Analysis of Insulating Properties of Skin (Rodent)

BME 200/300

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Date: 12/13/2023

Abstract

The metabolic rates of mice have been found to be affected by the thermodynamic properties of their skin—a factor that can be modified genetically, environmentally, and nutritionally. Metabolism is an important indicator of overall health and has wide-ranging effects within a body, including prevention of diet-induced obesity and tumor resistance. In order to explore these relationships in mice and find possible applications to humans, skin insulation data must be collected. Currently, the only cost-effective method that researchers use is infrared cameras that are affected by evaporative cooling, causing inaccurate results. Therefore, there is no cost-effective method to accurately and efficiently measure the thermal conductivity of materials, specifically skin samples. The solution is placing the sample on a heat-conducting plate with attached temperature sensors so that the skin is heated by pulses of 34℃ from the bottom and the temperature on the dorsal surface is measured. The accuracy of the device regarding temperature measurement, exclusion of evaporative cooling, and heating temperature is of utmost importance in the research setting, as data and results will be the reasoning for scientific claims. In addition, the device must be safe, easily usable in a laboratory setting, and cost-effective. With these considerations in mind, along with ease of fabrication and materials, an initial solution was produced. The design features a safe wall-powered heating element controlled by a microcontroller-thermistor circuit and accurate thermistor temperature sensor in a non-inverting amplifier. Tests were performed to evaluate the overall functioning, sensitivity, and accuracy of the device. The results led to the conclusion that the final prototype significantly improves upon current methods by eliminating the effects of evaporative cooling, while having inaccuracies due to inexpensive components.

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Introduction

Motivation

Animal testing is a vital experimentation technique and step in the design process for research labs and any research and design setting. Rodents such as mice and rats provide physiological models that possess many similarities to humans and are therefore often the primary choice for animal testing. In order for medical devices, pharmaceuticals, and biologics to advance to clinical trials and other human testing, animal testing is often required. Therefore, scientific advancement relies on the ability to conduct ethical animal testing on healthy rodents.

The insulative properties of rodent skin prompt significant changes in that rodents' energy metabolism. Heat-permeable skin allows for increased heat dissipation, improving the metabolic health of mice. Metabolism is a factor that directly relates to energy, sleep, and overall health with implications in preventing diet-induced obesity [1]. These factors are important in upholding the quality of animal models in research and testing, as well as providing more ethical conditions for rodents bred in laboratory captivity. Not only does the metabolic effects of skin improve laboratory testing and conditions, but there are established implications in human healthcare.

The thermodynamic properties of mice skin can modulate the metabolic rates of the animal as established, and this carries implications in obesity, disease susceptibility, and even tumor prevention [2]. This is important as research shows that rodent skins' adaptive qualities can be influenced by specific genes, the environment, or diet. As physiological models, these relationships in rodents can have applications to human health. According to the World Health Organization, over a billion humans worldwide are a part of the obesity crisis, with 4 million deaths per year being a direct result of obesity [3]. The treatment and prevention of this, along with potential oncology implications lead to skin insulation and metabolism research being vital.

To perform research and collect quantitative data relating to skin thermodynamic properties, a new product is necessary. This product is a biomedical device that allows for conduct of said research by measuring skin samples' thermal insulation. The ability to measure the changes in temperature across a rodent skin sample shows heat permeability relative to alterations in genetic expression, the environment, and/or diet of the rodent.

Existing devices and Current Methods

Figure 1: Omega infrared thermometer for surface temperature measurement [4]

Effective and non-invasive temperature measurement is often performed using infrared thermometers, sensors, or cameras, such as the Omega infrared thermometer shown in Figure 1. This method of temperature measurement is simple, cost effective, and allows for the observation of detailed patterns in temperature over a surface [4]. Mapping colors as an indicator of temperature provides the user with both a qualitative and quantitative perspective of what is occurring, and the images can be easily used for illustration of temperature data. The client has previously used this method of temperature measurement for collecting thermal insulation data in relevant projects using rodent skin samples. Simpler applications of this technology include most modern digital thermometers, which display a temperature reading from an infrared scan of a surface. Despite the benefits and overall ease of infrared temperature measurement, this method accounts for evaporative cooling (see *Biology and Physiology* Background) with no possible way to avoid this form of heat transfer impairing results. Therefore, data collected via this method is inaccurate when calculating the thermal conductivity of a sample.

Figure 2: Thermtest MP-1 device for measuring thermodynamic properties of samples [5]

The Thermtest MP-1 is a commercially available device that functions similarly to the intended product as outlined by the client requirements and preliminary designs. This device heats ex vivo samples from the ventral (under) side as the body heats skin in vivo, with computer controls allowing for customizable heat settings. On the dorsal (top) side of the skin, the temperature is measured and included software stores and interprets this temperature data as thermodynamic values of skin insulation [5]. The method of heating the skin sample between two rigid surfaces prevents the measurement of evaporative cooling, as the client requires. However, this competitive design costs $30,000 as described by the client after receiving a quote, making for an inaccessible product.

Problem Statement

In order to collect quantitative data necessary for the research of rodent skin thermodynamics and its effects, a biomedical device which can measure thermal insulation of a patch of ex-vivo mouse skin is required. An easy to use, reusable device is necessary to detect differences in temperature across the skin samples when under periodic pulsations of heat. Eliminating evaporative cooling on the skin improves the accuracy of the temperature measurements necessary to quantify insulation. The temperature data, taken within a specific accuracy and sensitivity, will be displayed graphically for ease of interpretation and exportable to MATLAB for analysis. Overall, this device will improve efficiency and accuracy in the thermodynamic testing of rodent skin in a cost effective manner.

Background

Biology and Physiology

The skin samples which the device is designed to use, are surgically collected from the back of recently euthanized rodents, most likely mice. Euthanization is a process commonplace in animal testing where the test, surgery, or dissection to be conducted on the animal requires it to be recently dead, or ex vivo. To administer euthanization, most labs place the animal in a chamber that is pumped with fatal concentrations of carbon dioxide. It is not uncommon for labs to apply general anesthetic via isoflurane inhalation to the animal in order to yield a painless death or allow for in vivo testing.

As mentioned, the purpose of said euthanization is to surgically remove the skin from the rodent's back. This skin is referred to as the dorsal skin, where the exterior of the skin is dorsal and the interior of the skin is ventral, originating from the anatomical definitions of direction relative to the body.

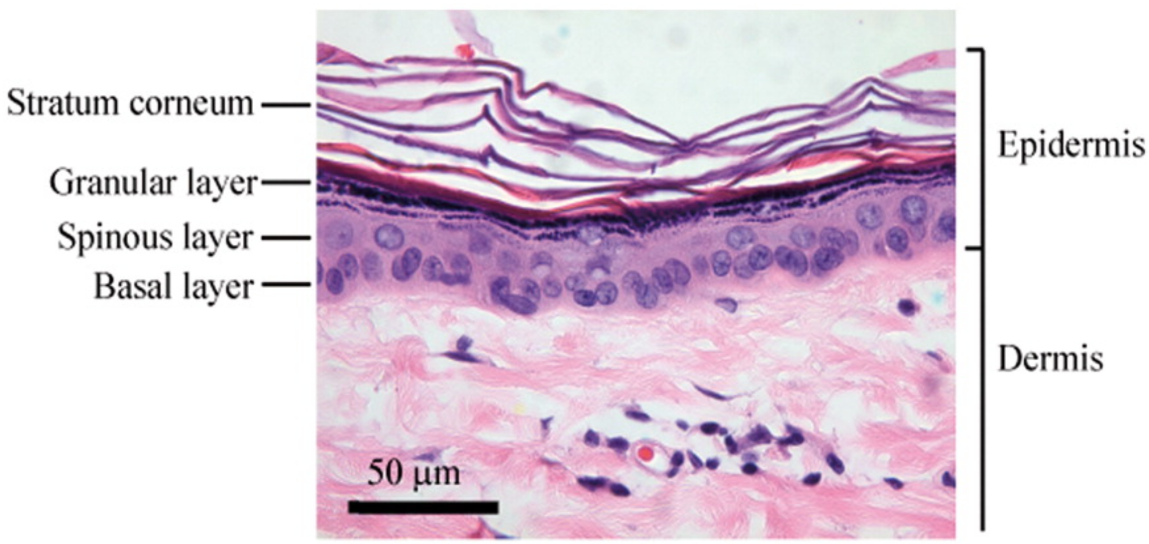

Figure 3: Detailed illustration of skin anatomy, showing the separate layers and cells using a staining microscopy technique [6].

The skin, apart from being the largest organ in the human body and the first line of defense against the outside world, is a complex system with detailed anatomy and physiological effects. As Figure 3 indicates, the anatomy of skin is detailed and involves many distinct layers. One of the functions of skin is temperature regulation, allowing heat to be dissipated from the body into the surroundings [7]. Control of afferent blood flow in dermal capillaries, which can be seen in Figure 3, allows for the magnitude of heat transfer across skin to be modulated. This is visible when a person is undergoing physical exertion and their veins become noticeably larger through the skin. However, the client states that the level of heat dissipation across the skin is not only controlled by blood flow in capillaries close to the surface, but also by the structure of the skin itself. The research of the client suggests genetic manipulation of proteins expressed in skin can alter the thermal conductivity of skin, particularly its insulation properties.

