Cool-sculpting: Optimizing Total Fat Loss During Cryolipolysis

MAE/BEE 4530: *Computer-Aided Engineering*

College of Agriculture and Life Sciences,
Cornell University, Ithaca, NY, USA

PREPARED BY:

Nicole ROSARIO	nar77
Jazmin KEMP	jsk282
Yasmeen MUSHTAQ	ykm2
Michelle BOTER	mb993

May 19, 2018

Contents

List of Figures

List of Tables

1 Executive Summary

Cryolipolysis has become a more prevalent, non-invasive fat loss procedure. Multiple studies have been performed to assess the efficiency of cryolipolysis techniques. This research includes optimization of cooling temperature used in the procedure and finding how the geometry of suction cup leads to better fat loss. Analysis of how adipose cells cool and at what rate they undergo apoptosis would allow us to optimize the total fat loss during the procedure. Current cryolipolysis research has not compared applicator shapes and their dimensions. This study investigates how altering the dimensions of the applicator head can increase fat loss and possibly be beneficial to more patients.

The region of fat being exposed to the treatment was approximated as a 3D slab that includes a skin layer and subcutaneous adipose tissue layer. The rate of heat flux to surrounding adipose tissue was observed under various head geometries in order to maximize fat cell loss. Geometries were designed in order to maximize the surface area to volume ratio, while keeping the volume of fat in the applicator head constant. As a result, locations of cold application were maximized, with the aim of achieving a greater percentage of damaged fat cell loss. To perform a sensitivity analysis, the dimensions of the cooling applicator and therefore the 3D slab were changed, temperature was decreased, and metabolic heat were changed. Heat transfer and the mass degradation were simulated using the commercial analysis software COMSOL multiphysics.

The amount of fat loss during cryolipolysis reaches a threshold. The original applicator model showed around a 5-6% total volume of cooled fat cells after one 60 minute session. Patients usually have to have multiple cooling sessions in order to reach a 20-50% total fat reduction over the course of a few months; therefore a 5-6% total volume of fat cells cooled supports this. Consequently the procedure is not suitable for patients who want to lose more than 10 pounds of fat; even after undergoing multiple treatments because a small amount of fat cells are cooling to the optimal temperature and dying. After designing a new applicator head with an increased surface area to volume ratio, we were able to increase the volume of cooled fat.

This analysis can give rise to new technology that can be used in other cosmetic surgery procedures. Currently, this cryolipolysis procedure is only available to patients who are within 5-10 pounds of their weight goals. By changing the dimensions of the applicator head and by changing the amount of fat loss that occurs post-op, the new shape of the applicator head can expand accessibility of the treatment to patients who are not within 5-10 pounds of their weight goal.

Keywords: cryolipolysis, cold, cooling, liposuction, fat, reduction, weight-loss, apoptosis, subcutaneous adipose tissue.

2   Introduction

In the course of the past two to three decades, obesity has become a very prevalent issue in the United States and across the globe. As of 2014, 37.7% of American adults were obese; this is more than one third of the population, and as studies have shown, current trends show continued increase in these figures [1, 2]. While many problems associated with being overweight tend to be health related, such as increased risk of diabetes and heart disease [3], other issues arise in terms of social and self perception that can be similarly harmful. Obese individuals experience many forms of discrimination which have developed from stereotypes portraying them as lazy, sloppy, undisciplined, and less competent [4]. Regular exercise and a healthy diet can sometimes result in enough fat loss to bring an individual to their desired weight. However, fairly often, individuals look to cosmetic fat loss procedures in order to lose the last few stubborn pounds of fat in problem areas.

Some of the most reputable cosmetic fat loss procedures consist of highly invasive surgical processes such as abdominoplasty ("tummy tuck") and liposuction. Of the two, liposuction continues to be the most popular method of excess fat removal, with 246,354 total procedures reported in the U.S. in 2017 [5]. It consists of the aspiration of subcutaneous fat through small incisions in the area from which the fat is to be removed. As a highly invasive procedure, it raises concerns in terms of wound healing, possibility of infection, recovery time, and use of anaesthesia, among other issues. Due to this, less invasive procedures such as injection lipolysis and non-invasive procedures like laser, temperature, and radiofrequency treatments have become increasingly popular. In 2017, the number of total non-invasive procedures performed in the U.S. was 356,378, just under the amount of highly invasive procedures combined, 376,107 [5].

Cryolipolysis circumvents the problems associated with surgical methods as it is a non-invasive procedure which requires no anaesthetics or post procedural recovery time and has shown to cause no significant side effects in clinical trials [6]. This relatively novel practice consists of the cooling of subcutaneous fat, the layer located under the epidermis and dermis, to temperatures low enough to cause cell apoptosis (programmed cell death). This treatment reduces the number of fat cells (adipocytes) and decreases subcutaneous fat layer thickness. The cooling is done from the outside

2

in, through the placement of metal plates outside the skin with moderate vacuum suction used to draw tissue into the applicator and to optimize the position and contact between plates[7]. These plates cool the cells to an optimal temperature cold enough to kill fat cells, yet not cold enough to cause damage to the layer of skin above it, usually between 3.8°C and 5°C [8].

The appreciable reduction of fat occurs over a 2-3 month period, as the gradual removal of adipocytes through a clearing process set forth by inflammatory reactions. The exact percentage of reduction of fat layer thickness will vary, but has been found to be between 30-50% [9], while other studies estimate it at about 23% [6, 8]. This amount of fat reduction occurs after the patient goes through multiple sessions of the procedure over the course of the 2-3 months [8]. The availability of cooling plates in a variety of shapes and sizes permits cooling of different fat shapes and volumes. Larger and deeper applicators allow for higher-volume fat reduction. Smaller and flatter applicators target small areas more precisely [11]. Because a fairly consistent (per patient) percentage of the targeted fat volume is reduced with each treatment, the selection of applicators to determine the size and specificity of target area can determine how much fat in a certain area can be expected to metabolise with each treatment.

Initial preclinical studies observed that adipose cells were more susceptible to lower temperatures than surrounding tissues; this knowledge led to the development of cryolipolysis [7]. In one specific study, feasibility of the controlled fat cooling was determined using a -7°C copper plate which was applied with antifreeze solution to a single Yucatan pig. After 3.5 months of observation, results indicated a maximal relative loss of 80% of superficial fat loss [12]. The temperature was later lowered gradually, in order to optimize fat loss, leading to fat damage in the area. These results put a threshold temperature of freezing that fat can endure. Later, the model was introduced to the human population, however percentage of fat reduction was limited to 30% [9]. Practitioners do not yet know how they might optimize fat removal through the appropriate selection of applicator head geometry.

2.1 Problem Statement

This study focuses on the effect of applicator head geometry on optimization of fat reduction This was done through sensitivity analysis in order to develop a new design that increases fat reduction. In doing so, the cryolipolysis procedure may become available to a larger number of patients seeking fat loss.

2.2 Design Objectives

There are three primary goals for the development of model:

1. Identify parameters that have an impact on the total amount of adipose tissue cooling to at least 5°C.

2. Perform a sensitivity analysis to determine whether changing dimensions of the applicator and temperature used during the procedure will have an effect on total fat loss.

3. Design a new applicator that will increase the percentage of cooled adipose tissue in comparison to the original applicator model used.

2.3 Assumptions

In order to successfully reach our goals and simplifying the physical situation while maintaining the most realistic model, multiple assumptions were used.

1. Procedure was performed on abdominal regions

2. Heat generation was restricted to the subcutaneous fat layer in the abdominal regions

3. Water and fat cells did not absolutely freeze since the temperature did not reach their freezing points

4. There was no convection due to blood flow

5. There was no blood perfusion in the skin

6. Blood perfusion was present from surrounding capillaries only in the subcutaneous fat layer

3 Methods

3.1 Schematic

The domain over which cooling occurs is a fat "lump" that takes the shape of the cooling applicator, shown in **Figure 1(a).** The fat lump was modeled as a cylinder section with the approximate dimensions of the Advantage™ cryolipolysis applicator, as seen in **Figure 1(b)**. Due

to expected geometric and thermodynamic symmetry, the "lump" was divided using its axes of symmetry and simplified into a quarter of the original domain; this schematic is shown in **Figure 1(c)**.

