

Comparative Evaluation of Microneedle Designs for Drug Delivery Using COMSOL

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Abstract—Microneedle-based drug delivery provides a minimally invasive alternative to conventional transdermal methods. In this study, we used 2D axisymmetric simulations in COMSOL Multiphysics to compare how three common microneedle designs—solid, coated, and hollow—deliver ibuprofen through skin layers. All models were built with the identical geometry and material assumptions, applying Fick’s laws of diffusion and using the same starting drug concentration. We integrate two key metrics for evaluation: how quickly the drug reached the base of the dermis and how concentration changed over time. Our results show, solid microneedles reached the highest peak concentration, coated ones delivered the drug faster at first but in smaller total amounts, and hollow microneedles released the drug slowly and steadily without ever peaking during the simulation window. We conclude that solid microneedles strike the best balance between delivery speed and overall dosage—making them a strong candidate for next-generation drug delivery patches.

Index Terms—Microneedles, stratum corneum, dermis, COMSOL, ibuprofen

I. INTRODUCTION

MICRONEEDLES are a revolutionary drug delivery model, as they are effective, minimally invasive, and have potential for self-administration. This apparatus takes the form of a patch with an array of micron-sized needles containing the desired drug. Patches are applied to the patient’s skin and microneedles penetrate the surface, creating channels through which the drug can enter the epidermis and diffuse into deeper layers of the skin [1]. Optimization of microneedle drug delivery could be crucial in bringing an efficient and pain-free drug delivery device to the market. To achieve this, drug delivery patch research has focused significantly on modeling the optimal shape of microneedles to investigate the most efficient design. Studies have notably focused on four different types of microneedles: solid, coated, dissolving, and hollow. A consequence of experimental microneedle designs has been the lack of proper modeling of their unique biological transport phenomena. A notable study, characterizing diffusion in skin tissue via microneedle-based methods, has shown the need for multidimensional computational modeling [2]. In addition, studies that have emphasized using proper physics simulations have yet to compare efficacy across different microneedle shapes [3].

In this paper, we will investigate which microneedle design delivers ibuprofen, commonly a modeled drug, most effectively through transdermal application across multiple skin conditions. The success of using microneedles to deliver ibuprofen transdermally relies on the drug’s diffusion characteristics along with the specific design features of the

microneedles. Our investigation will be a series of three dimensional COMSOL based modeling simulations to evaluate the effect of microneedle shapes on ibuprofen diffusion rates and distribution profiles within human skin tissue. We aim to establish the best microneedle design to achieve maximum delivery efficiency.

II. METHODS

TO avoid complexity and still achieve biologically valuable results, our models followed these assumptions: no reaction processes due to the drug, a dilute concentration of drug solute, and a simplified structure of the skin anatomy. The lack of any sort reaction ensures our model is solely prioritized to drug diffusion for therapeutic delivery; the inclusion of reaction should be an individual study. The dilute concentration of drugs ensures diffusion coefficients will not be dependent on time, consequently, allowing this model to be based on Fick’s laws of diffusion for analytic relevance. We will be creating COMSOL simulations to achieve results. In order to conduct a fair comparison between microneedle designs, all models were generated as identical as possible in geometry and physics. To take advantage of the symmetry of drug delivery patches, our COMSOL spatial dimensions were chosen to be 2D axisymmetric, to revolve around the R axis. As we are modeling for diffusion, our selected physics was time dependent transport of diluted species. The model is designed to be responsible for the 3 layers of skin geometries: stratum corneum, epidermis, and dermis represented as an independent cylinder, with a distinct transport of diluted species physics throughout, allowing for each layer of skin to have its own partition and diffusion coefficients defined by [4], labeled in Table I. The dimensions of the cylinders are lengths of $15\mu\text{m}$, $100\mu\text{m}$, $1150\mu\text{m}$ respectively, and all with a common radius of $500\mu\text{m}$. Embedded into the upper layers of the skin is the cone-shaped microneedle model with a height of $400\mu\text{m}$ and a radius of $200\mu\text{m}$, which is attached to a cylindrical patch of radius $500\mu\text{m}$. Boundary conditions were imposed on the fluxes at interfaces between the components of the system. At the interfaces of layers of skin and the microneedle or coating, the fluxes in the two layers were set to be equal in magnitude and opposite in sign. The outside edge of the cylinder ($r=500\mu\text{m}$), represents a line of symmetry between the microneedle in our model and the neighboring microneedle in the patch matrix. Therefore, a no flux condition is imposed at this boundary due to symmetry. At the bottom of the skin