Layers such as adipose tissue and lamellae found within the skin are responsible for a mammal's heat transfer [8]. Adipose tissue lies further beneath the surface level of skin and is important in heat storage which allows the body to maintain the proper temperature [9]. Skin lamellae regulates the heat transfer to and from the environment as it is closer to the surface of the skin [10]. Due to this composition and the high concentration of lipids in skin, high temperatures above normal physiological body temperature (37℃) can damage the skin and the lipid structure within [2]. Understanding these important features of the skin can help with a better understanding of what causes its adaptive heat transferring properties. By influencing one or more of these characteristics through genetic, dietary, or environmental changes, it is possible that heat transfer can be positively or negatively influenced.

Via the multitude of ways in which skin and associated systems affect heat transfer, metabolism is able to be regulated or adjusted. The metabolism of an organism is biologically defined as the net sum of anabolic and catabolic processes [1]. In other terms, metabolism is the thermodynamic balance of processes and reactions that both consume chemical/thermal energy and produce it.

$$C_6H_{12}O_6 \text{ (glucose)} + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{heat energy}$$

Equation 1: Chemical equation for cellular respiration [11]

Cellular respiration is a driving force behind an organism's metabolism. The higher the energy demands of the organism, the more rapidly it undergoes respiration or a similar process and thus the more heat that is produced according to Equation 1 [1,11]. Generally, such metabolic processes impact the necessity for heat dissipation. However, as the client outlines, the ability for heat dissipation as a result of skin insulation can be applied in reverse, allowing for increased metabolic activity and affording the production of more thermal energy.

Metabolism has far reaching and numerous implications in the overall function and health of mammals, specifically rodents in this case. As the example of cellular respiration shows, higher metabolic rates would lead to the consumption and use of more nutrients such as glucose as is the case in Equation 1 [11]. It is well known that carbohydrates such as glucose from a person's diet that are not consumed are converted into lipids and stored over time. Therefore, high metabolic rates prevent the formation of these lipid storages, or fat deposits. Increased metabolism is an effective method of preventing and treating diet-induced obesity, avoiding its far-reaching consequences.

Evaporative cooling is a phenomena that the skin uses as a method of temperature regulation in the form of perspiration. During physical exertion or in a hot environment, sweat glands expel liquid water and solvents onto the surface of the skin as a result of high surface temperatures. Over time and especially in drier environments, this liquid evaporates as a result of the energy input from the heat of the skin [12]. The absorption of heat by the sweat removes thermal energy from the body, thus cooling the body [6]. This exact process also occurs when heating a tissue sample. As the tissue is exposed to heat, water within the sample will evaporate, removing energy from the system and dissipating it into the environment. The result is that the sample is cooled, and measurement of how a material interacts with heat is affected.

Electronics

The design will have a bioinstrumentation focus, and thus the understanding of electrical components is important. The design requires a heating element, a thermistor and affiliated amplifier circuit, and microcontroller. The design team went through a process to decide what each component would be as is discussed in the Design Evaluation, and much of the reasoning for electronics decisions and preliminary design features are outlined in this section.

Integral in the design is an Arduino Uno microcontroller. It can supply 3.3 V, 5 V, and provide a ground connection while receiving output from the circuit described below. C++ code allows the Arduino to read the voltage of analog inputs and make decisions to power connected components on or off.

A thermistor is a variable resistor that changes its resistance based on the temperature of its environment. The magnitude of the resistance change and whether it increases or decreases with temperature depends on the material of the thermistor. A PTC thermistor's resistance is directly proportional to temperature. On the other hand, a NTC thermistor is inversely related to temperature and decreases its resistance with increases in temperature. The change is rarely perfectly linear beyond a defined temperature range and can be influenced by the rest of the circuit connected to the thermistor. According to the datasheet outlining the product specification of the thermistors purchased for this device, the PTC relationship between resistance and temperature is linear and can be modeled as such within the intended temperature range. As a result, the calibration curve fit will be linear, where the thermistor used in this design changes its resistance along the following equation:

$$Temp = Slope * R + Yin$$

Equation 2. The relationship between the temperature and thermistor resistance, where the slope and y-intercept of the linear equation are found using a calibration curve, and R indicates resistance.

This was experimentally determined by measuring the resistance of the thermistor using a digital multimeter at different known temperatures in and around the intended range outlined by the client.

To be able to convert these resistance values into temperature data, the thermistor must be integrated into a circuit, where the output can be read and then substituted into the equations of the thermistor and circuit. The equations to use are determined by the circuit topology.

The design team elected to use a voltage divider outputting directly into a non-inverting operational amplifier (op-amp). Simply, the op-amp receives an input voltage and outputs a voltage that is multiplied by the gain of the amplifier circuit. The gain is calculated based on the resistance of the resistor connected to the input of the op-amp (R1 in Equation 3) and the resistor connected across the input and output of the op-amp (R2 in Equation 3) using the following equation:

$$Gain = \frac{V_{out}}{V_{in}} = \left(1 + \frac{R_2}{R_1}\right)$$

Equation 3. Gain equation of a non-inverting operational amplifier with resistors R_1 and R_2.

$$Vout = \left(1 + \frac{R_2}{R_1}\right)Vin$$

Equation 4. Output voltage of the non-inverting amplifier circuit with respect to input voltage derived from the gain equation (Equation 3).

The op-amp cannot create energy, so its amplification is limited by its power supply, which is 5 V from the Arduino for this circuit. This maximum is too close to the 3.3 V being input into the circuit and would result in the Arduino receiving only 5 V due to the gain of the non-inverting amplifier quantified in Equation 3. Thus, incorrect temperature values would be calculated. Meanwhile, too small of an input voltage makes it difficult to then differentiate between different temperatures, as the output voltage is dependent on input voltage and a limited gain as shown in Equation 4.

These problems can be fixed simultaneously by adding a voltage divider into the circuit upstream of the op-amp. A voltage divider functions opposite of an op-amp, outputting a smaller voltage than it receives based on the resistors that make up the divider. This allows the value of the voltage output to be specifically controlled and can be calculated using the following equation where resistor R3 is directly connected to voltage input and resistor R4 is directly connected to ground:

$$V_{out} = V_{in}\frac{R_4}{R_3 + R_4}$$

Equation 5. The output voltage of a voltage divider circuit with resistors R_3 and R_4.

Equations 4 and 5 above can be combined and then solved for the resistance of the thermistor to derive an equation that can be used by the Arduino to find said resistance value of the thermistor where V_{out} is the total voltage out of the circuit and the V_{in} is the original voltage input from the Ardino into the voltage divider. Note that the V_{out} of the voltage divider is the V_{in} of the op-amp. For the device's circuit R2 is the thermistor and will be written as R_T.

$$RT = \frac{V_{out} R_1 (R_3 + R_4)}{V_{in} R_4}$$

Equation 6. The resistance value R_T of the thermistor as determined from the voltage divider and op-amp.

Given that R_1 = 220 Ohms, R_3 = 1 MOhm, R_4 = 2.2 kOhms, and V_{in} = 3.3 V, all values but V_{out} and R_T, are known. V_{out} is continuously being measured by the Arduino, thus Equation 2 can be used in conjunction with Equation 6 to find the relationship the Arduino uses to solve the temperature measured by the thermistor. While these resistance values are defined in each resistor's product specifications, there is a degree of approximation of the values substituted into Equation 6. Each resistor, including thermistor, has a tolerance value associated with it that accounts for this approximation. This is a percent range around the expected, specified resistance value that the manufacturer allows for the component. These resistors have a ±5% tolerance, meaning that any resistance value from above could be 5% more or less than the stated value.

$$T = \frac{V_{out}(220)(1E+6)(2.2E+3)}{3.3(2,2E+3)}$$

Equation 7. The resistance value of the thermistor as calculated by the Arduino substituting in values for the resistors and input voltage.

Finally, by combining the calibration curve equation of the thermistor in Equation 2 and Equation 6/7, a relationship can be developed directly between the ambient temperature and output voltage. For the calibration curve, data for the relationships between thermistor resistance, output voltage, and temperature, along with graphical illustrations, see **Appendix B**. The final equation that is implemented into the Arduino code (**Appendix E**) is as follows:

$$Temp = 487.0 * Vout - 149.0$$

Equation 8. The final equation provided to Arduino relating temperature to the output voltage of the circuit numerically.

There is one last issue that needs to be addressed, however. Arduino has to convert the voltage value into bits to use as data, and the more bits used the closer the data will be to the actual voltage value. The Arduino Uno uses 10 bits to store voltage values, and it is programmed to expect voltages from 0 V to 5 V. The resolution of a microcontroller is defined by the following equation:

$$Resolution = 2^n$$

Equation 9. The resolution of a microcontroller is described by this relationship, where n is equal to the number of bits.