(a)

(b)

(c)
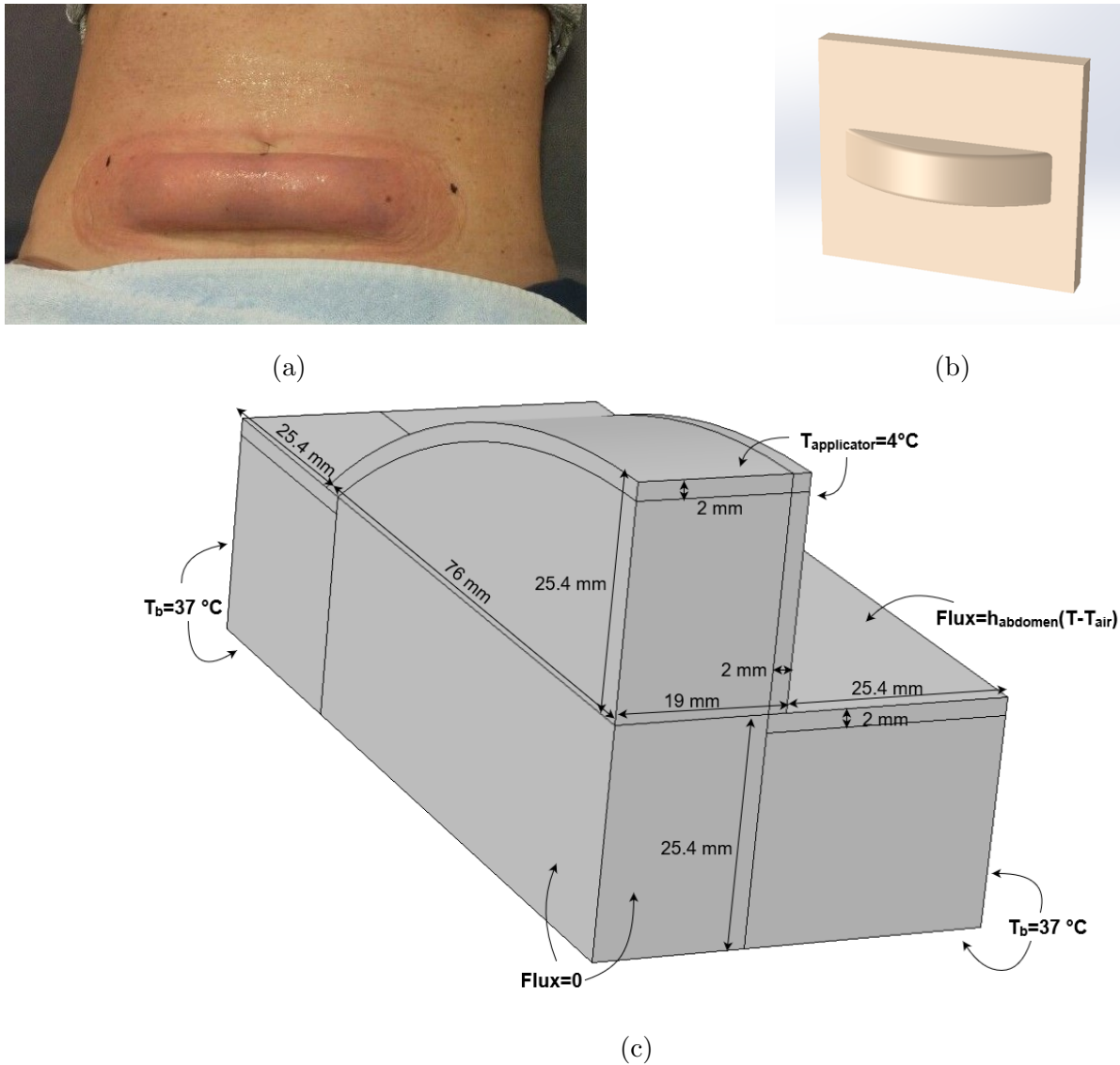
Figure 1: Domain of study. (a)This is an image of post-procedure cooled abdomen fat. [10] (b)This is the model of skin-fat "lump" to be cooled in COMSOL. (c)This is a simplified schematic, taking into account axial symmetry used in COMSOL.

The final computational domain, seen in **Figure 1(c)**, includes sections on the outside of the cooling domain, to effectively study a semi-infinite geometry. Furthermore, a 2mm thick layer of skin was included over the fat inside and out of the cooling domain, in order to account for differences in material properties that exist in the real life situation.

3.2 Governing Equations and Boundary Conditions

The physics used for our model was heat transfer via conduction through human skin and subcutaneous adipose tissue. The transient term of the governing equation for biological heat transfer was used to account for the changing temperature as the tissues freeze. Heat generation was also included in our model because the body at all time generates heat; this is mostly important for the subcutaneous fat layer being cooled. The governing equation used for the model is given below:

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C_{pa}} \left[\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \right] + \frac{Q_{metabolic}}{\rho C_{pa}} + \frac{\rho_b C_b \dot{V}_b (T_a - T)}{\rho C_{pa}} \tag{1}$$

where C_{pa} is specific heat, k is thermal conductivity, T is temperature, t is time, $Q_{metabolic}$ is metabolic heat, ρ_b is density of blood, C_b is specific heat of blood, $\dot{V}_b$ is volumetric flow rate of blood per unit volume of tissue, and T_a is body temperature.

3.3 Input Parameters

Input parameters are required to solve the governing equation for our model. These parameters for our model were calculated using data found in various literature [17][18][19]. The given parameters that were implemented in COMSOL can be seen in **Table 3** in **Section 3.3.**

The material properties of fat and skin were calculated from the molecular composition of each material and the parameters for each of these components. Skin and fat are comprised of three main molecular components: fat, protein, and water [15]. The heat capacity (C_{pa}), thermal conductivity (k), and density (ρ) are different for each component; so the effective parameters needed to have a weighted calculation for each. All three of these parameters were also dependent on temperature. The expressions used to create a weighted calculation were temperature dependent, yielding a temperature dependent effective parameter as shown below:

$$C_{pa} = \frac{dH}{dT} = \frac{A}{100}(F) + \frac{B}{100}(P) + \frac{C}{100}(W) \tag{2}$$

$$k_{eff} = \frac{A}{100}(F) + \frac{B}{100}(P) + \frac{C}{100}(W) \tag{3}$$

$$\rho = \frac{A}{100}(F) + \frac{B}{100}(P) + \frac{C}{100}(W) \tag{4}$$

where F is the property for fat, P is the property for proteins, W is the property for liquid water, A is percent fat, B is percent protein, and C is percent water. The percent of each molecular

6

component found in skin and fat are shown in **Table 4** in **Section B.** The parameter expressions dependent on temperature for each molecular component that was used in the equations to find the effective parameters can be found in **Table 5** in **Section B.** The calculated values for the effective parameters of fat and skin can be found in **Table 1** below. These values were calculated using temperature in °C.

The calculated values for the effective parameters of fat and skin can be found in **Table 1** below [17, 18, 19]:

Table 1: Temperature dependent physical parameters. This table lists the final expressions the physical parameters for of skin and fat layers used as material definitions in the model.

	Skin	Fat
$\rho\left[\frac{kg}{m^3}\right]$	$1070 - (0.199)T - (2.17 \times 10^{-3})T^2$	$946 - (0.378)T - (3.87 \times 10^{-4})T^2$
$k\left[\frac{W}{m \cdot °C}\right]$	$0.404 + (9.51 \times 10^{-4})T - (4.64 \times 10^{-6})T^2$	$0.221 - (2.19 \times 10^{-3})T - (9.19 \times 10^{-7})T^2$
$C_p\left[\frac{kJ}{kg \cdot °C}\right]$	$3.24 + (4.88 \times 10^{-4})T + (2.12 \times 10^{-6})T^2$	$2.21 + (1.31 \times 10^{-3})T - (3.66 \times 10^{-6})T^2$

Each parameter's behavior was plotted between 0°C and 37°C, the temperature range employed in the model, all of which are shown in **Figure 2.**

For thermal conductivity and density, there was a significant amount of change as temperature decreased; enough where that it was extremely important to consider temperature dependent values instead of a constant thermal conductivity and density for both skin and fat. It was also interesting to see that the thermal conductivity for fat was increasing as temperature decreased since it was expected for thermal conductivity of solids to increase as temperature is also increasing. However, the trend that is shown here matched another study on thermal conductivity of animal meats and fats. It shows that the thermal conductivity very slightly varies as temperature changes and that it does increase as temperature decreases[20].