($z=0$), an outward flux is defined as

$$N = k_{abs}(C_{skin} - C_{blood})$$

where $k_{abs} = 7 \times 10^{-7} m/s$ is the mass transfer coefficient for the absorption of a small molecule from the skin into the bloodstream, C_{skin} is the concentration of the drug in the skin at the interface, and C_{blood} is the concentration of the drug in the blood, which is assumed to be zero as all of the drug that is absorbed is assumed to be swept away quickly by blood flow [4]. The overall model represents a cylindrical cutout of a singular microneedle attached to a drug delivery patch embedded into differing layers of the skin. Any notable differences between each microneedle model is solely due to their unique shape and diffusion profile. Our drug of choice is a commonly modeled, physics supported, drug, ibuprofen. We initiated the concentration of ibuprofen to be variable of the microneedle shape to maintain fairness in simulation. Finally, for optimized accuracy, this simulation was ran with Physics-controlled mesh with fine element size.

TABLE I
PHYSICAL PARAMETERS

Coefficients	Stratum Corneum	Epidermis	Dermis	Interstitial Fluid
D (cm ² /s)	1.74×10^{-9}	2.59×10^{-9}	1.03×10^{-7}	6×10^{-7}
Diffusion Φ	0.079	0.078	0.15	1.0
Partition				

A. Solid Microneedles

Solid microneedles are typically made from rigid materials such as metals, silicon, or strong polymers. Their mechanical strength enables them to penetrate the stratum corneum and epidermis efficiently, creating microchannels that facilitate the diffusion of transdermal drugs. Solid microneedles are non-dissolvable and drug-free. There is no drug in the microneedles themselves, rather, the drug is located in the patch it is attached to. After the skin is perforated with microneedles, the drug diffuses sequentially into the stratum corneum, epidermis, and dermis.

B. Coated Microneedles

The primary difference between coated microneedles and solid microneedles lies in the distribution location of the drug. Coated microneedles are a type of solid microneedles that are functionalized by applying a thin layer of drug formulation onto the surface of the needle shafts. Upon insertion into the skin, the coating rapidly dissolves in interstitial fluid, releasing the drug into the skin layers, typically the stratum corneum and epidermis.

C. Hollow Microneedles

Hollow microneedles are miniature needle structures with a central bore or lumen, designed to deliver liquid formulations directly into the skin through pressure-driven injection. Unlike

solid and coated microneedles that rely primarily on passive diffusion, hollow microneedles enable active drug delivery through flow. Therefore, during our construction of the model of hollow microneedles, we consider the additional components of flow and diffusion factors. In the hollow microneedle model, laminar flow physics are added in addition to the transport of diluted species. The Reynolds number (Re) is calculated to be around 118, using the density and viscosity of water ($1000 kg/m^3$ and $10^{-3} Pas$, respectively), the diameter of the needle tip ($10 \mu m$) and the velocity of the fluid in the needle ($1.18 \times 10^7 \mu m/s$). As $Re < 2000$, this flow is in the laminar regime, and laminar flow physics apply. For the laminar flow, an inlet flow with a velocity of $1.18 \times 10^7 \mu m/s$ from Benbrook *et al.* is applied to the needle tip, and an outlet is applied to the bottom of the skin [3].

III. RESULTS

USING our COMSOL simulations, we designed two metrics to evaluate drug delivery efficiency. The first metric is calculating the time it takes for any percent of drug to make contact with the bottom of our model. The second metric, following a similar philosophy, measures the concentration at the bottom of our models over time. To evaluate changes in drug concentration within the skin over time, we divided the analysis into three distinct phases as follows.

Stage 1: [0–10] minutes

Stage 2: [11–29] minutes

Stage 3: [30–1000] minutes

This way, we set different time intervals in our COMSOL simulations. The first stage is 0.0833 minutes, the second stage is 1 minute, and the third stage is 5 minutes.