Based on Equation 9, the resolution of the Arduino Uno is 2^{10}, which is equal to 1024. That means there are 1024 (0 to 1023) total possible bit combinations to map all of the voltage values from 0 to 5. Therefore the V_{out} that the Arduino reads directly from its input pin will need to be multiplied by 5/1023 to get the actual voltage value before any calculations can be done.

The Arduino and heating element are connected to a beefcake relay, which is a digitally controlled switch. The relay is constitutively closed, meaning that when unpowered this switch allows for voltage to pass from the wall into the heating element, but when it receives a 5 V digital signal from the Arduino the relay opens and cuts the power to the heating element, turning it off. The relay is necessary as the Arduino doesn't have the capability to control 120 V by itself. The Arduino determines when to turn the heating element on or off depending on the temperature it calculates from the thermistor circuit and equations shown above. It compares the temperature value to 34℃ and opens the relay when the heat pad reaches this temperature, conversely the Arduino will flip the switch back to closed when the thermistor reads that the heating element has cooled to 30℃. Both of these temperature values can be changed, but this logic allows the circuit to automatically pulse heat through any samples within the set range.

Research Required to Design and Build Prototype

In order to consider all potential design options for this device and fabricate a prototype, the design team needs to determine what materials are feasible for the design. Initial material options will be reusable to allow for repeated temperature measurements and testing, so one major component of this process is the cleaning of materials. The components of the design that come in contact with the mouse skin are the top plate of the heating element and the surface of the temperature sensor. Since ex-vivo tissue will be used, the presence of bacteria or otherwise contaminating tissue is likely. For the use of this device, sterilization is not necessary and general sanitizing or cleaning will suffice. Therefore, the materials' interactions with antimicrobial products must be known.

Similarly, the materials which comprise the heating element and other parts of the design that are exposed to heat must maintain intended performance under those conditions. Material that withstands frequent temperature changes and temperatures of 34℃ includes most metals and hard plastics [13]. Further, a material that does not absorb heat or act as insulation from the heating element to prevent heat loss and allow for greater efficiency is optimal, such as copper and aluminum [14]. For prototypes, cost-effective plastics and resins compatible with 3D printers will be used. Such materials are safe in short-term use at 37℃ [13,15]. For material considerations, cost effectiveness is also an important consideration that requires research. A 12x12 $inch^2$ piece of copper costs $24.99, whereas aluminum costs $12.19 for a 12x12 $inch^2$ piece [16]. The temperature sensor needs to be able to fit over the small skin sample in order to get readings representative of the whole sample. Most of the temperature sensors would comfortably fit on the 2x4 cm ex-vivo skin sample. When comparing the relative diameters of temperature sensors though, there are a couple of considerations. Thermistor temperature sensors have the most variety in size, ranging from 0.075 mm to 5 mm [17]. Thermocouple temperature sensors would cover a larger area of the skin sample as most sensors range from 2 mm to 6 mm in diameter [18]. Lastly, a thermopile temperature sensor has a diameter range relatively in between those two sensors mentioned above, 0.6 mm to 2.1 mm [19].

To ensure the device abides by experimental and laboratory standards, research was conducted surrounding the standards and specifications involved in the formulated design. This device must comply with National Safety Standard IEC 61010-031 Ed. 20 b: 2015, which specifies specific safety standards that electrical devices must follow in order to be utilized. Under IEC 61010-031, the device should be able to be utilized without risk of electrical shock and burn, excessive temperature and mechanical hazards [20]. Most specifically, IEC 61010-2-010 Ed. 4.0 b:2019 discusses safety and accuracy of measurement surrounding devices that are heating materials, which should be easily applicable to the device as the temperature is not getting extremely hot [15]. Along with its use, standard 1910.304(f)(2)(iii) states that the conductor, short circuit and protective device, which in this case would be the box, must have similar operating lifetimes for ease of use and to prevent damaging of the specified parts [20]. Because it is an electrical device, the National Electrical code sets specifics as to what the device can and cannot do in NFPA 70. This includes the fact that the circuit cannot exceed a voltage of 1,200 amps.

Client Information

The client Dr. Caroline Alexander is a Professor of Oncology and principal investigator in the Mcardle Laboratory for Cancer Research, which is in the UW Carbone Cancer Center Developmental Therapeutics program. Her research on the relationship between rodents' metabolism and the heat permeability of their skin has opened new possibilities in improving health as there are implications in cancer, along with factors that could be replicated in humans [2].

Design Specifications

The overall objective of this biomedical device is to provide instrumentation capable of measuring and displaying the thermal insulative properties of rodent skin samples. The device should do so with accuracy such that the measured temperature is within 0.5℃ of the actual temperature, be reusable for repeated tests, and be resistant to changes in temperature within 20-40℃. As a result, materials used for the heating element will need to be resistant to temperatures of 40℃. Examples of a cost efficient material that meets this set of specifications includes copper, aluminum, and hard plastics [13,14,15]. The heating element component of this device will be programmed to heat the sample to 34℃ in a pulsatile manner. For the temperature sensor, it is imperative that the effects of evaporative cooling are not measured, and therefore the sensor will be incorporated into a plate that contacts the skin sample. The device as a whole should last five years and continue to produce accurate results through its use. Due to the repetitive nature of this research, the device should not impair the routine or current protocols which have already been established within the laboratory. For example, the device should fit within the designated area. It is important that the device is designed to accommodate the 2x4 cm skin samples that will be used. Overall, the device will be lightweight, compact, and easy to operate in addition to all of the quantitative and mechanical requirements. For the full product design specifications, refer to the Product Design Specifications located in **Appendix G**.

Preliminary Designs

Heating Element

Wall Power Heating Element:

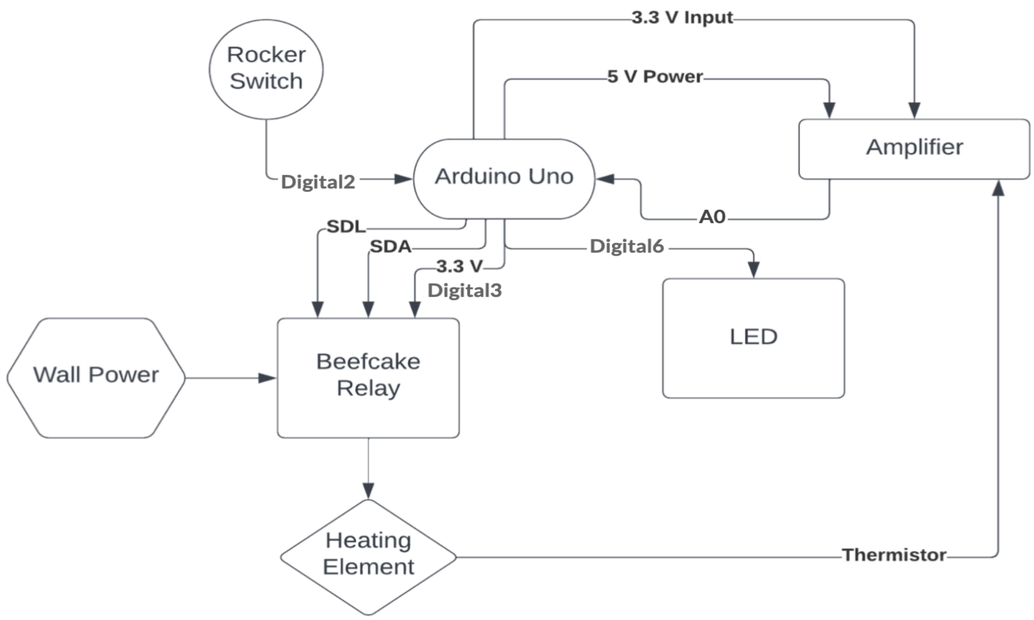

Figure 4. A custom hardware block diagram showing the components and flow of a heating element circuit which uses wall power.

A heating element design centered on wall power being the primary power source would be constructed in a way represented by the block diagram above in Figure 4. A beefcake relay, whose functioning is described in the Electrical Background section, would be incorporated in order to process the wall power and send it to the heating element. The relay is controlled by the Arduino, which can modulate the mechanical switch in the relay with voltage signals. The Arduino decides to send a signal based on a rocker switch and thermistor. If the rocker switch is in the off position and/or the thermistor circuit detects a temperature greater than 34℃, the Arduino microcontroller and downloaded code would instruct the beefcake relay to not send wall power to the heating element turning it off. Similarly, if the thermistor circuit detects a temperature less than 30℃, the Arduino microcontroller and downloaded code would instruct the beefcake relay to send wall power to the heating element. The thermistor circuit functions as a negative feedback mechanism for the heating element. The thermistor is part of a non-inverting amplifier circuit, whose voltage output is directly proportional to temperature. This voltage output is received by the Arduino microcontroller in analog pin 0 as shown in Figure 4. Using a calibration curve and circuit calculations discussed in detail in the Electrical Background section, an equation relating the output voltage to temperature in the Arduino code allows for the described operations to be performed.