Specific heat had minimal change as temperature decreased, but we thought it was significant enough to consider the changes in the model. It is important to note that the specific heat also does not peak on the temperature range used in the model, which coincides with the fact that the adipose tissue nor the skin are freezing.
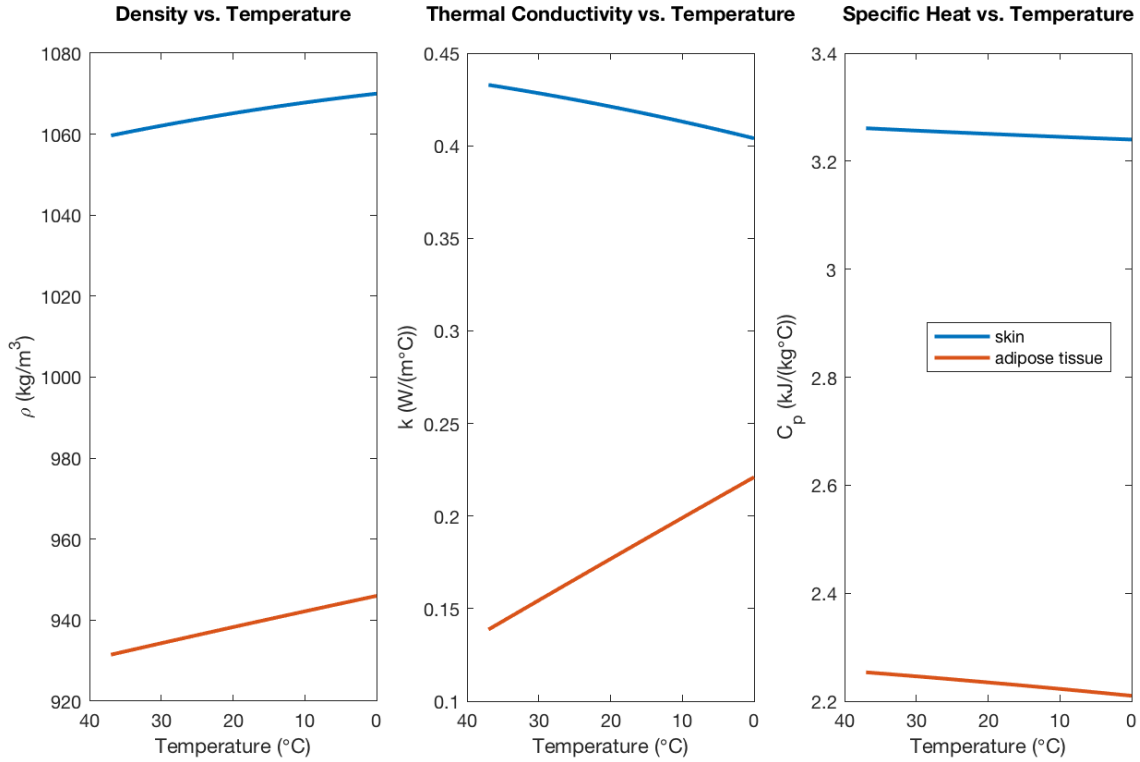
Figure 2: Interpolation plots of Parameters used in COMSOL. The leftmost graph shows the density values used in the cooling model at different temperatures. The center graph shows the thermal conductivity values used in the cooling model at different temperatures. The rightmost graph shows the specific heat values used in the cooling model at different temperatures.

3.4 Initial and Boundary Conditions

The initial condition for the model was set at body temperature in the fat and skin layers. Since the 3D model is only a quarter of the applicator, there is zero flux along the y and x axis. There is convection from air along the unexposed flat skin on the z=25.4mm axis. The temperature of the air is then 20°C. Heat conduction takes place along the curved boundary and at the x=19mm axis of the model as well. This axis is the right side of the protruding shape in the model. The initial and boundary conditions are shown above in **Figure 1(c).**

3.5 What Happens to the Fat Cells?

It is important to note that during the cryolipolysis procedure being modeled, fat cells are not absolutely freezing, which is why the latent heat of fusion was not used for modeling. The fat cells are being cooled to a cold enough temperature that creates irreversible damage to the cell.

This damage triggers necrosis of the cell or cell death due to injury. A study done by Morley and Fursey showed that fatty tissues of beef, pork, and lamb have apparent specific heats that peak at temperatures near $-10°C$ [21]. Therefore, the assumption was made that human fat cells would absolutely freeze below $0°C$ as well. In that case, the model would have to take into account the possibility of skin damage, and the latent heats of fusion for water and fatty tissue.

4   Results & Discussion

4.1   Mesh

An extremely fine free tetrahedral mesh was assembled in COMSOL and is depicted below in **Figure 3.**
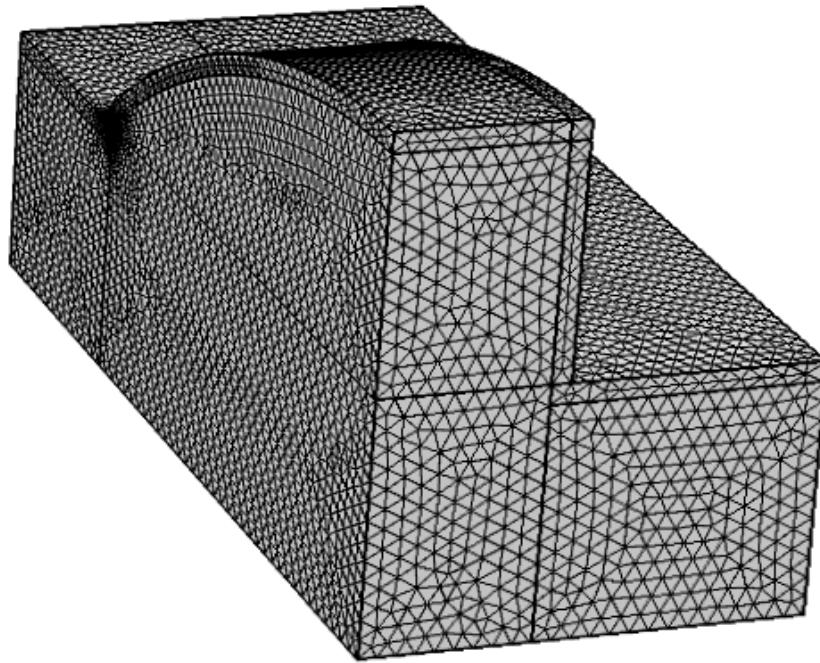
Figure 3: Image of the tetrahedral mesh over the domain. The mesh was built using COMSOL Multiphysics software and its fineness was chosen through a mesh convergence analysis. This is an extremely fine mesh.

One free tetrahedral mesh was built for the entire domain of the fat and tissue material. For the current configuration, a complete mesh consists of 867907 domain elements, 73903 boundary elements, and 3065 edge elements. The total number of degrees of freedom solved for was 1172594 plus 280659 internal degrees of freedom.

To insure there was minimal spatial discretization error, a mesh convergence analysis was performed, which is described more in the next section.

4.2   Mesh Convergence

A mesh convergence analysis was run at a point between the section of fat within the applicator and the section of fat below that. This was meant to ensure the accuracy of the data provided by our chosen mesh by comparing the temperature changes over time for each of the studied meshes as shown in **Figure 4.**
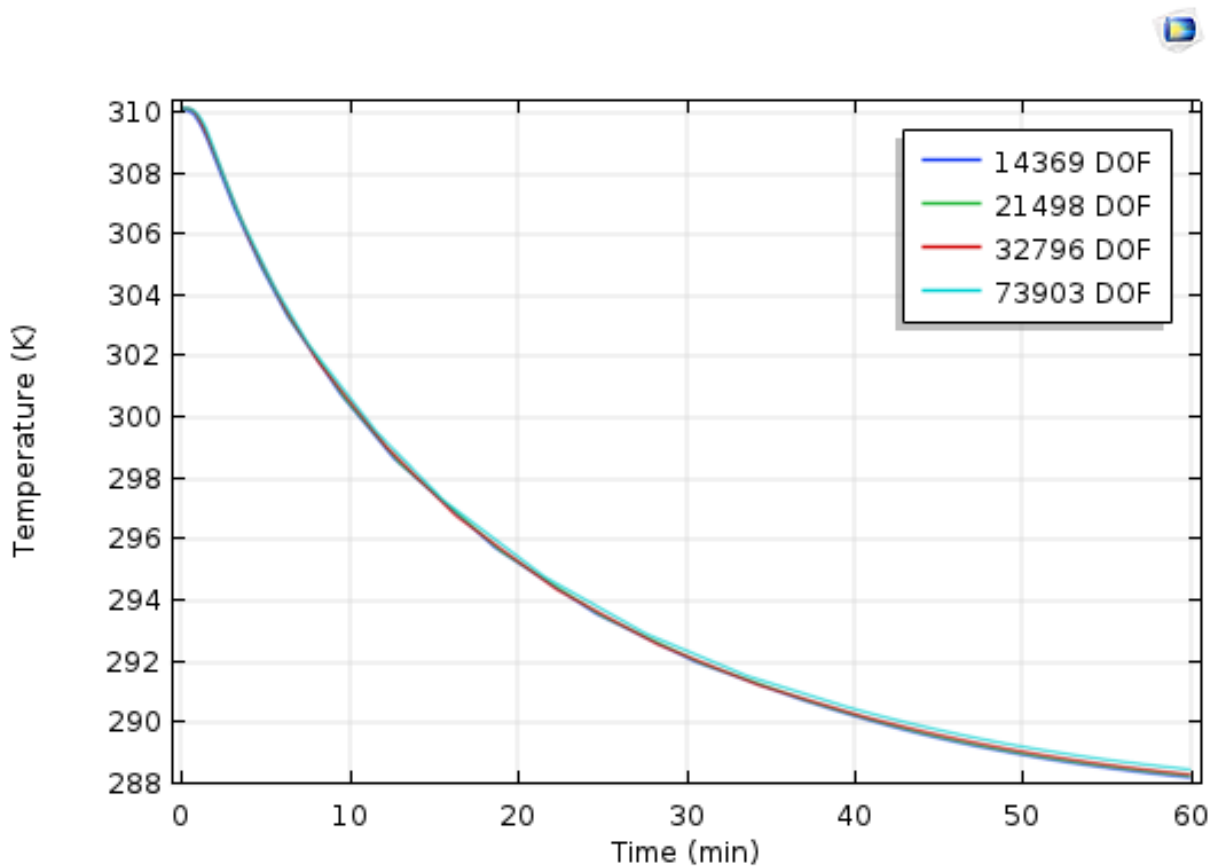
Figure 4: Mesh convergence analysis. Temperatures taken at point $x = 0.01m$, $y = 0m$, $z = 0m$.