A. Solid Microneedles

Our solid microneedle COMSOL model utilized a time-dependent study step to evaluate the drug delivery behavior facilitated by microneedles and selected several representative time points (0, 10, 30, 1000 minutes) for analysis (Fig. 1).

Intuitively, at the initial time point, all of the the drug is localized entirely within the drug patch region, with negligible diffusion into the underlying skin layers. The concentration in the stratum corneum, epidermis, and dermis should be near zero (Fig. 1A). When the model reaches a time of 10 minutes, notable drug diffusion begins through the layers of the skin. There is visible penetration from the patch into the stratum corneum and upper epidermis (Fig. 1B). Within this time interval concentration gradients begin to generate, indicating the start of transdermal transport. When the model reaches 30 minutes (Fig. 1C), the drug has further diffused into the deeper layers of the skin, including the mid-epidermis and upper dermis. The concentration profile broadens, showing active diffusion across the skin barriers. And finally, when model time equals to 1000 minutes (Fig. 1D), after prolonged exposure, the drug reaches a quasi-steady state with distribution throughout the entire skin thickness. Significant concentrations are observed in the deeper dermis, suggesting effective long-term delivery. Notably, the diffusion of the

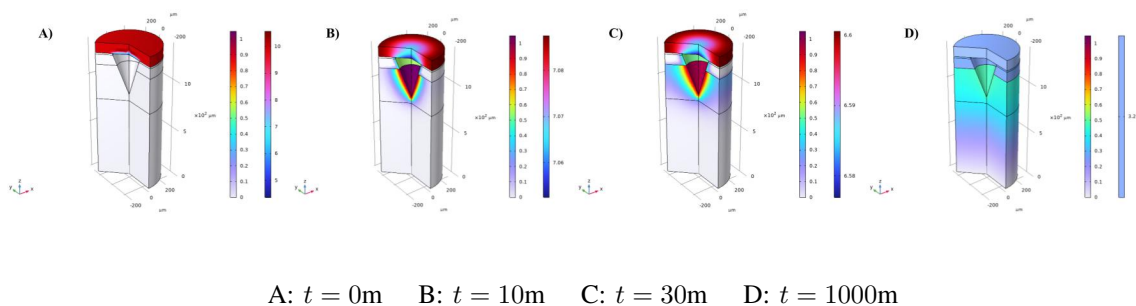


Fig. 1. Concentration profile at different time points in the solid microneedle model.

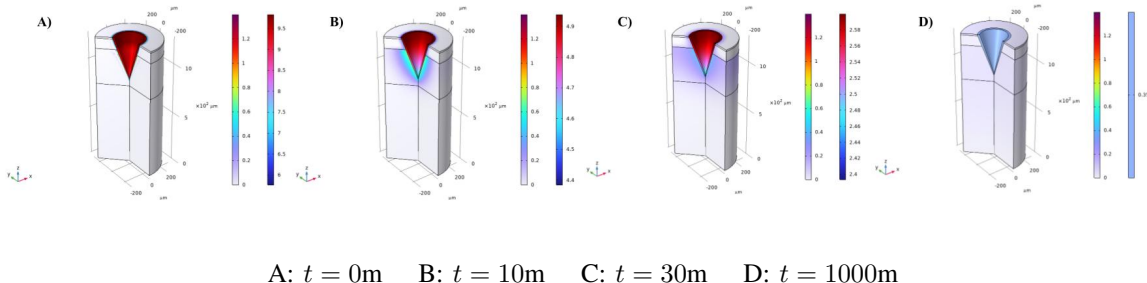


Fig. 2. Concentration distribution at different time points in the coated microneedle model.