Battery Power Heating Element:

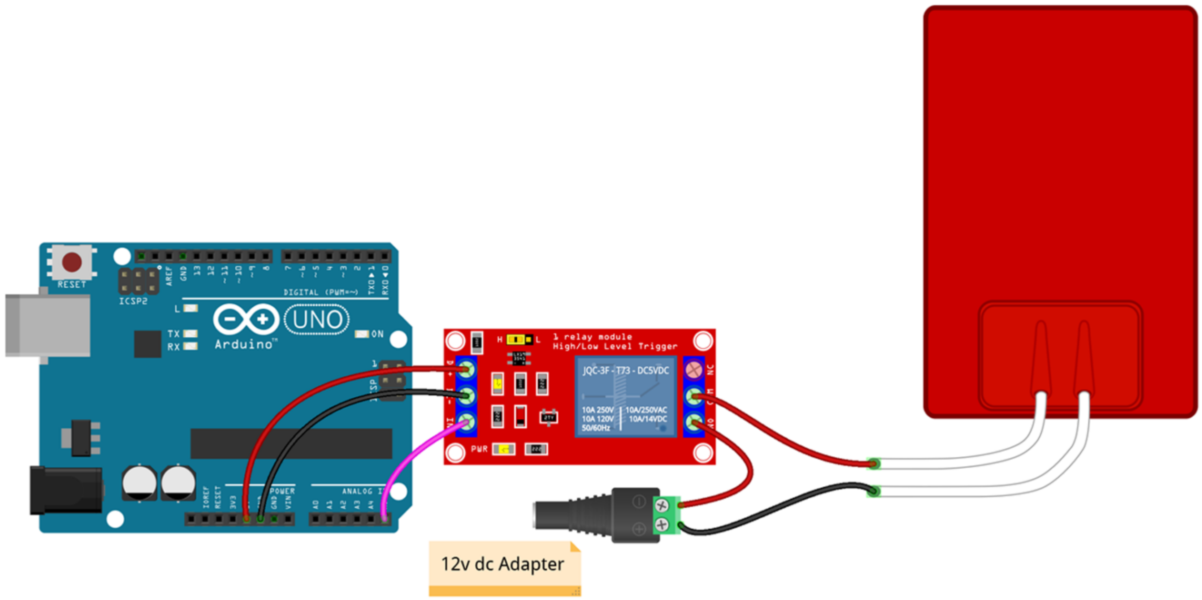

Figure 5. A Fritzing diagram showing the battery incorporated into a circuit with an Arduino microcontroller (left) and heating element (right) [21].

This design includes a battery that powers the heating element as opposed to 120 V wall power. As in the wall power heating element design, the Arduino microcontroller modulates the heating element through a relay, which is the central component as shown in Figure 5 above. [21] Not shown in the diagram is the negative feedback system utilizing a thermistor circuit to ensure the heating element does not heat past 34℃, which would be identical to the block diagram made for the wall power heating element depicted in Figure 4, discussed in the Electrical Background section, and shown in greater detail in the thermistor temperature sensor design (Figure 6) below.

Temperature Sensor

Thermistor Temperature Sensor:

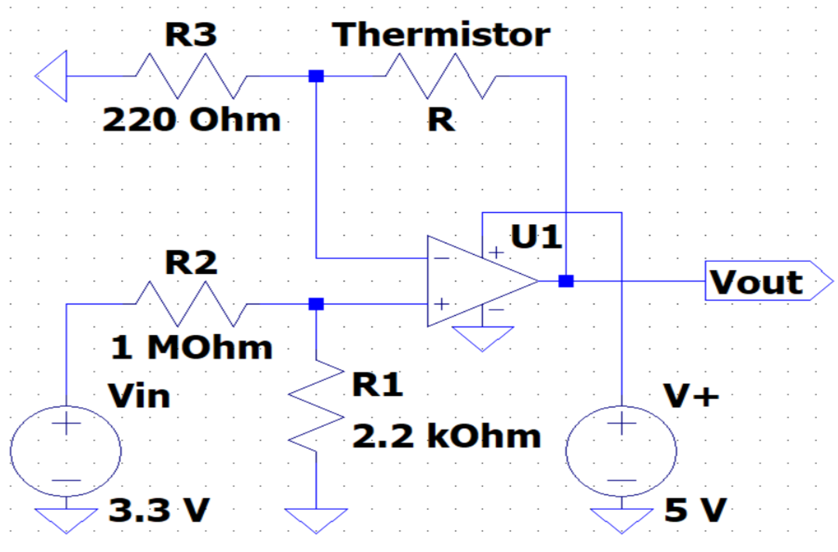

Figure 6. This LTSpice schematic shows the circuit design incorporating a thermistor that is used in the thermistor temperature sensor design.

The thermistor is a variable resistor that responds to changes in temperature with corresponding changes in temperature exhibiting a linear relationship, as discussed in the Electrical Background section. In the shown conformation, the thermistor resistance would dictate the gain of the circuit, directly influencing the output voltage received by the Arduino microcontroller. This circuit design is that of a voltage divider into a non-inverting amplifier, thus the following equation applies:

$$Gain = \frac{V_{out}}{V_{in}} = \left(1 + \frac{R_2}{R_1}\right)$$

Equation 3. Gain of non-inverting amplifier, where R_2 represents the thermistor in Figure 6.

This circuit thus provides the ability to measure temperature as a result of differences in output voltage. The Arduino receives this output voltage in an analog pin, and the combination of analog to digital conversion, an equation relating temperature to thermistor resistance, and an equation relating thermistor resistance to voltage (discussed in the Electrical Background section) provide an equation (Equation 9) that can be implemented in the Arduino code to convert the output voltage, V_{out} in Figure 6, to temperature values for data collection. This same method is used in the modulation of the heating element in the designs above.

Thermocouple Temperature Sensor:

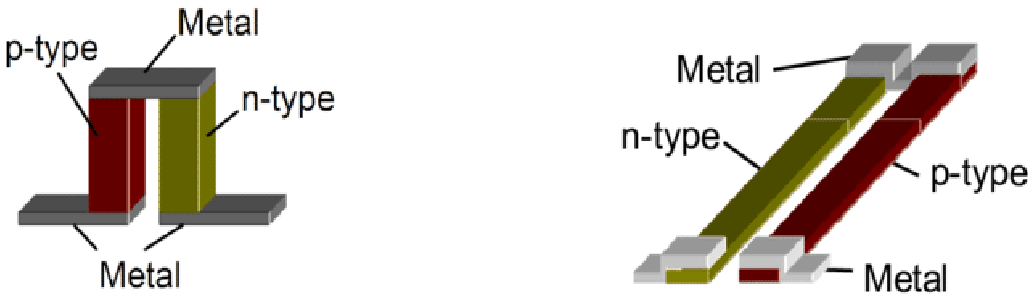

Figure 7. Illustration of a vertical configuration of a thermocouple (left) and of a horizontal configuration of a thermocouple (right) [21].

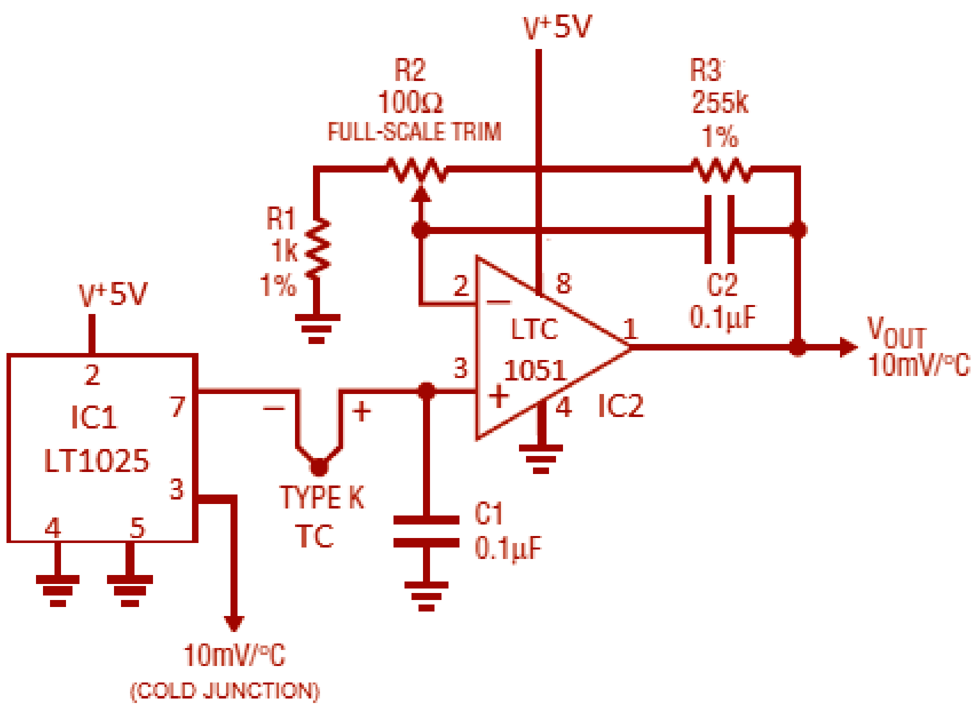

Figure 8. This circuit schematic shows the circuit design incorporating a K-type thermocouple that would be used in the thermocouple temperature sensor design.