All four curves overlap, evidencing no significant difference in temperature when running the mesh convergence for our four mesh sizes. This means the largest mesh would likely provide very similar data to the one provided by our finest mesh. However, the finest mesh was used in order to avoid using low quality elements when calculating the solution.

4.3   Cooling Results

Heat transfer was implemented in COMSOL to model the cooling process during application. **Figure 5** shows how much of the protruding adipose tissue reaches temperatures at or below 5°C.
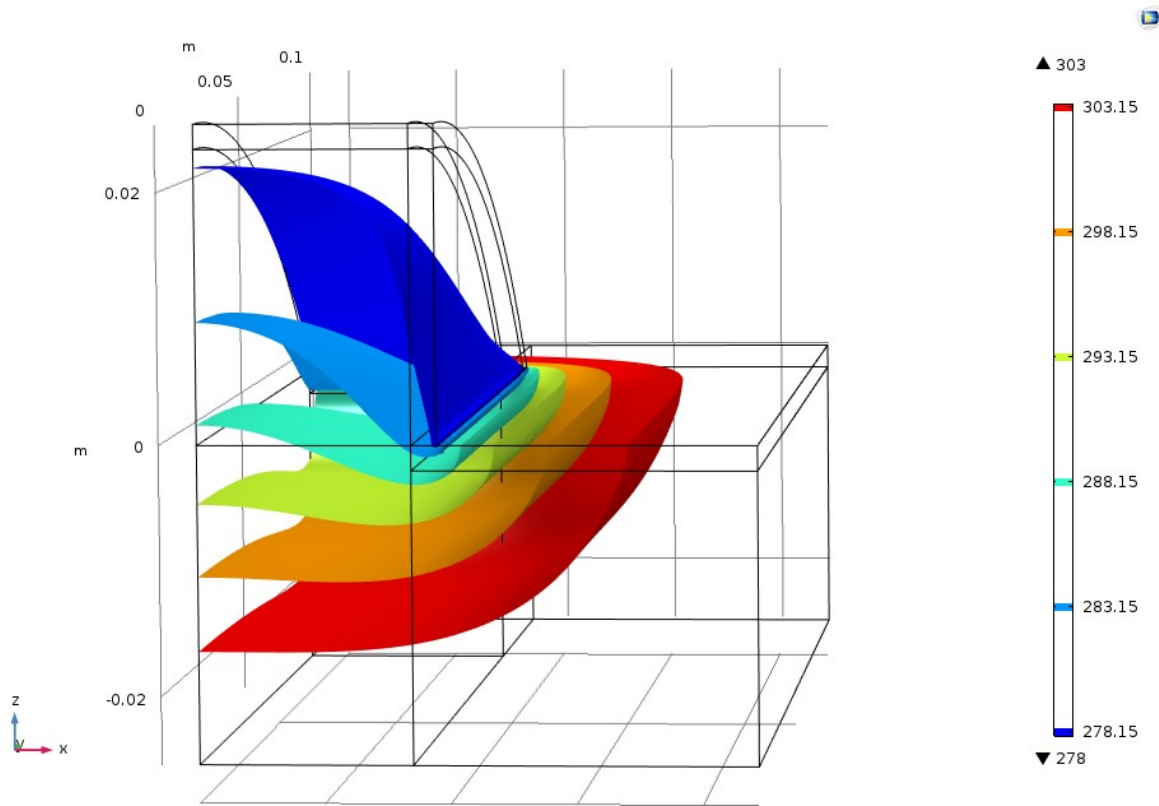
Figure 5: Isothermal plot of temperatures. The isothermal contours show how a specific temperature is distributed throughout the model. The coldest areas reflect where the cooling boundaries are in the model.

The coldest regions are located closer to the cooling applicator. The isothermal contour plots curves towards the boundary where the cooling is applied showing how these regions of adipose tissue are cooling the most.

A plot of volume fractions of cooled cells against time is shown in **Figure 6** to more clearly show how the volume of fat at or below 5°C changes over time as well as the highest percentage of cooled fat after one 60-minute session. The highest percentage of cooled fat in our model is less than 6%, which is expected from one session since multiple sessions yield a fat loss between 20-50% depending on the person. This was calculated using a MATLAB code, appended in **Section A.**
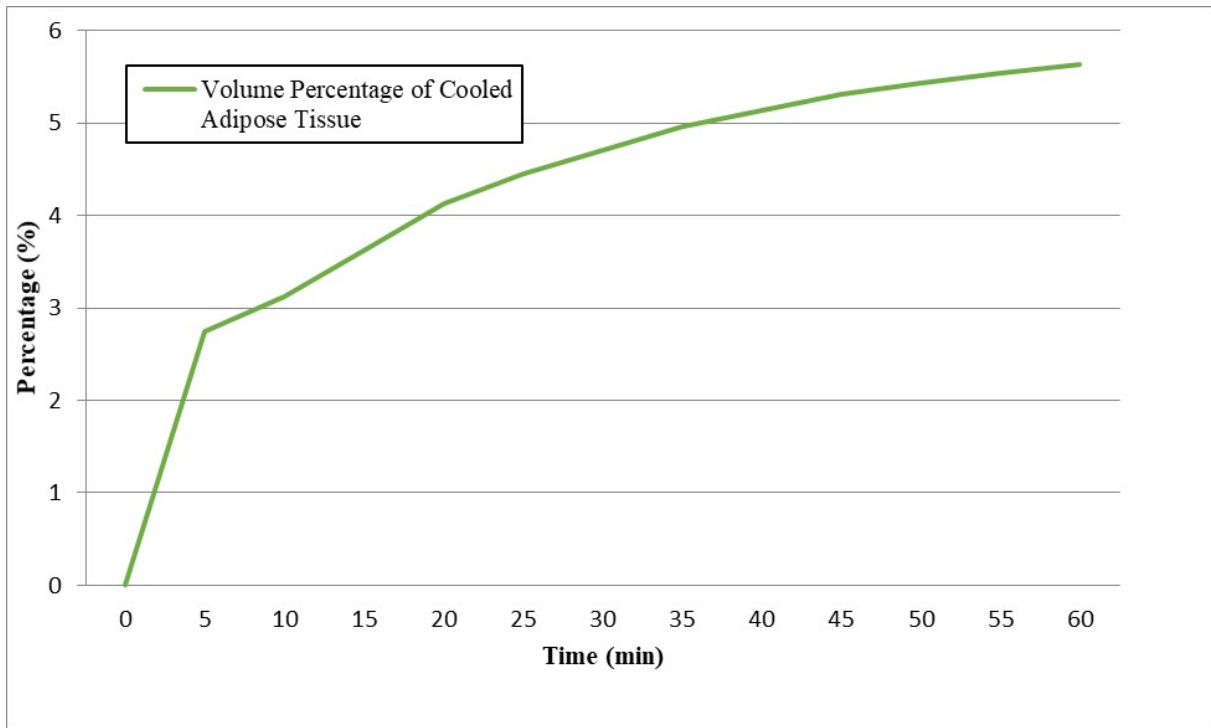
Figure 6: Cooled adipose tissue volume percentage plot vs. time. This is a plot that shows the percentage of cooled adipose tissue in the model as time increases

The model shows that in the span of 60 minutes, only 5.6% of the total fat in the applicator cooled to temperatures below 5°C. The fat was rapidly cooled during the first 5 minutes, and eventually began to plateau over the course of the hour. This suggests that this process may be limited in the amount of fat that can be cooled to a specific temperature.

