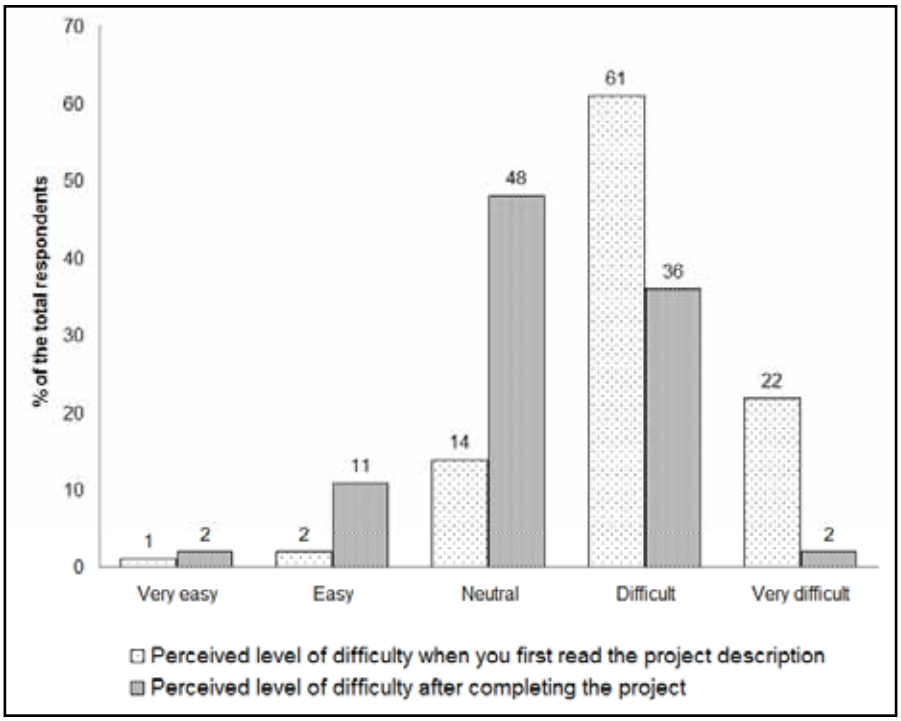

Figure 4. *Percentage of the total respondents selecting the perceived level of difficulty of the design project i) when the project description is first read, and ii) when the project is completed, based on a five-point Likert scale. The numbers displayed on top of the individual columns indicated the percentage of the total respondents selecting the particular option.*

CHALLENGES/LESSONS LEARNED

The main challenge of the project is that the students do not have prior knowledge about drug delivery systems. In addition, drug delivery is an emerging field, comprising a wide range of literature. Thus, it is essential to draw a proper framework for the scope of the project, simulate interest among students, and illustrate the importance of mass transfer in these drug delivery devices. Additionally, it is important for students to understand the various fabrication techniques of drug delivery devices before they embark on reviewing related literature materials. Due to the limitation of time and resources in the course, however, students are not able to get hands-on experiences with various fabrication techniques. One possible area for improvement is to conduct a laboratory tour where various fabrication techniques will be demonstrated on the spot. This will be complementary to the existing laboratory courses since these fabrication techniques are not currently covered.

Many of the students lacked the skills in translating a descriptive problem statement into a working MATLAB® code. Deciding on the amount of help to render the teams was not easy. On one hand, sufficient amount of help should be provided so that the teams would be able to start working on the project. On the other hand, too much guidance would be tantamount to spoon-feeding and would deprive the teams of a chance to learn from their mistakes. To overcome this situation, simple examples can be used as teaching materials to illustrate the problem and the solution, after which there should be time given for team trial and error before being advised by the student facilitators through consultations.

The open-ended component of the project was intended to allow room for creativity in responses from the various teams. Since the requirements were not clearly specified, questions about what type of areas to focus on were asked by many teams. In addition, the teams did not know the percentage of credit for the three sections of the project and thus, they were unsure of the amount of effort required for individual sections. The problem can be circumvented by informing teams upfront of the weightage of the individual components.

CONCLUSION

In the course of this project, the students have been assessed on the current techniques for the fabrication of drug delivery devices and the design of these delivery devices using MATLAB® software. Since this is the first time that the project is being implemented, there are many areas that can be further improved. This particular project can potentially serve as an interesting model for other mass transfer courses.