To use a thermocouple in a temperature sensor circuit, an additional amplifier LT1025 is necessary. Contrary to a thermistor, which alters resistance due to changes in temperature, the voltage output of a thermocouple is directly affected by changes in temperature. This voltage output is sent into a non-inverting operational amplifier circuit similar to the thermistor circuit, however also requiring the use of a filter to mitigate noise.

Thermopile Temperature Sensor:

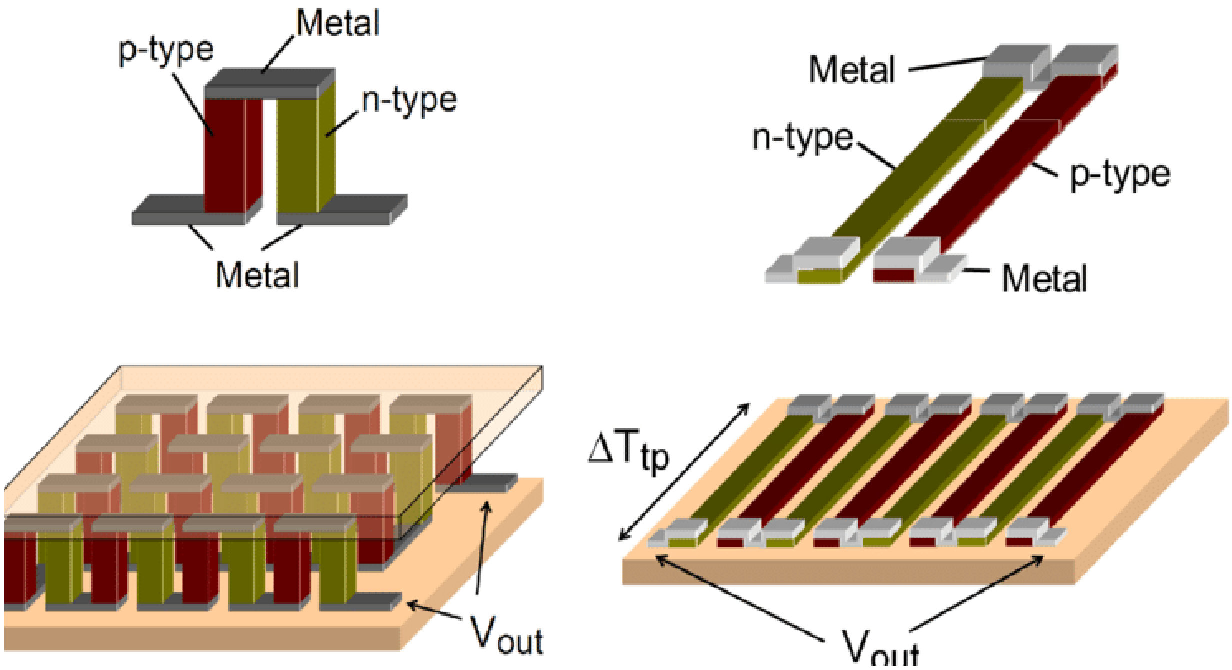

Figure 9. Illustration of a thermopile being composed of thermocouples in series, with thermocouples (top) and respective thermopiles (bottom) [22].

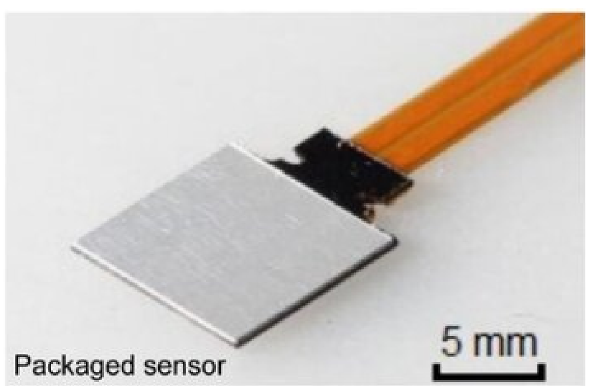

Figure 10. Flat plate design thermopile that would be incorporated into the thermopile temperature sensor circuit [23].

The circuit design that would incorporate the thermopile is similar to that of the thermocouple design, as a thermopile is made up of a series of thermocouples. Thermopiles, however, offer a greater temperature range and sensitivity due to a greater voltage output [23].

Design Evaluation

Design Matrices

Heating Element

Table 1: Design Matrix for evaluation of heating element preliminary designs according to a set of five weighted criteria. Highlights indicate the highest score(s) of each section.

Design Categories (Weight)	**Wall Power Heating Element** 		**Battery Power Heating Element** 	
Safety (30)	2/5	12	4/5	24
Accuracy (25)	4/5	20	3/5	15
Ergonomics (20)	3/5	12	3/5	12
Cost (15)	4/5	12	1/5	3
Ease of Fabrication (10)	4/5	8	2/5	4
Total (100)	**64**		**58**	

Temperature Sensor

Table 2: Design Matrix for evaluation of temperature sensor preliminary designs according to a set of five weighted criteria. Highlights indicate the highest score(s) of each section.

Design Categories (Weight)	Thermistor Temperature Sensor 		Thermocouple Temperature Sensor 		Thermopile Temperature Sensor 	
Accuracy (35)	4/5	28	5/5	35	1/5	7
Ease of Fabrication (20)	4/5	16	3/5	12	2/5	8
Cost (20)	4/5	16	3/5	12	2/5	8
Size (15)	5/5	15	4/5	12	3/5	9
Safety (10)	4/5	8	3/5	6	3/5	6
Total (100)	**83**		**77**		**38**	

<u>*Design Category Descriptions*</u>

Safety:

Safety is an important principle that considers the possible risks that could occur in the use of the device. This includes the durability of the device, specifically when regarding the heating element's interactions with materials surrounding it. The method of powering the device and its heating element also carries possible risks depending on which power supply method is used. For this reason safety is weighted 30 on the *Heating Element Design Matrix* in Table 1, while only 10 on the *Temperature Sensor Design Matrix* in Table 2 because the designs for temperature sensing circuits inherently have very low risk and safety concern.

Ergonomics:

Ergonomics refers to the ease of use for the person operating the device. This criteria assesses the interaction between the user and various interfaces, including the on/off control and power source. The researcher(s) operating the device should not have to go through additional training, as well as adjust the layout of their workspaces as the device should be intuitive and compatible for lab spaces. Additionally, the design of the heating element should allow for easy placement of the skin samples. These aspects pertain to the heating element design and its corresponding circuit, thus receiving a weight of 20 on the *Heating Element Design Matrix* in Table 1.

Size:

The size criteria refers to the overall size that the electronic circuit takes up necessary to operate the temperature sensor and corresponding controls. A larger circuit will be inherently harder to incorporate into the design of the device. The size category specifically for the temperature sensor designs assesses the circuit required to operate the respective component and its ability to be compact, and received a weight of 15 on the *Temperature Sensor Design Matrix* in Table 2.

Accuracy:

Accuracy is a vital aspect to any instrumentation design and refers to the proximity in which components function and measure. For the *Heating Element Design Matrix*, it is important that the heating element heats to 37℃ as intended and expected, rather than heating the sample too much or too little. For this reason, accuracy received a weight of 25 on the *Heating Element Design Matrix* in Table 1. For the temperature sensor, accuracy of measurement is clearly of utmost importance and the purpose of detecting temperature. Inaccuracies in measurement and data collection will have severe effects in the quality of the research, justifying the weight of 35 on the *Temperature Sensor Design Matrix* in Table 2.

Cost:

Cost considerations are crucial when evaluating the design of both the heating element and the temperature sensor. In the context of the *Heating Element Design Matrix*, the cost category encompasses the materials needed for the heating element and its associated circuitry. This includes the expense of heating materials and power consumption. Given the expectation that many components may be readily available for purchase, the cost factor is assigned a weight of 15 in the *Heating Element Design Matrix* in Table 1. For the *Temperature Sensor Design Matrix* (Table 2), cost considerations extend to the materials required for the temperature sensing circuits as well any calibration/testing equipment. Because some potential temperature sensors are expensive, cost management becomes a significant aspect of the design process. Therefore, cost is accorded a weight of 20 on the *Temperature Sensor Design Matrix.*

Ease of Fabrication:

Ease of fabrication is important for all designs as they must be within the ability of the design group to learn and prototype within the time period of a semester. That means the rating for each design accounts for the complexity of the circuit required to implement each component and how the component will integrate into the overall system. The availability of electrical components was also considered, as many are readily available through the Makerspace or from past instrumentation courses. Ease of fabrication is weighted at 10 for the *Heating Element Design Matrix* in Table 1 as the design team expects more of the device to be easily purchasable. The weight for the *Temperature Sensor Design Matrix* in Table 2 is 20 as research is necessary to fabricate the circuits, as well as perform calculations, create calibration curves, and test them.

Design Matrix Evaluation

Heating Element (Table 1)

Safety:

The wall powered heating element scored a 2 in safety because of the fact that a 120 V outlet is required to power the device, creating risk such as shock or electrical fire. The exposed cord from the device to the outlet could also pose safety concerns depending on how the device is positioned in its intended environment. The battery powered heating element scored a 4 in safety as there are far less safety concerns of a contained battery compared to that of the wall powered element. The batteries would not be exposed to the user and would allow for the device to be portable without the risk of the cord. However, the battery would still generate electric potential and could produce heat as a result.