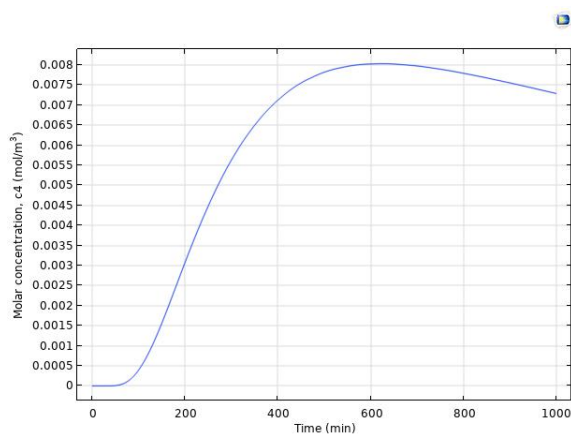


Fig. 3. Molar concentration at the bottom of solid microneedle model over time in the

drug through the stratum corneum is limited, both in rate and final concentration, primarily due to the inherently low diffusion coefficient of this outermost skin layer. We also specifically focused on the drug concentration at the bottom of the skin to evaluate the delivery efficiency of the solid microneedles system. We plotted the time-dependent curve of drug concentration at the bottom of the skin (Fig. 3).

Demonstrated on the plot, the ibuprofen reaches the bottom of the skin approximately at 70 minutes, and the concentration at the bottom peaks at around 550 minutes. Interestingly, after 710 minutes, the drug concentration at the bottom of the skin begins to decline, which may be attributed to continued diffusion into the surrounding tissue.

B. Coated Microneedles

In parallel with the solid microneedle design, a COMSOL simulation was also developed for the coated microneedles to investigate drug delivery behavior (Fig. 2)

In coated microneedles, the drug is applied as a thin film onto the surface of the needle and rapidly dissolves upon insertion into the skin, initiating localized delivery at the microneedle penetration site. (Fig. 2A). Again, intuitively we should expect all concentration to be localized at its origin, in this case in the outer perimeter of the microneedle. When time equals to 10 minutes in the model, the diffusive front extends into the upper skin layers adjacent to the microneedles insertion site. A steep concentration gradient forms around the microneedles tip and shaft, reflecting rapid release from the coating microneedles (Fig. 2B). When time equals to 30 minutes, the drug has spread horizontally and vertically through the stratum corneum and into the upper epidermis. Compared to solid microneedles, diffusion here is more localized to the insertion site, but occurs earlier due to the immediate availability of the drug (Fig. 2C). Until the end of simulation (Fig. 2D), the drug continues to diffuse throughout the skin layers, reaching a more uniform distribution. The coated microneedles model demonstrates efficient short-term delivery followed by sustained diffusion. Similarly, we also plotted a curve illustrating the concentration changes at the bottom of the skin (Fig. 5). Akin to the solid microneedle design, the drug reaches the bottom of the skin approximately at 75 minutes and peaks at around 315 minutes. After 455 minutes, the drug concentration at the bottom of the skin begins to decline. Compared to the solid microneedle model, the concentration for this design is reached earlier and the peak is much lower in magnitude. This can be explained with

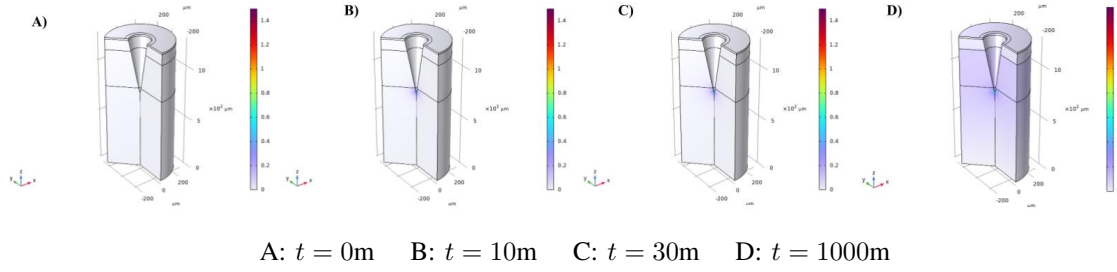


Fig. 4. Concentration distribution at different time points in the hollow microneedle model