4.4   Validation

In order to evaluate the quality of the obtained data, these were compared against that obtained in a 2014 clinical study [22]. During said study, Sasaki, Abelev, and Tevez-Ortiz obtained subdermal temperature data at intervals of 15 minutes during an hour-long cryolipolysis procedure. To achieve this, an ultrasound device was used, with a subdermal thermocouple placed 1.5cm below the dermal-fat interface and midway between the side walls of the applicator. Their cooling temperature was just below 0°C and ambient temperature was recorded at 23°C, therefore, we modified our model to fit these changes in variables [22]. The results yielded from this change and those obtained in the clinical study and plotted against time in **Figure 7** below.
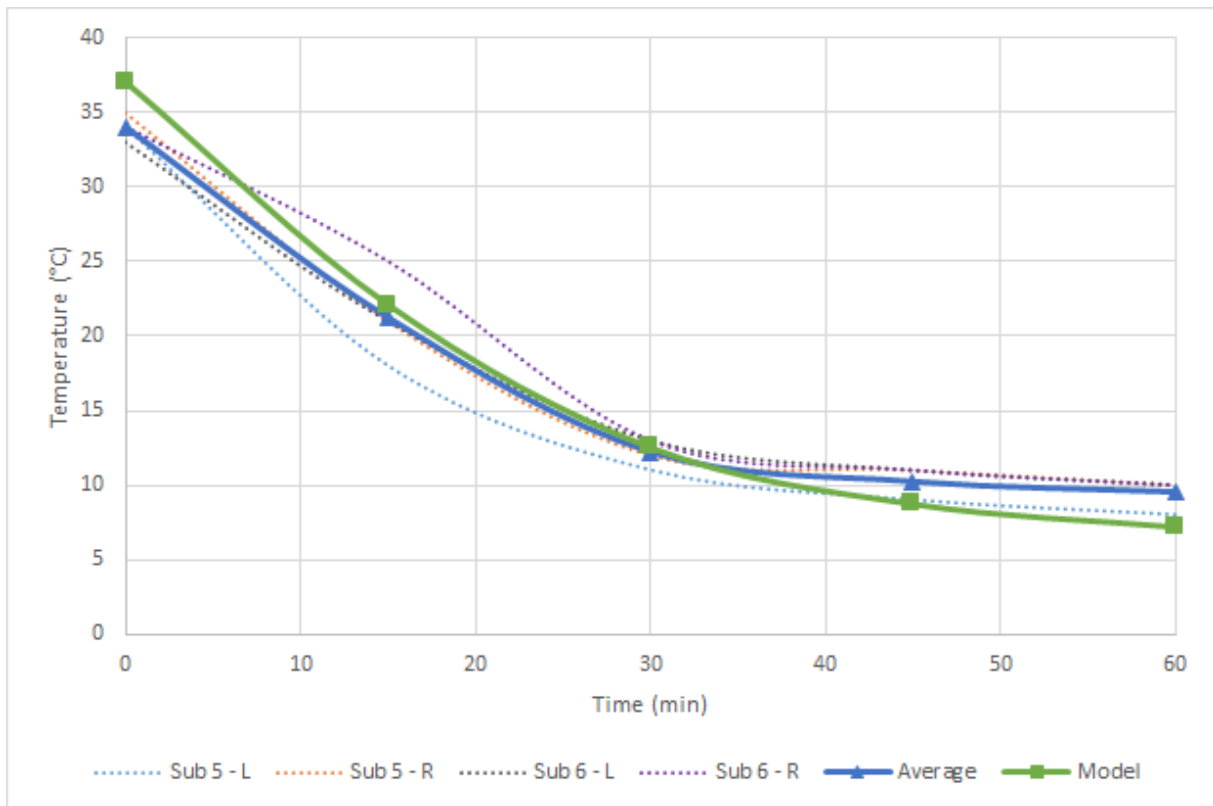
Figure 7: Subdermal temperature as a function of time. Temperatures at depth of 1.5cm below dermal-fat junction obtained from clinical study on the left and right sides of the abdomen compared to the temperature gradient obtained from the COMSOL model [22]. Shown in the graph are the results from different subjects on the right and left side of the abdomen, the average of the subjects, and the model.

The data obtained from our model closely adhered to the average data found in clinical studies. It differed the most at the beginning and end of the period of study, but even then, this difference tended only to be by at most 2°C, still remaining close to the temperature reached on the left side of test subject 5.

4.5 Sensitivity Analysis

To test the effects of changes in geometry on the temperature gradient and amount of fat cooled to 5°C, a sensitivity analysis was done on the dimensions of the applicator. The thickness and width of the applicator were varied whilst the volume of the domain of freezing and the height remained constant. This was done so that the volume fractions of frozen fat found would correspond to comparable values in each case. Firstly, the volume of the domain was described in terms of the other geometric values as follows:

$$V = \frac{t}{2}[\theta r^2 - w(r - h)] \tag{5}$$

$$A = \frac{1}{2}\theta r^2 - \frac{1}{2}w(r - h) + rt \tag{6}$$

where r is the radius of the circular section delimiting the domain, given by $r = \frac{w^2+h^2}{2h}$, θ is the angle of the arc and is given by $sin\theta = w/r$, w describes the length of our domain along the y-axis, h is the height of the lump at its furthest point from the skin and was set to a constant value of 25.4mm, and t is the thickness of the cooling domain. The surface area, A, was varied while keeping the volume and height of our domain constant. In order to do this, the width and thickness of the applicator were changed; a relationship between only width and thickness was found and was used to determine the values of all geometric parameters at every surface area value. The simulation was then run for every geometry.

Once data was obtained from COMSOL, MATLAB was used to analyze the data and find volume fractions at or below a certain temperature. This was done by taking the number of nodes at the temperature of choice in the fat domain and dividing it by the total number of nodes within the fat domain. The MATLAB code used for this process can be found in Appendix A and results are shown in **Table 2** and **Figure 8** below.

Table 2: Volume fraction of fat within the cooling domain under a 278 K after a 1 hour session. Results were obtained through MATLAB computation. Here, 44.3 cm^2 is the original surface area of the applicator.

Surface Area (cm^2)	47.1	45.5	44.3	42.2	41.7
Volume Fraction	0.0643	0.0590	0.0560	0.0445	0.0382
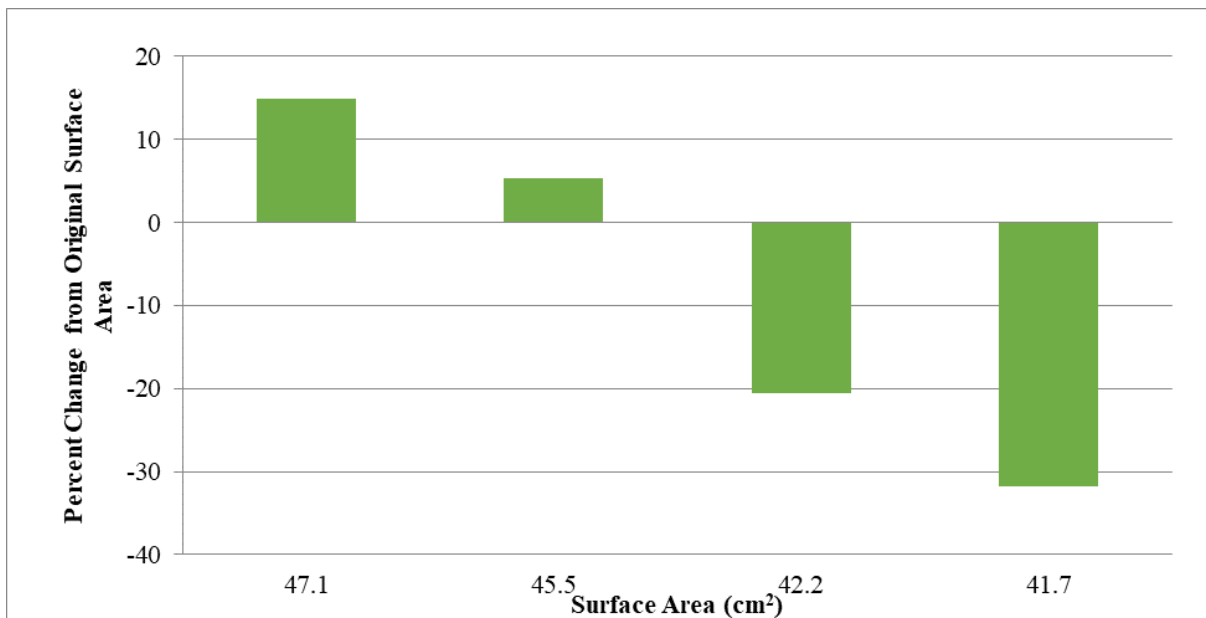
Figure 8: Surface area sensitivity analysis. The percent change of the volume of fat cooled to 5°C with applicators of different surface areas from the original 44.3cm^2 applicator surface area.

The fraction of fat at lower temperatures increased as the surface area of the domain increased. As this surface area to volume ratio increases, the portions of the domain that are exposed to lower temperatures increases, resulting in lowered overall temperatures throughout the domain.