Accuracy:

The wall powered heating element design scored a 4 because wall power is a more reliable source of energy and would allow for fewer electrical connections. The battery powered design scored a slightly lower score of 3 due to the fact that electrical connections always pose the risk for energy loss and increase the likelihood that output voltage is lost. This fact alone would make the temperature of the heating element appear less to the Arduino microcontroller in the feedback circuit causing errors in heating temperature. It is most likely that it would heat samples above 34℃ and compromise the accuracy of the heating element.

Ergonomics:

Both the wall powered and battery powered designs scored a 3 in the ergonomics section. Each design is about equally intuitive to the user, but both have different components which the user must consider. The on/off control of both designs would be similarly simple, as a rocker switch would be used in both. The largest considerable difference is that the battery powered design will require battery replacement/charge occasionally, while the wall powered design would need to be plugged into an outlet. Both of these considerations are minimal and carry no significant difference in magnitude. Each design allows for compatibility in lab space and should not require additional training to use.

Cost:

The wall powered heating element scored considerably higher than the battery powered heating element. With a score of 4, the wall powered heating element would provide a reliable and cost efficient way for our client to take many temperature readings. With a score of 1, the battery powered heating element was not as optimal as batteries for use in electric circuits are expensive. Finding a reliable battery that can output a steady electric potential for repeatedly powering the heat source would require a significant expense, and there has been no funding/budget outlined on this project so far.

Ease of Fabrication:

The wall powered heating element scored a 4 over the battery powered element as the circuit design for wall power is much simpler and requires fewer components than that of the battery power. Although wall power introduces safety concerns that can impair fabrication and testing, proper precautions will be taken. As mentioned, the battery power design would require recharging or replacing of the battery, and this would introduce a maintenance aspect that the design team and/or client would be responsible for.

Temperature Sensor (Table 2)

Accuracy:

The thermocouple temperature sensor received a score of 5 in the accuracy section due to a slight uptick in accuracy compared to that of the thermistor temperature sensor. Thermocouples measure temperature in a different manner that more directly alters voltage output, as opposed to a thermistor which does not directly output voltage and rather changes resistance. Due to tolerance in the thermistor and the calibration curve producing an *approximate* equation, there is greater potential for error compared to the direct modulation of output voltage that the thermocouple induces. The thermopile temperature sensor design received a weight of 1 in this category because thermopiles are capable of measuring evaporative cooling even when in direct contact with the samples, which would take thermodynamic factors into account that the researchers are strictly attempting to avoid.

*Ease of Fabrication***:**

The thermistor temperature sensor scored the highest in this category with a 4, followed by thermocouples which scored a 3 and thermopiles that scored a 2. This is because the thermistor circuit does not require the use of an additional amplifier and filters as the thermocouple and thermopile would.

Cost:

The thermistor temperature sensor scored the highest in this category with a 4. The costs of each potential temperature sensor are similar and are all relatively low-cost, however the thermistor is the least expensive. The thermocouple scored a 3 in this design matrix as they are normally slightly more expensive than thermistors and thermopiles scored a 2, as they are the most expensive option. Additionally, as mentioned in the Ease of Fabrication evaluation, thermocouples and thermopiles require the use of an additional operational amplifier and incorporation of a filter, which requires more components.

Size:

The thermistor temperature sensor design scored a 5 in the size category. This is due to its compact size and more simplistic overall circuit. Being a resistor, it fits well into the circuits and would not require additional elements such as filters and multiple amplifiers. Contrarily, a thermocouple scored 4 due to the fact that it is larger than a thermistor and requires more wires and electrical components, expanding the scale of the design unnecessarily. Thermopiles which scored a 3, are series connections of thermocouples, and are therefore larger components even though they require similar circuit components.

Safety:

The thermistors scored a 4 in safety as the safety concerns involved circuit is relatively low with only one open circuit and simplistic design. Though relatively safe as well, thermocouples scored a 3 in safety because there are two operational amplifiers involved, creating a slightly higher risk for short circuiting and heat generation. Thermopiles scored a 3 in safety as well for this reason.

Proposed Final Design

Based on the evaluation of the design matrices, it was decided that a wall power heating element and a thermistor temperature sensor are the optimal proposed final designs. This conclusion was made as a result of the wall power heating element scoring highest in the *Heating Element Design Matrix* shown in Table 1, winning in 3/5 criteria, and the thermistor temperature sensor scoring highest in the *Temperature Sensor Design Matrix* shown in Table 2, winning in 4/5 criteria.

The wall powered heating element was found to be favorable by the design team because the components necessary to fabricate the design are more cost effective. Batteries and the components used in their integration are expensive and not without their inaccuracies in electric potential generation as the voltage of the battery will decrease over time. Similar reasoning made the thermistor temperature sensor favorable, such as a simpler circuit that requires fewer components and has fewer electrical connections, meaning it is safer, more cost effective, and smaller in size.

The cumulative proposed final design features a heating element with a flat surface meant for placing the skin sample. The heating element has been determined to be powered via a 120 V wall outlet, and the heating element circuit directs this wall power into a beefcake relay. Modulating the beefcake relay is an Arduino microcontroller, which can turn the beefcake relay on or off either by an on/off rocker switch, or due to the analog input from the output voltage of a thermistor circuit. A thermistor in contact with the heating element will be part of a non-inverting amplifier circuit, able to provide an output voltage to the Arduino that corresponds to temperature. Based on an equation converting voltage to temperature derived from a calibration curve or the thermistor specifications present in the Arduino code, the Arduino can turn power on to the heating element if it is below 34℃ or off if it is above 34℃. On the dorsal surface of the skin sample, a flat thermistor will be in contact with the sample. Similar to the heating element, the thermistor will be incorporated into a non-inverting amplifier circuit able to send an output voltage to the Arduino microcontroller where it is converted to a temperature value. This temperature value relative to the 34℃ heat applied to the skin is the essential data which the researchers need, so it will be displayed.

Final Design

The final design of the device to measure thermal insulation of rodent skin samples is made up of an integrated circuit featuring the wall powered heating element and the thermistor temperature sensor. The combination of these electrical circuits allows for the temperature to be measured on each side of the skin sample.

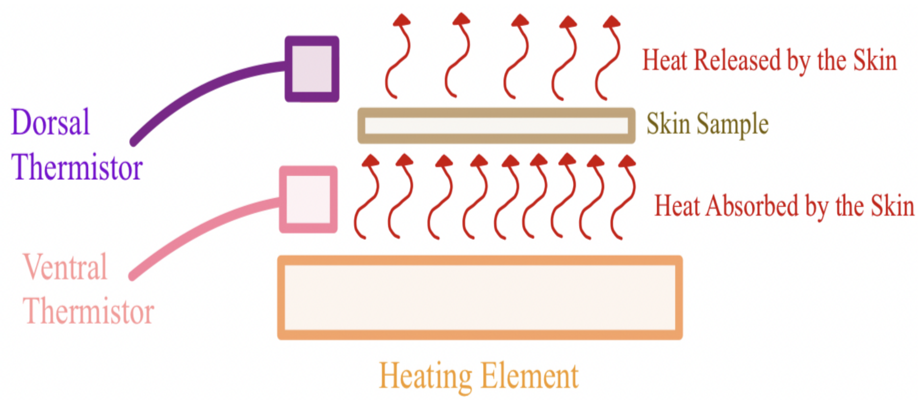

Figure 11. Illustration of the overall design and how the electrical components interact with the skin.

As Figure 11 shows, the ventral thermistor, which is part of the wall powered heating element circuit, measures the temperature below the skin sample. Because the skin sample is directly contacting the heating element, the temperature of each surface reaches an equilibrium quickly and is assumed to be equal. Therefore, this ventral thermistor not only modulates the power to the heating element in order to control its temperature, but it also measures a baseline temperature which can be compared to by the dorsal thermistor. The dorsal thermistor is part of the thermistor temperature sensor circuit and operates the same as the ventral thermistor, which has been described in the Electrical Background and Preliminary Designs sections. The dorsal thermistor measures temperature on the top surface of the skin and displays it with the baseline from the ventral thermistor. By comparing the temperature values and the difference between them relative to time, the skin sample's resistance to heat transfer can be quantified.