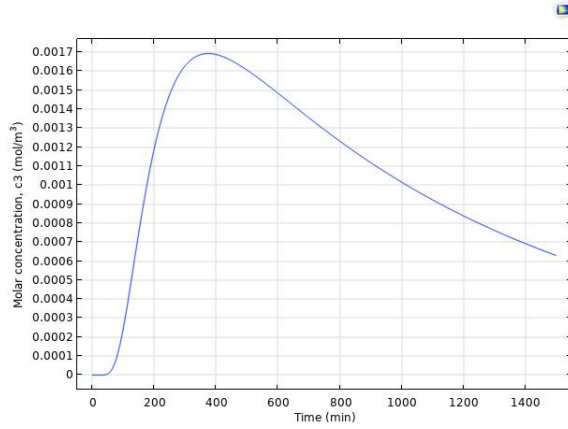


Fig. 5. Molar concentration at the bottom over time in the coated microneedle model

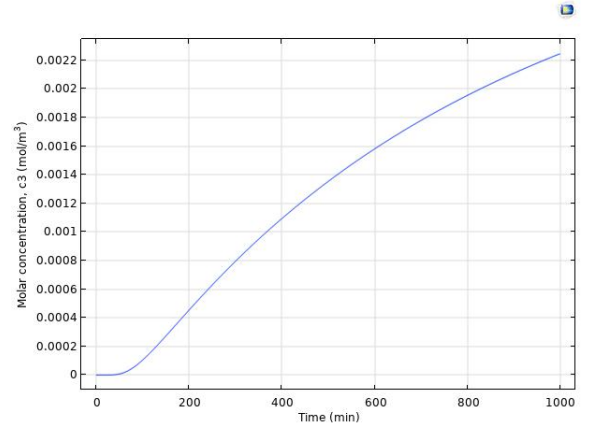


Fig. 6. Molar concentration at the bottom over time in the hollow microneedles model

consideration that, under the same concentration condition of 10 mol/m^3 , the solid microneedle model contains a substantially greater drug volume than the coated microneedle model. Thus it can be intuitively reasoned that there will be less drug everywhere.

C. Hollow Microneedles

For our final microneedle design, Hollow microneedles, the distributions of drug concentration are as follows.

At the initial state (Fig. 4A), the drug is concentrated in the reservoir region above the needle and within the hollow core, a distinct geometry as opposed to the previous two. As such, there is no measurable diffusion into the skin yet, as the injection process has not begun. When time equals to 10 minutes (Fig. 4B), ibuprofen begins to flow actively through the needle's internal channel into the insertion site, driven by pressure difference. A visible gradient forms near the needle outlet, indicating the onset of localized delivery and initial tissue penetration. When time reaches 30 minutes (Fig. 4C), drug flow becomes much more apparent through the internal channel and outlet to the different skin layers. A stronger gradient map begins to show near the insertion site. Lastly, when time equals to 1000 minutes (Fig. 4D) a gradient map more rich in contrast shows the ibuprofen drug diffusing into the skin with an origin centering at the tip of the needle. As the previous two microneedle models, we also examined the time-dependent drug concentration at the bottom of the skin in the hollow microneedle model (Fig. 6).

The Hollow microneedle model concentration dynamics within the skin differ noticeably from those observed in the solid and coated microneedles models. Drug first reaches the bottom of the skin at approximately 80 minutes. Between 80 and 1000 minutes, the concentration at the basal layer continues to increase steadily, but does not reach a peak within the simulated time frame. This suggests that, in the hollow microneedles system, drug delivery to deeper skin layers is more gradual and sustained, likely due to the combined effects of pressure-driven flow and subsequent diffusion.

IV. DISCUSSION

A. Comparison of the Three Microneedle Models

Based on the analysis of the simulation results above, we compared the characteristics of the three different types of microneedles. Table II

TABLE II
COMPARISON OF MICRONEEDLE TYPES

Feature	Solid MN	Coated MN	Hollow MN
Delivery method	Diffusion	Diffusion	Flow + diffusion
Drug location	Patch	Needle surface	Reservoir
Basal onset time	$\approx 70min$	$\approx 75min$	$\approx 80min$
Basal peak conc.	$\approx 550min$	$\approx 315min$	Not reached
Flow involved	No	No	Yes
Drug volume	High	Low	Low

The table can summarize the time at which ibuprofen first reaches the bottom of the skin. Contrasting between the three microneedle models clearly show similarity in time to reach the bottom. There is, however, distinctions in both the solid microneedle model and the coated microneedle model. The drug concentration at the basal layer increases more rapidly, whereas in the hollow microneedle model, the concentration increases at a slower rate. This indicates that hollow microneedles may be more suitable for delivering drugs that require sustained release.