A sensitivity analysis was also done on the applicator temperature and metabolic heat to test the effects of these input parameters. Metabolic heat can differ slightly depending on the person so the analysis was done with a 10% increase and decrease in the heat generation. Temperature was increased and decreased by 1°C to see how much change will result. Other input parameters were not chosen because they are dependent on temperature in out model; therefore, these expressions cannot be changed. The percent change was calculated and the results are shown in **Figure 9**.
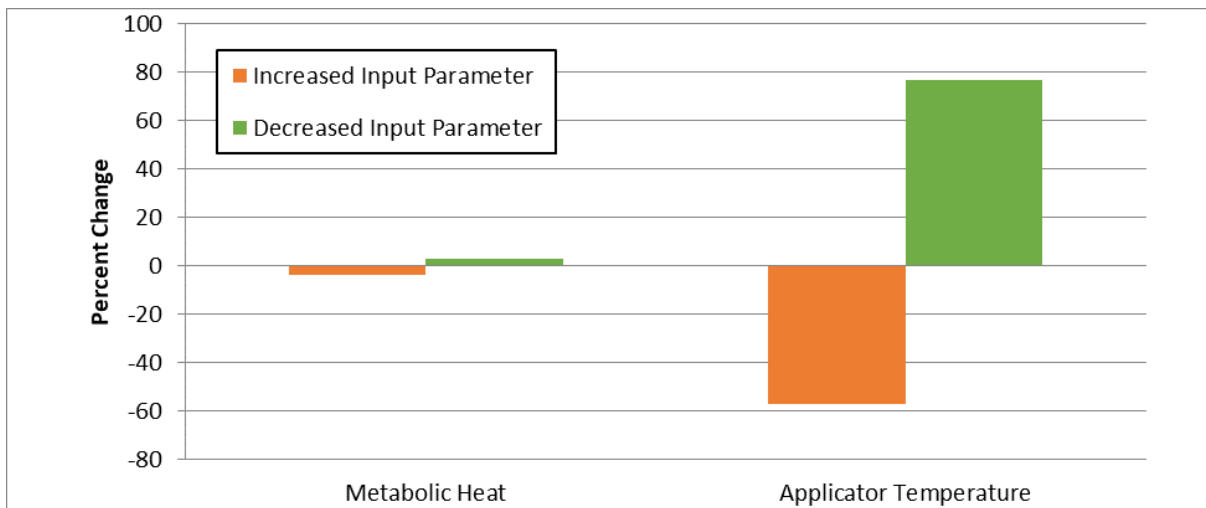
Figure 9: Input parameter sensitivity analysis. The percent change of volume of fat cooled to 5°C from the original input parameters.

It was also expected for the model to be more sensitive to temperature change than any other parameter since it is dependent on heat transfer. However, a 75% change is extremely significant and shows that lowering the temperature even 1°C can have major effects on fat loss for the patient. The model is also not very sensitive to change in metabolic heat, which would be beneficial for any patience that differs in this area.

4.6   Design Improvements

Using the results from the model of the original applicator design, we designed a new applicator that would increase the amount of fat cells being cooled to at least 5°C. **Figure 10** below shows the new applicator schematic, dimensions, and boundary conditions used in COMSOL.
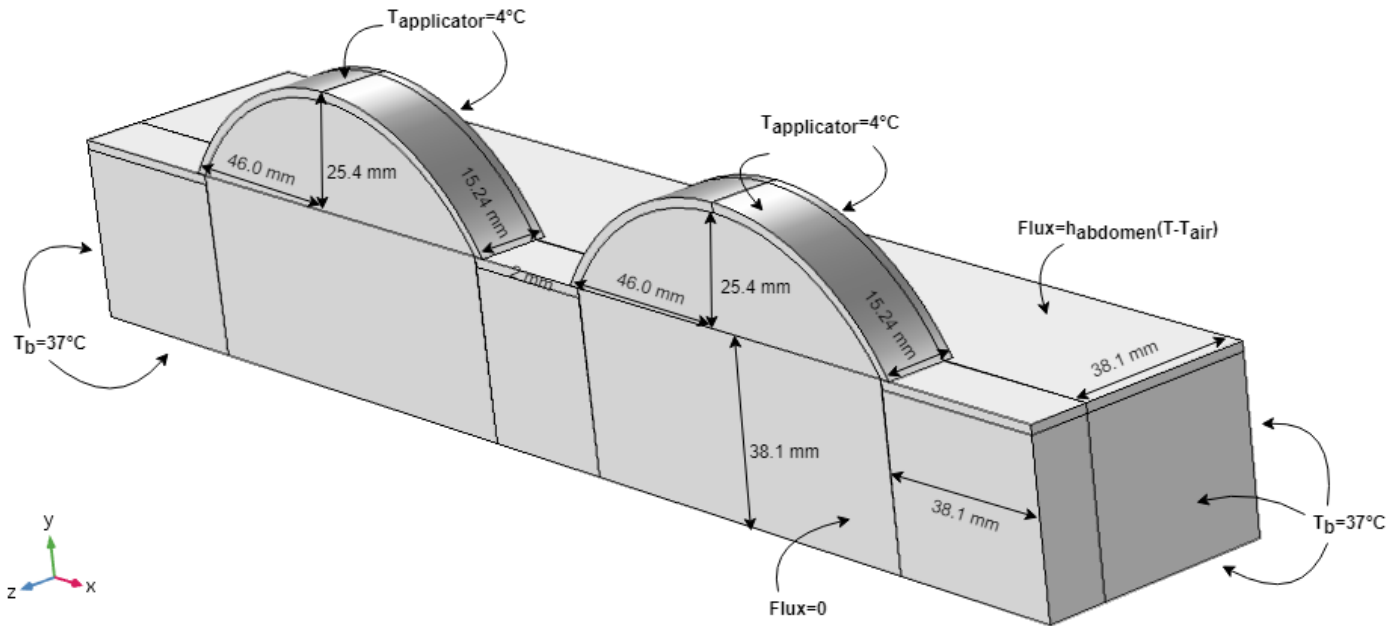
Figure 10: New applicator domain of study. This is a schematic of a simplified domain of the new applicator design used in COMSOL. It takes into account axial symmetry used in the model.

In order to increase the volume of fat being cooled, we needed to increase the surface area of skin being exposed to the cooling surface of the applicator. We also wanted to maintain the volume of fat being cooled as well as the height of the suction cup constant to better compare the results of the new applicator. We did this by designing an applicator head that had two suction cups that would uptake the same volume as the original single-cup applicator. This increased the area of contact between the skin surrounding the adipose tissue and the cooling surface of the applicator. The results obtained from running the model for a 60-minute session are shown below in **Figure 11** and **Figure 12**.
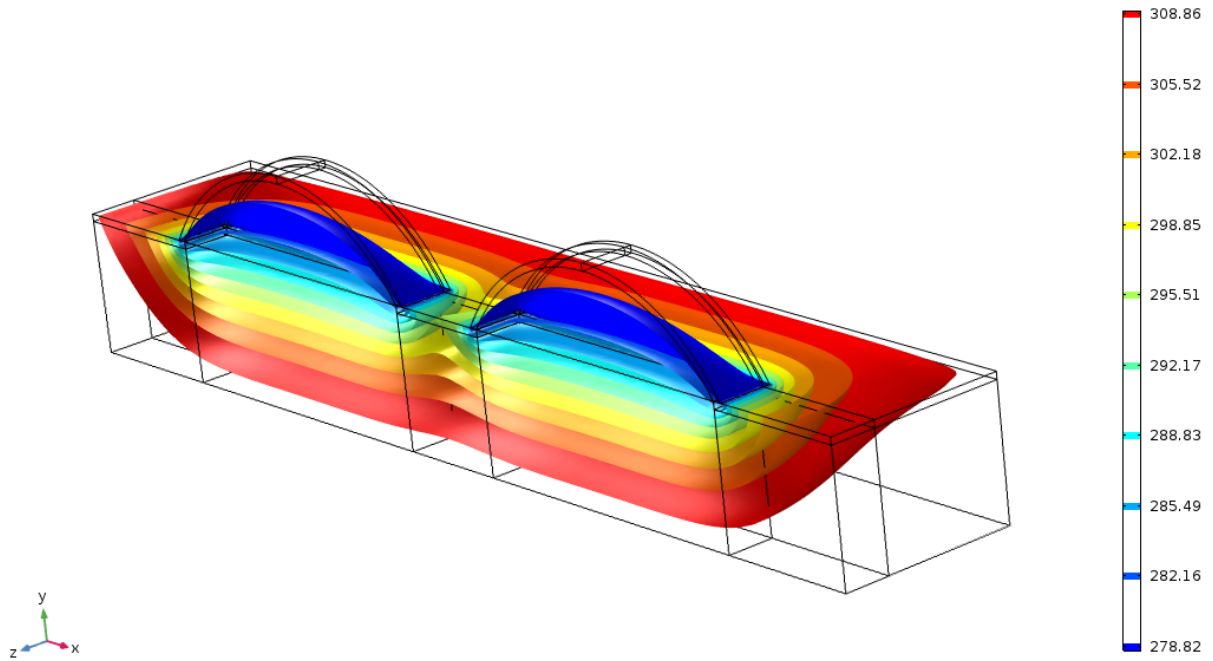
Figure 11: Isothermal contour plot of new applicator. The isothermal plot shows how specific temperature are distributed throughout the new domain after an application time of t=60 min.