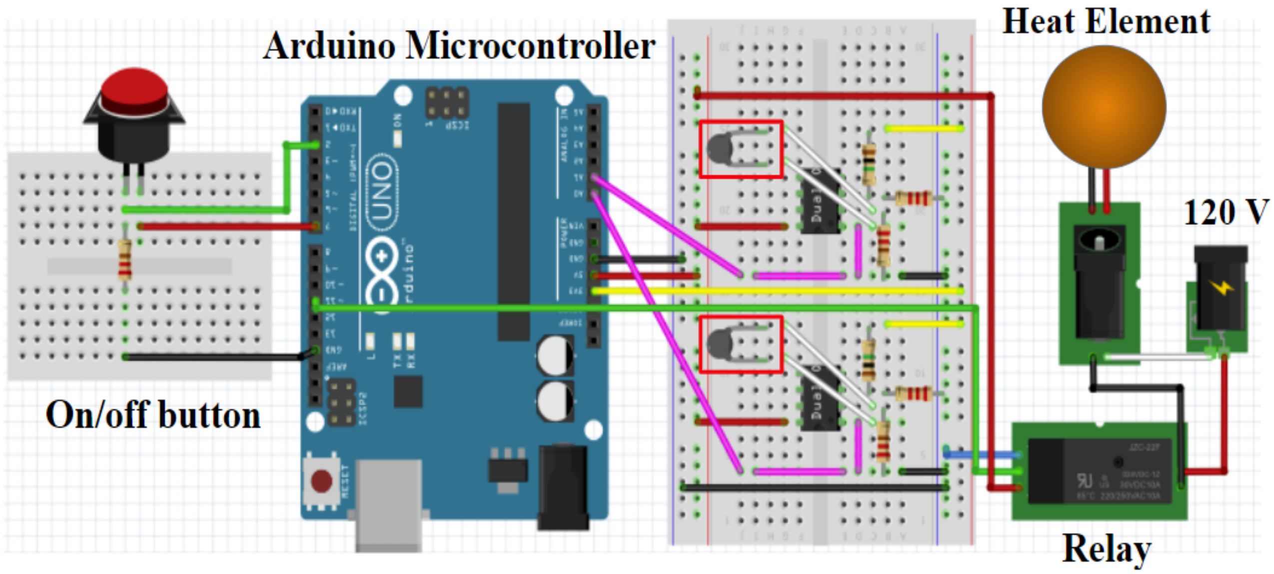

Figure 12. Custom Fritzing diagram of the complete assembled circuit, showing an illustration of the schematic, connections, and components.

Figure 12 displays the final circuit design which was the main focus of this semester's design process. Shown in Figure 12 are the two thermistor circuits, one for the ventral thermistor and one for the dorsal thermistor. These circuits were constructed on a breadboard (located middle/right), and the two thermistors are highlighted in red in Figure 12. These circuits use the Arduino (located middle/left) 3.3 V pin as input and are powered by the Arduino 5 V pin. Each output voltage which relates to temperature is received by the Arduino in analog input pins from the pink wires in Figure 12. A digital pin on the left side of the Arduino connects to the relay (located bottom right) and allows the Arduino to modulate the status of the relay switch. 120 V wall power (located middle right and labeled in Figure 12) is sent through the relay and to the heating element via a DC adapter. The entire circuit is controlled by a rocker switch (located top left), whose status is sent to a digital input pin on the Arduino and can override the ventral thermistor to turn the heating element off.

Since the circuit was constructed on a breadboard for prototyping purposes and uses wires, comprehension of images of the circuit is difficult as Figure 13 shows below. This is the reasoning for using a Fritzing diagram to neatly and concisely model the circuit for visualization purposes.

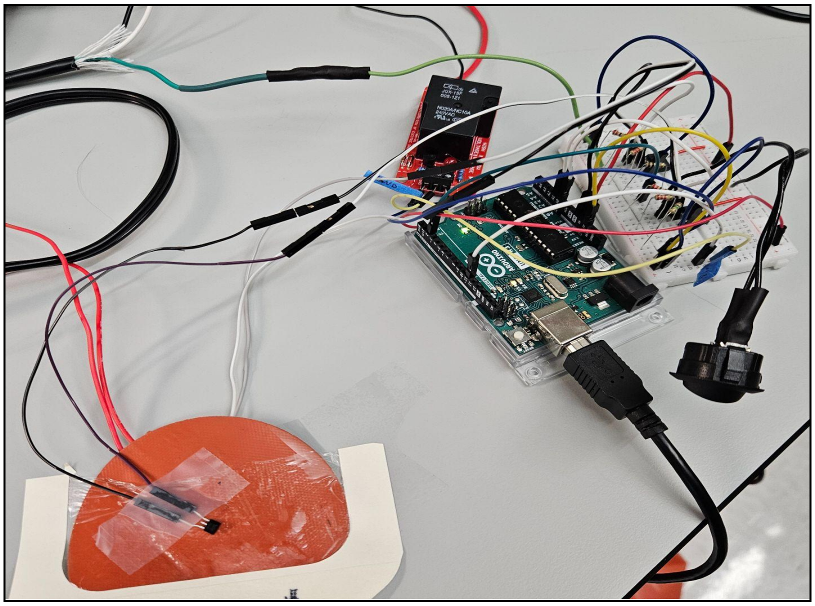

Figure 13. Image of the complete, unenclosed circuit in use during testing. Shown is the Arduino, breadboard, and relay (top right) and heating element and thermistors (bottom left).

Fabrication and Development

A. Materials

Fabrication included the use of electrical components and the construction of an electronics box. The electrical aspect of the design used two universal operational amplifiers and two thermistors. A female wall plug, two-pronged DC voltage adapter, and beefcake relay were used to power the heating element. All of these components were generously provided by Dr. John Puccinelli and the UW-Madison Biomedical Engineering department. A binary (on/off) rocker switch and 7 total resistors were used (2 220 Ohm, 1 1.0 kOhm, 2 2.2 kOhm, and 2 1.0 MOhm). Sparkfun copper wires with colored insulation connected all of the components, which were placed on a Sparkfun breadboard. Lastly, an Arduino microcontroller controlled the functioning of the circuit and data was displayed on an accompanying computer running Arduino IDE. The exterior box was constructed with polylactic acid, or PLA. This material can form 3D printed objects at very low temperatures making it ideal for the simplistic design of the box.

B. Fabrication Process

Because a breadboard was used, fabrication of the circuit amounted to simply inserting wires and components directly into the breadboard and Arduino pins. However, soldering was required to connect the wall power cord and female outlet to the DC adapter, and then the DC adapter to the heating element. The project box was able to be created after the circuit was assembled to allow for proper size, as the box's design relied heavily on the dimensions and orientation of the developed circuit. Using a program called FUSION360, the team was able to construct a box with a dovetail lid that allowed for a spacious and easy enclosement for the circuit. Using a drill press, holes were then fabricated into the box in the appropriate locations in order for the thermistors, heating element, rocker switch, and Arduino power cord to exit the box and for the wall power cord to enter the box.

Testing and Results

Heating Element Verification

First, to ensure that the heating element functioned as intended and other testing could be performed, the heating element verification was implemented. This test simply monitored the temperature on the top surface of the heating element and ensured that the ventral thermistor circuit was able to properly modulate it. This was done by powering the device and applying the ventral thermistor to the top surface of the heating element. Over the course of one minute, the temperature values of the heating element were then recorded using the Arduino IDE serial monitor.

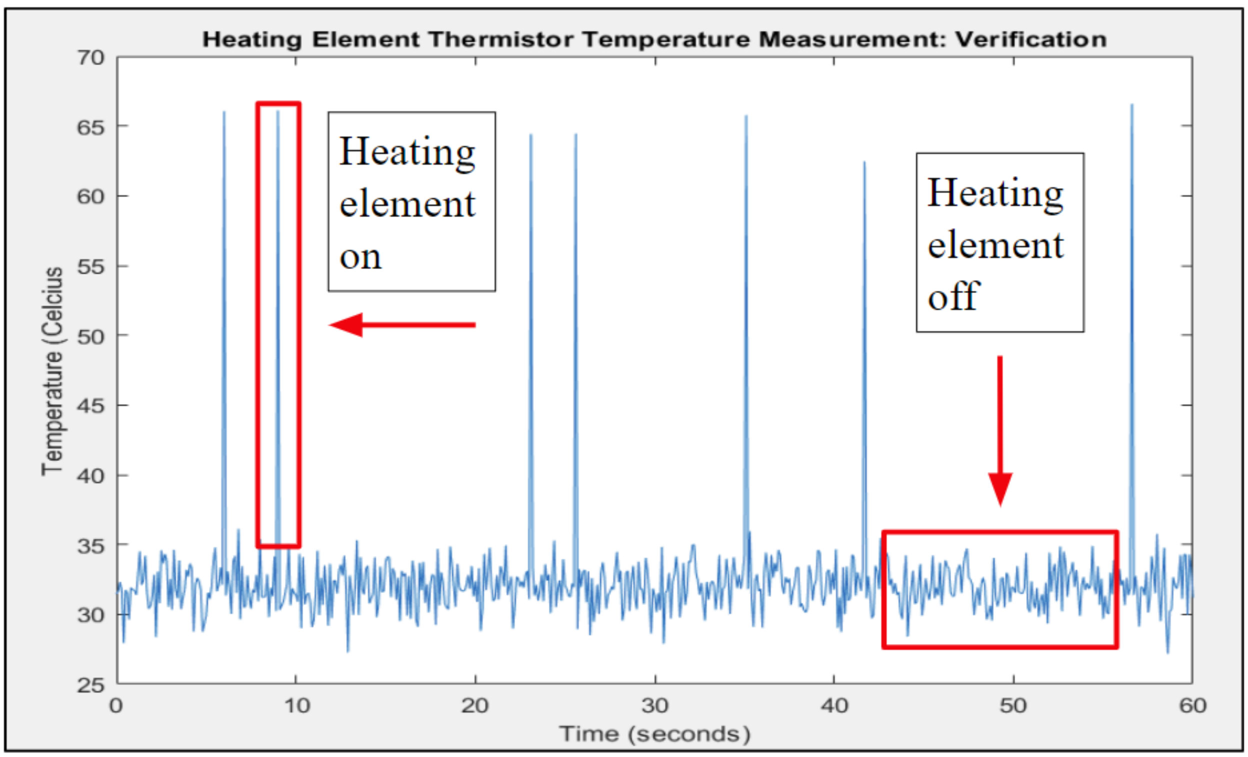

Figure 14. MATLAB graph showing the temperature on the surface of the heating element over the course of one minute.