Additionally, we observed a significant difference in the peak concentrations among the three models. The solid microneedle model exhibited a notably higher maxima concentration at the basal layer compared to the other two, indicating higher delivery efficiency under the given conditions. Due to the varying geometries between the designs, our initial assumptions may have not translated well throughout the different microneedle shapes. This is a tradeoff we were willing to take in order to compute a fair and unbiased comparison for drug delivery efficiency. It is important to note that our simulations were conducted under a fixed initial drug concentration of 10 mol/m^3 across all models. In practice, however, the total drug volume delivered by solid microneedles is significantly larger than that of the other two types, resulting in a higher overall drug dose. This explains why the solid microneedle model exhibited a much higher peak concentration at the bottom of the skin. If the total administered drug amount were fixed across all models, the results would likely differ. Therefore, in real-world applications, the selection of microneedle type should be tailored to the specific pharmacological properties and delivery requirements of the drug. However, in terms of objective drug delivery in efficiency and speed, solid microneedles stand as a pillar in drug delivery patches.

B. Future Work

In future work, more comprehensive simulations should be conducted under varying drug concentrations and administration volumes to better reflect clinical and experimental diversity. Many other types of microneedles, for example a dissolving microneedle design, will be included in the simulations. Future studies may also focus on patient-specific skin properties, such as thickness, hydration level, or barrier integrity, to determine the optimal microneedle type for different skin types, thereby promoting personalized transdermal drug delivery strategies. Moreover, evaluating the productivity and cost associated with developing each microneedle model could offer valuable insights for scalable manufacturing and practical implementation. We predict further studies to incorporate less assumptions and envision a realistic framework.

V. CONCLUSION

In this work we have provided a COMSOL based comparison and evaluation of differing microneedle shapes for drug delivery patches. We measured their effectiveness with two derived metrics: time to reach ultimate end of model and how quickly it gets there. Our results indicate similarities between

solid and coated microneedle shapes, with drug arrival times being very identical; and a standalone concentration profile for the hollow microneedle design. Ultimately, each microneedle can be utilized and tailored for a specific type of drug, the hollow design for example could specialize in therapies that take time. Yet, using our gold standard of drug, ibuprofen, the solid microneedle resembles a high quality shape for drug delivery patches. This study highlights the strong potential of solid microneedles to serve as a benchmark design for future drug delivery systems.

ACKNOWLEDGMENT

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APPENDIX A MEETINGS

Date	Agenda	Minutes
March 20	Availability, Project Brainstorming	Available: Monday & Thursday 2:30–4:30 PM; Primary idea: microneedle drug delivery; secondary idea: lactate measurement; Discussed studying different skin types, aging, microneedle geometries; Action: research similar models, decide on parameters to vary
April 9	Microneedle Background, Timeline Planning	Reviewed microneedle background literature; Noted research gap in skin type effects; Created project timeline from April 15 to May 9; Action: revise introduction, research parameters and geometry
April 23	Check-in Meeting with Erfan	General progress check-in with Erfan (no specific notes recorded)
April 28	Model Progress Review	Coated model nearly complete; Dissolving model as internal reaction; Hollow model flow discussion; Initial conc. 10 mol/m^3 ; Discussed boundary conditions and geometry differences; Action: run model for geometry
May 1	Geometry Effectiveness, Model Assignment	Dissolving model is difficult; Effectiveness metrics: time to bottom, bottom concentration; Helen: solid/coated + methods notes; Christine: hollow/dissolving + geometry notes; Qile: results/discussion; Mario: methods; Goal: COMSOL done by May 4; Final Zoom on May 7/8
May 7&8	Manuscript Writing	Review