Figure 11 above shows that cooling was able to penetrate deeper into the adipose layer, as is evidenced by the topmost 5°C contour. The contour remains at a lower depth than that shown in **Figure 5**; therefore the affected volume above the contour is significantly larger. This difference is expressed in quantitative terms in **Figure 12** below.
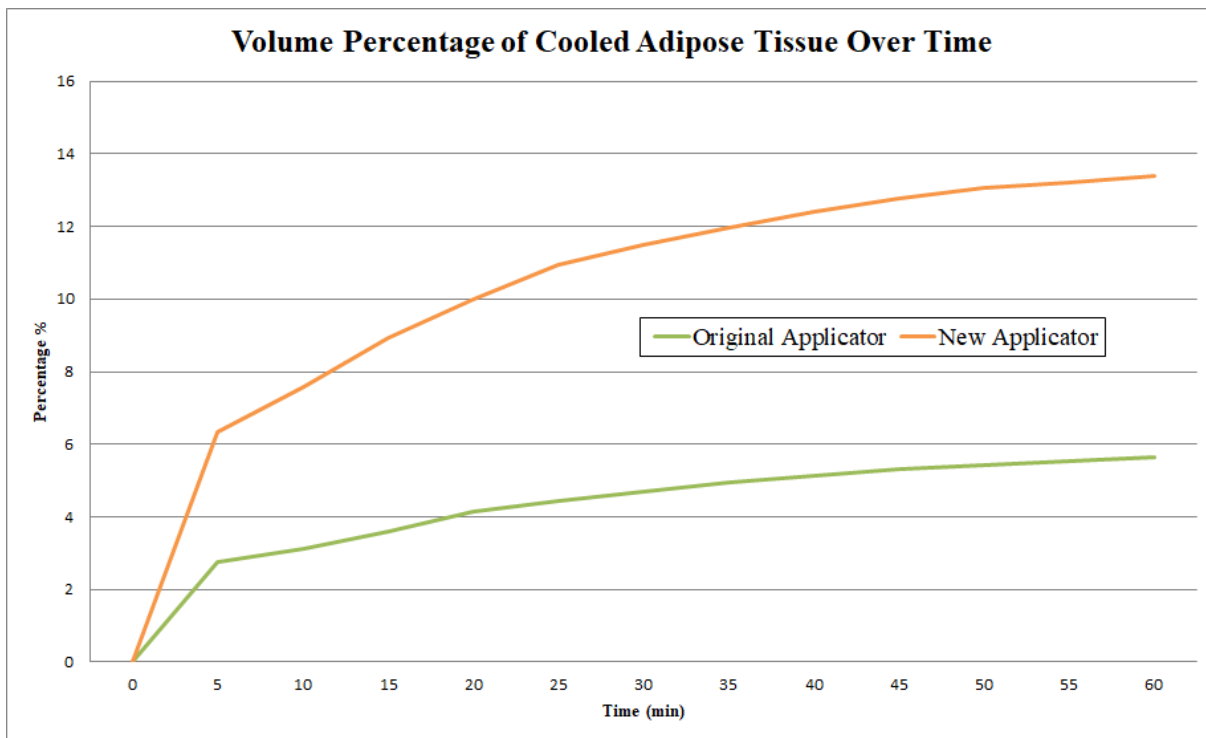
(a)
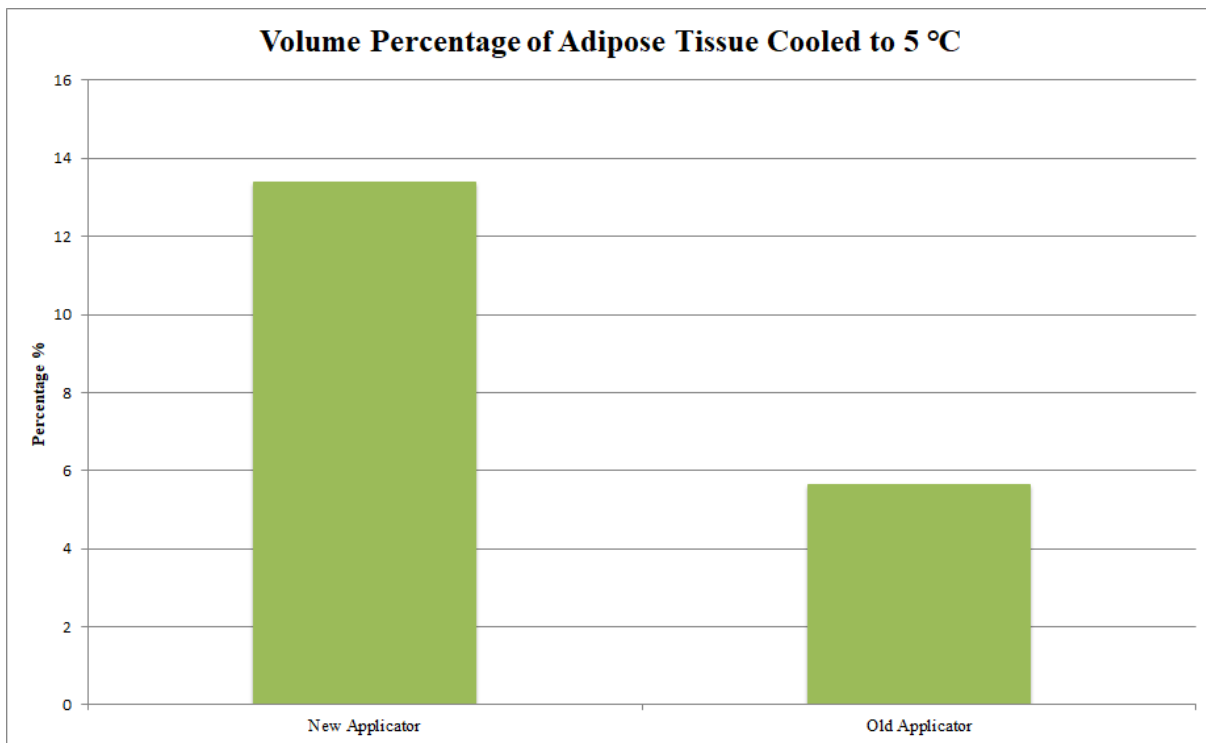
(b)

Figure 12: Cooling results for new applicator. (a) The line graph shows the percent of fat being cooled to 278K over a 60 minute period. (b) The bar graph shows the total percent of cooled fat at the end of one complete procedure.

As depicted in **Figure 12(b),** the new applicator was able to cool a total of 13.4% of fat tissue to 5°C, which is more than twice increase from the original applicator, which only cooled 5.6%. In **Figure 12(a),** it is evident that the new applicator reached the same cooled volume fraction as the original applicator within the first five minutes of the procedure. *Based on these results, we can conclude that increasing the surface area exposed to the cooling boundary may be effective in increasing the amount of fat cells cooled and decreasing the time it would take to cool them.*

5   Conclusion & Future Improvements

During this project, we aimed to find a way to increase the amount of fat loss during this procedure by increasing the percentage of fat being cooled to 5°C. The modeled developed to accomplish this was a 3D heat transfer model with metabolic heat generation, blood profusion heat generation, and temperature dependent parameters. The results from modeling the original applicator and the new design show that the key to increasing the total amount of fat cooled to the appropriate temperature was to increase the surface area exposed to the cooling boundary. From our sensitivity analysis, it was determined that temperature and surface area had the most impact on the total amount of cooled adipose tissue. By creating a new applicator with a greater surface area to volume ratio, we increased cooling volume by more than 200 percent. This increased percentage in cooled fat from the new applicator creates the possibility of other procedural improvements. Improvements can include decreasing procedure time, decreasing the number of procedures needed for reaching fat loss goal, and increasing the number of patients the procedure is available to.

There are very few studies on cryolipolysis because it is a relatively new procedure. Creating more studies can lead to the improvement of the cryolipolysis procedure and the modeling process. Our new applicator was able to cool the same volume of fat cells as the original applicator in significantly less time. If the procedure time is decreased, a clinician can see more patients. One also runs less risk of damaging skin if exposure time is shortened. In addition, by performing further studies on increasing fat cooling, patients may not need as many procedures to reach their goal weight. This could lead to less procedural costs for patients. Presently, the procedure is only available to patients who have a weight loss goal of 5-10 pounds. A possible future endeavor should focus on how effective this procedure is for patients looking to lose more weight. The results from the original model suggest that there may be a limit to the amount of fat that can be lost after the procedure. However, this has not been explored. More clinical studies should target patients who

are seeking to lose more than 10 pounds.

A possible future improvement to modeling this process would be finding and using more accurate temperature dependent parameters for human skin and fat cells. Currently, there is not an abundance of data on these types of parameters for human cells. If there are more updated studies, then the procedure can be modeled more realistically. The more realistic the model, the more accurate the results, and the more we can improve cryolipolysis methods.

References

[1] Ogden, C. L., Carroll, M. D., Fryar, C. D., & Flegal, K. M. (2015). *Prevalence of obesity among adults and youth: United States, 2011-2014* (pp. 1-8). US Department of Health and Human Services, Centers for Disease Control and Prevention, National Center for Health Statistics.

[2] Flegal, K. M., Kruszon-Moran, D., Carroll, M. D., Fryar, C. D., & Ogden, C. L. (2016). Trends in obesity among adults in the United States, 2005 to 2014. *Jama,* 315(21), 2284-2291.

[3] Saydah, S., Bullard, K. M., Cheng, Y., Ali, M. K., Gregg, E. W., Geiss, L., & Imperatore, G. (2014). Trends in cardiovascular disease risk factors by obesity level in adults in the United States, NHANES 1999-2010. *Obesity,* 22(8), 1888-1895.

[4] Puhl, R. M., & Heuer, C. A. (2009). The stigma of obesity: a review and update. *Obesity,* 17(5), 941-964.