ACKNOWLEDGMENTS

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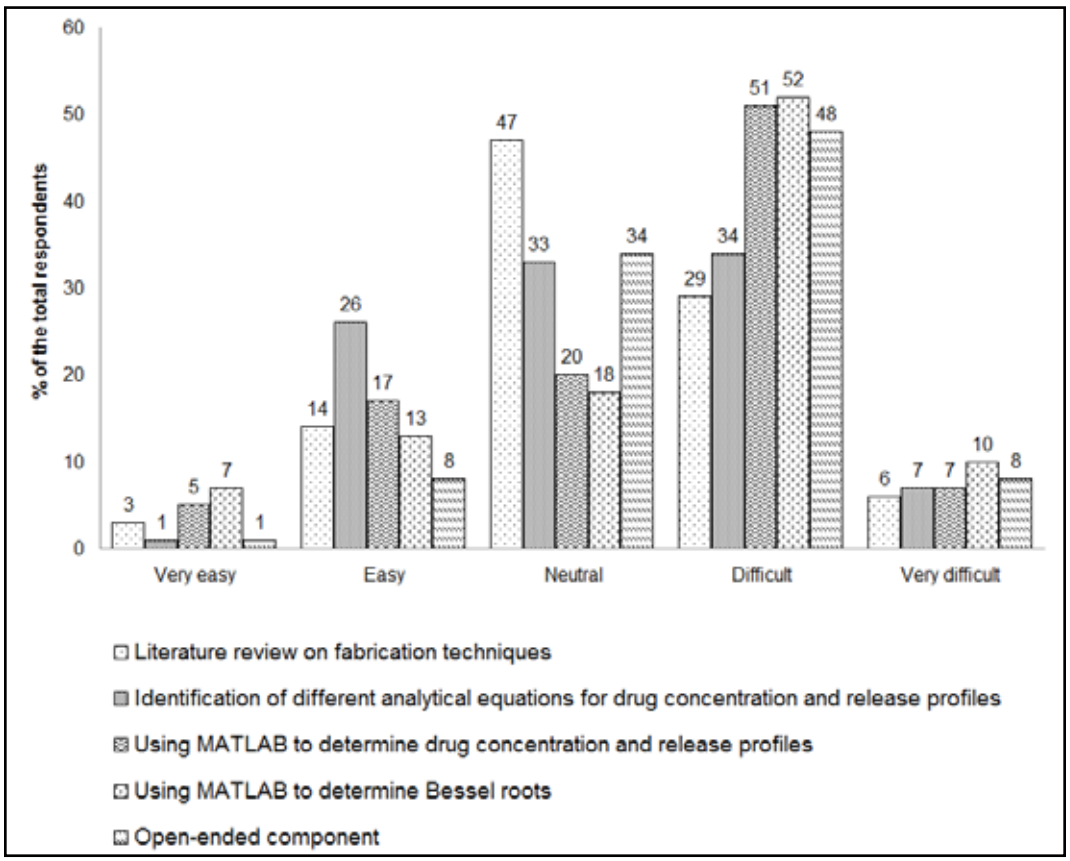

Figure 5. *Percentage of the total respondents selecting the perceived level of difficulty of the various components of the design project, namely i) literature review on fabrication techniques, ii) identification of different analytical equations for drug concentration and release profiles, iii) using MATLAB® to determine drug concentration and release profiles, iv) using MATLAB® to determine Bessel roots, and v) open-ended component, based on a five-point Likert scale. The numbers displayed on top of the individual columns indicate the percentage of the total respondents selecting the particular option.*

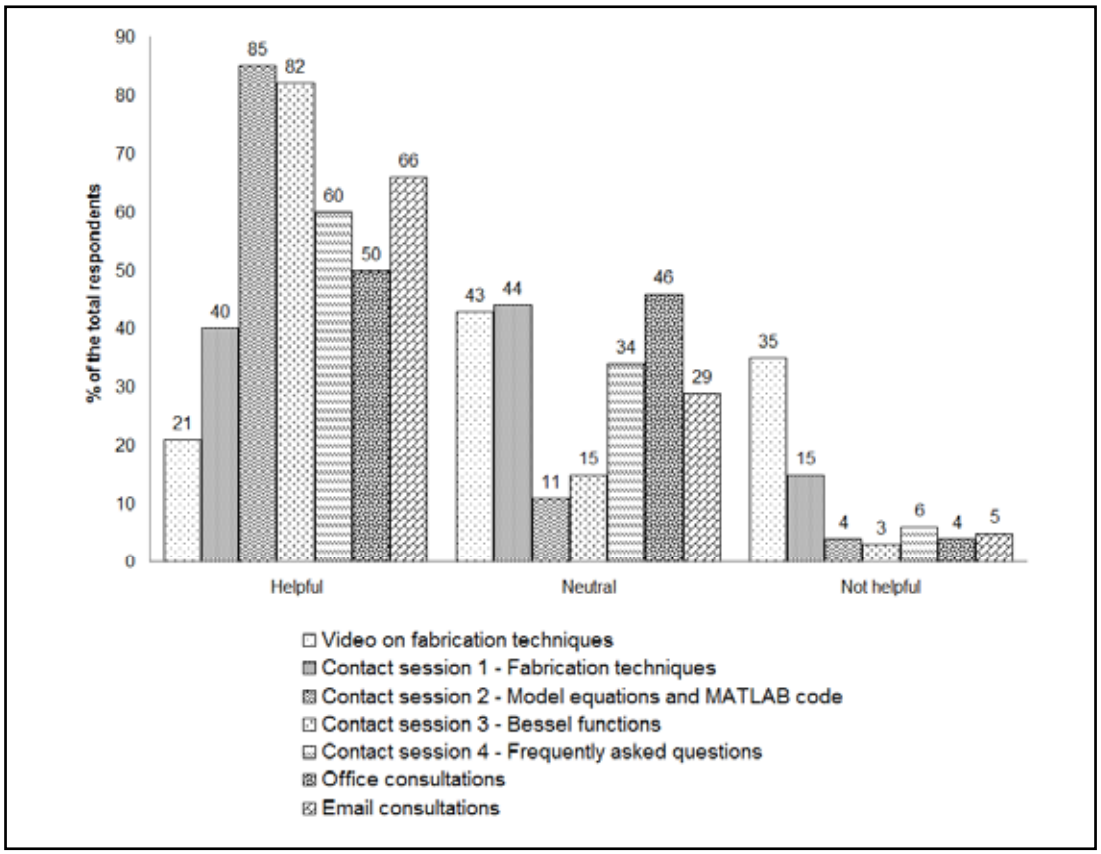

Figure 6. *Percentage of the total respondents selecting the usefulness level of the various resources available for the design project, namely i) video on fabrication techniques, ii) four contact sessions, iii) office consultations, and iv) e-mail consultations, based on a three-point Likert scale. The numbers displayed on top of the individual columns indicate the percentage of the total respondents selecting the particular option.*

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