APPENDIX B PERSONAL GOALS

A. *Christine Yuna Jang*

My personal objective in undertaking this project was to acquire hands-on experience using COMSOL Multiphysics and apply that experience to a topic I'm deeply interested in: drug delivery using microneedles. I aimed to move beyond theory and explore how computer modeling could support microneedle performance analysis and simulation. My goal was to contribute to a viable research project that could result in a clear, organized manuscript while developing the technical skills to run COMSOL effectively. I suggested modeling microneedles using COMSOL, which became our final group project topic. I personally used COMSOL to design the geometries of solid, coated, and hollow microneedle variants. My focus was on ensuring that the modeling process and simulation results were scientifically accurate and functional. By developing the initial geometries, I enabled my teammates to apply boundary conditions, coefficients, and additional physics settings. I also contributed to debugging, fine-tuning parameters, and improving simulations based on results and feedback. The data generated from our COMSOL models provided the foundation for our final report and manuscript. This project helped me become more confident with computational modeling and further deepened my interest in microneedle research. It also demonstrated the valuable role simulation tools can play in supporting scientific exploration and communication. Overall, the project allowed me to accomplish my personal learning goals while making a meaningful contribution to a collaborative research effort.

B. *Helen Sun*

My goal for this project was to learn to apply COMSOL to real problems in drug delivery. I hoped to learn how to translate a system in the real world into a COMSOL model by simplifying the system using assumptions and determining the most accurate geometries and boundary conditions. I also wanted to build more knowledge and intuition on building computational models and develop a better sense of what physics and studies to use for certain projects/systems. I worked towards this goal by helping to build the COMSOL models for our microneedle systems. Working with Christine and the geometries that she developed, I helped define the boundary conditions and parameters for the model.

C. *Qile Wu*

At the initial stage of the project, I reviewed relevant literature to understand the structural characteristics of different types of microneedles. I also discussed with my team members and helped determine our research topic — using COMSOL to model and compare the drug delivery performance of three microneedle models in skin. During the COMSOL modeling phase, I worked on building the coated microneedle model (which was later optimized by Helen — many thanks to Helen). In the manuscript writing stage, I contributed by completing most of the Results and Discussion section. Overall,

this group project allowed me to revisit and reinforce my skills in using COMSOL, broadened my understanding of the mechanisms of microneedle-based drug delivery and the differences among various microneedle models, and enhanced my ability to communicate and collaborate effectively with others.

D. *Mario Quicana*

I have not had the best time working with the COMSOL labs in the homework, mostly because I had trouble understanding the computational modeling and the physics itself. With this project, I was able to understand from a fundamental level the why and how. This Microneedle drug delivery COMSOL model seemed as a perfect project to help me build the understanding required for future engineering modeling. While I did try my best with the solid microneedle design, ultimately, I was unable to produce a competent model, but I at least I can say that I tried. I focused on the development of this manuscript, ensuring linearity, proper technical discussion, and overall writing. I mostly developed the abstract, introduction, methods, and conclusions. I assisted in developing a comprehensible framework for submission.

APPENDIX C
SIGNED PROJECT CONTRACT

Contract for Final Project

We, the undersigned, have agreed to work together on a final research project. Each of us understands that we are jointly responsible for the final product as a whole, and though we may split the work up amongst ourselves, all of us will be expected to comprehend and be able to explain any part of the final product.

For a 4 unit course with one unit of lab, each student is expected to attend 3 hours of lecture, 3 hours of lab, and perform ~6 hours of work on their own on a weekly basis. Each of us understands that we will personally be responsible to put in approximately 4-6 hours of work per week into the final project. If you are unable to do so due to **unforeseen** and **extraordinary** circumstances, it is *your* responsibility to inform the instructor *as soon as possible* so that alternate arrangements can be made. The instructor reserves the right to assign different grades to various members of the group if the workload is not distributed and carried out evenly.

Each of us promise to adhere to the Berkeley Code of Student Conduct (<http://students.berkeley.edu/uga/conduct.asp>) and understand that plagiarism of any kind will not be tolerated.

Project group title: Comparative Evaluation of Microneedle Designs for Drug Delivery Using COMSOL

Brief description of project (in its current form):

Microneedle patches have been successfully integrated into the emerging field of drug delivery research, offering a promising minimally invasive alternative. This study uses computational modeling to quantify the delivery efficiency of ibuprofen dependent on microneedle shape. Using 2D asymmetric COMSOL simulations, based on Fick's laws of diffusion, we modeled three different types of microneedles: solid, coated, and hollow, to test which design is better optimized for drug delivery performance.

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