[5] American Society of Plastic Surgeons. (2018). *2017 Plastic Surgery Statistics.* Retrieved March 11, 2018 from https://www.plasticsurgery.org/documents/News/Statistics/2017/plastic-surgery-statistics-report-2017.pdf

[6] Dierickx, C. C., Mazer, J. M., Sand, M., Koenig, S., & Arigon, V. (2013). Safety, tolerance, and patient satisfaction with noninvasive cryolipolysis. *Dermatologic Surgery,* 39(8), 1209-1216.

[7] Jalian, M.D. & H. Ray & Avram, JD, M.D., Matthew M. (2012). Body Contouring: The Skinny on Noninvasive Fat Removal, *Elsevier Incorporated,* 31(2), pp. 121-125

[8] Avram, M. M., & Harry, R. S. (2009). Cryolipolysis™ for subcutaneous fat layer reduction. *Lasers in Surgery and Medicine,* 41(10), 703-708.

[9] Klein, K. B., Zelickson, B., Riopelle, J. G., Okamoto, E., Bachelor, E. P., Harry, R. S., & Preciado, J. A. (2009). Non-invasive cryolipolysis™for subcutaneous fat reduction does not affect serum lipid levels or liver function tests. *Lasers in surgery and medicine,* 41(10), 785-790.

[10] Zwivel's Complete Guide to CoolSculpting: Cost, Results, and Reviews. (2018, January 28). Retrieved from https://www.zwivel.com/coolsculpting

[11] Coolsculpting Experts by Sensational Skin. *Why Coolsculpting Experts?* Retrieved from http://coolsculptingexperts.com/cswp/coolsculpting-applicators/

[12] Manstein D, Laubach H, Watanabe K, et al (2008): Selective cryolysis: A novel method of non-invasive fat removal. Lasers Surg Med 40:595-604.

[13] Holmes, K. R. (2010). *Thermal Properties.* University of Texas. Austin: Texas University.

[14] Ravi, S., Dharmarajan, R., & Moghaddam, S. (2015). Measurement of Capillary Radius and Contact Angle within Porous Media. Langmuir, 31(47), 12954-12959. doi:10.1021/acs.langmuir.5b03113

[15] Datta, A. K. and V. Rakesh. An Introduction to Modeling of Transport Processes: Applications to Biomedical Systems. Cambridge University Press.

[16] de Dear, R. J., Arens, E., Hui, Z., & Oguro, M. (1997). Convective and radiative heat transfer coefficients for individual human body segments. *International Journal of Biometeorology,* 40(3), 141-156. Retrieved from https://link.springer.com/content/pdf/10.1007/s004840050035.pdf

[17] Forbes, C. M. (1953). The Composition of the Adult Human Body as determined by Chemical Analysis. *The journal of biological chemistry,* 359-366.

[18] Thomas, L. (1962). The Chemical Composition of Adipose Tissue of Man and Mice. *The journal of physiology,* 179-188.

[19] Choi, Y. (1986). Effects of temperature and composition on the thermal properties of food. *Food engineering and process application* Volume 1: Transport Phenomenon , 93-101.

[20] Morley, M.J. (1966). Thermal conductivities of muscles, fats, and bone.*Food Science and Technology* 1(4), 303-311.

[21] Morley, M.J. (1988). The apparent specific heat and enthalpy of fatty tissue during cooling. *International Journal of Food Science and Technology,* 467-477.

[22] Sasaki, G. H., Abelev, N., & Tevez-Ortiz, A. (2014). Noninvasive selective cryolipolysis and reperfusion recovery for localized natural fat reduction and contouring. *Aesthetic surgery journal,* 34(3), 420-431.

A MATLAB Code

The following code was developed using MATLAB in order to calculate approximate volume fractions.

For the original applicator:

```matlab
filename = 't0.675Data.txt';
fileID = fopen(filename,'r');

nodes=90880;

formatSpec = '%f';

A = readmtx(filename,nodes,4,formatSpec);

fclose(fileID);


inApp = 0;
under280 = 0;
under279 = 0;
under278 = 0;
n = 1;
for n = 1:nodes
    if A(n, 3) > 0
        inApp = inApp+1;
        if A(n, 4) < 280
            under280=under280+1;
            if A(n, 4) < 279
                under279=under279+1;
                if A(n, 4) < 278
                    under278=under278+1;
                end
            end
        end
    end
end
```

```matlab
33
34 per280 = 100*under280/inApp;
35 per279 = 100*under279/inApp;
36 per278 = 100*under278/inApp;
37
38 disp(filename)
39 disp ('under 280:')
40 disp(per280)
41 disp ('under 279:')
42 disp(per279)
43 disp ('under 278:')
44 disp(per278)
```

For the new design:

```matlab
1
2 filename = 'NewAppTime0.txt';
3 fileID = fopen(filename,'r');
4
5 nodes=110252;
6
7 formatSpec = '%f';
8
9 A = readmtx(filename,nodes,4,formatSpec);
10
11 fclose(fileID);
12
13
14 inApp = 0;
15 under280 = 0;
16 under279 = 0;
17 under278 = 0;
18 n = 1;
19 for n = 1:nodes
20     if A(n, 2) > 0.028906
21         inApp = inApp+1;
22         if A(n, 4) < 280
23             under280=under280+1;
24             if A(n, 4) < 279
```

```matlab
25                  under279=under279+1;
26                  if A(n, 4) < 278
27                      under278=under278+1;
28                  end
29              end
30          end
31      end
32 end
33
34 per280 = 100*under280/inApp;
35 per279 = 100*under279/inApp;
36 per278 = 100*under278/inApp;
37
38 disp(filename)
39 disp ('under 280:')
40 disp(per280)
41 disp ('under 279:')
42 disp(per279)
43 disp ('under 278:')
44 disp(per278)
```

B   Input Parameters and Symbols

Table 3: Constant parameters. The table lists the constant parameters found from literature used to implement model.

Input Parameter	Value	Source
T_a	$37°C$	[13]
ρ_b	$1025\frac{kg}{m^3}$	[13]
V_b	$1.66 * 10^{-14}\frac{m^3}{m^3 \cdot s}$	[14]
$Q_{metabolic}$	$1400\frac{W}{m^3}$	[15]
h	$2.8\frac{W}{m^2 \cdot K}$	[16]
T_{air}	$20°C$	[16]

Table 4: Mass fraction of water, protein, and fat (lipids) found in skin and fat tissue. This table list the mass fractions used to calculate the weighted **Equations 2, 3,** and **4.**

Molecular Compound by Mass	*100 = Percent	
	skin	fat
water	0.5771	0.103
protein	0.2733	0.027
fat (lipids)	0.1423	0.872

Table 5: Temperature-dependent expressions used in the effective parameter equations.The table lists the constant value, value for T coefficient, and a value for T2 coefficient that make up the complete expressions for each molecular component for each material parameter.[19]

Parameter	Molecular Component	Constant	T-coeff	T^2-coeff
k	water	0.57109	1.76E-3	-6.70E-6
	protein	0.17881	1.20-3	-2.72E-6
	fat	0.18071	-2.76E-3	-1.77E-7
	fiber	0.32962	1.40E-3	-2.91E-6
ρ	water	997.18	3.14E-3	-3.76E-3
	protein	1329.9	-0.518	0
	fat	925.59	-0.418	0
	fiber	1311.5	-0.366	0
C_p	water	4.1762	-9.09E-5	5.47E-6
	protein	2.0082	1.21E-3	-1.31E-6
	fat	1.9842	1.47E-3	-4.80E-6
	fiber	18459	1.83E-3	-4.65E-6

Table 6: Symbols of parameters used in the model. This is a complete list of the parameters and their definitions use in the governing equation and implementation of the model.

Parameter	Definition
T_a	Body temperature
ρ_b	Density of blood
ρ	Density
C_b	Specific heat of blood
C_p	Specific heat
$\dot{V}_b$	Volumetric flow rate
$Q_{metabolic}$	Metabolic heat generation
h	Convective heat coefficient
T_{air}	Ambient air temperature
k	Thermal conductivity

C CPU and Memory Usage

Computation of a typical run took 1936 seconds (32 minutes and 12 seconds). It used a physical memory of 4.69 GB and a virtual memory of 5.06 GB.

D   Team Member Responsibilities

Table 7: Team member responsibilities

Team Member	Yasmeen Mushtaq	Nicole Rosario	Michelle Boter	Jazmin Kemp
Wrote abstract		x	x	x
Edited abstract	x	x	x	x
Wrote introduction	x	x	x	
Edited introduction	x	x	x	x
Wrote method		x		x
Edited method	x	x	x	x
Wrote results		x		x
Edited results	x	x	x	x
Wrote discussion		x		x
Edited discussion	x	x	x	x
Wrote summary and conclusion	x		x	x
Edited summary and conclusion	x	x	x	x
Wrote bibliography	x	x	x	x
Edited bibliography	x	x	x	x
Prepared processed data table		x		
Reviewed processed data table	x	x	x	x
Prepared figures or tables	x	x	x	x
Checked figures or tables	x	x	x	x
Assigned tasks to group members		x		x
Collated parts provided by others	x	x	x	x
Edited document for consistency	x	x	x	x