As Figure 14 depicts, there were periods of the heating element being active (powered) and inactive. The spikes in temperature show the heating element in the active state. While the periods in activity and inactivity show proper functioning of the ventral thermistor circuit, relay, and wall power DC adapter, Figure 14 indicates two important issues. First, the temperature spikes during the active state of the heating element are overwhelmingly severe. The heating element is such that it heats up rapidly, and to high temperatures above what is necessary. In fact, around 65 ℃, which Figure 14 shows the heating element surface to approach, damage can be done to the lipid structure of the skin per the client. However, the heating element heats so fast that this is within the sampling frequency of the Arduino, and cannot be modulated any faster. As a result, it has been determined by the design team and client that a new, higher quality heating element is necessary (see Future Work section in Discussion). Also, the reciprocating nature of the temperature data when the heating element is off likely indicates that the circuit is affected by noise, in which case a filter might be necessary (see Future Work section in Discussion).

Despite these issues that the Heating Element Verification usefully exposed, the test showed that the heating element and overall device could safely and accurately be used in the testing of synthetic skin for data collection as described in the following test.

Tegaderm Layer Test

In order to determine if the thermistor temperature sensor and affiliated circuitry had appropriate sensitivity, measuring the dorsal temperature across variable layers of skin was important. Since sample skin is costly and requires the euthanization of a rodent, the design team and client pursued an alternative. Tegaderm, a synthetic skin substitute, is a simple polymer sheet that possesses thermodynamic properties similar to that of skin and is used in wound healing. Measurements of the thermal insulation collected using the bioinstrumentation product were gathered for 0 (control), 1, 2, 4, and 8 layers of Tegaderm. The Tegaderm was placed on the heating element as an ex vivo skin sample would be, then heated by the heating element. Data was collected for 10 seconds by measuring the temperature of the dorsal side of the skin using the thermistor circuit. The full protocol for this test can be found in **Appendix A**.

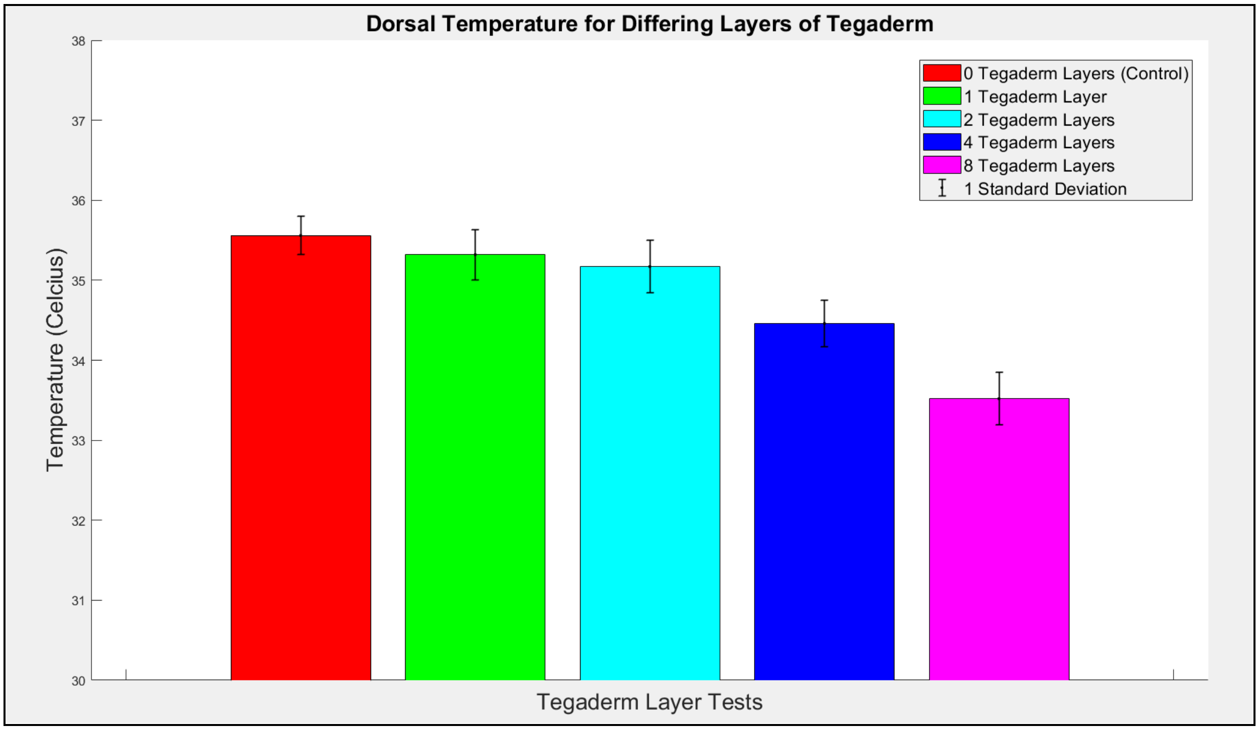

Figure 15. MATLAB bar graph depicting the mean dorsal surface temperature for the variable Tegaderm layer testing groups.

As a result of the data collected during the described testing, Figure 15 was generated. This bar graph illustrates the difference in mean dorsal temperature and was suitable for the presentation of data. By conducting statistical analysis, this test confirmed the expectation that thicker skin samples would increase insulative character. Statistical analysis via ANOVA testing revealed that there was a statistically significant difference between each test group, as the p-value for this test was 1.00E-5, far below the Bonferroni test multiple-comparison correction α value of 0.01. As a result, the null hypothesis that there was no difference in the means between each of the 5 groups was rejected, and the alternative hypothesis that the device is adequately sensitive to measure the difference between each of the 5 groups was accepted. Overall, the results of the Tegaderm Layer Test indicate a high degree of sensitivity, which is important as expressed by the client requirements and PDS.

Skin Temperature Test

The test necessary to determine if the device is affected by evaporative cooling was the skin temperature test. For this test, the team used the infrared temperature sensor and the thermistor temperature sensor of the assembled device. Temperature measurements were taken from the back of a team member's hand, where the infrared sensor and thermistor temperature sensor concurrently collected data for 10 seconds, and these temperatures were recorded. Because of the very large sample size of each group's data (1000 data points for the thermistor and 100d data points for the infrared thermometer), a one sided student t-test was a reasonable statistical tool for the analysis of the data. The full protocol for this test can be found in **Appendix A**.

Table 3. Means and standard deviations for the 10 second temperature readings from the thermistor temperature circuit and infrared camera.

	Mean (℃)	**Standard Deviation (℃)**
Thermistor	34.91	0.3520
Infrared	33.2	0.2938

Table 3 summarizes the statistical landmarks of the data collected as a result of this testing. Using a one-sided student t-test, for which the MATLAB code is in **Appendix F**, the p-value of 1.24E-7 was calculated. This p-value is small due to the difference between experimental group means and the large sample sizes. This p-value is also small such that it is less than the α value of 0.05, meaning that the thermistor sensor mean is significantly greater than that of the infrared thermometer. As a result, the null hypothesis that there was no difference in the means between each of the 2 groups was rejected, and the alternative hypothesis that the device is sufficient in ignoring the effects of evaporative cooling was accepted. While this data and its statistical analysis yield a safe assumption that evaporative cooling is completely ignored, this test does not evaluate this claim, but only compares the mean temperature between a device known to measure evaporative cooling and the design team's device. It is known and established in the background section that evaporative cooling decreases the surface temperature and thus its measurement, so a significantly increased value from the infrared thermometer is encouraging when attempting to ignore evaporative cooling. As a result, the design team will make the supported assumption that the thermistor sensor device is not affected by evaporative cooling as a result of known correlation, not causation. Overall, the results of the Skin Temperature Test indicate that evaporative cooling is likely ignored, which is important as expressed by the client requirements and PDS.

Discussion

A. Implications

Through testing, the final design showed that it was able to measure surface temperature more accurately than the laboratory's current infrared camera. As demonstrated by the Skin Temperature Test analysis in the Testing and Results section, the device compared to the infrared gun showed a statistically significant increase in mean temperature measurement. The quantitative results indicate that the device is almost certainly capable of measuring the temperature of the skin samples without the effects of evaporative cooling. Through the Tegaderm Layer Test, the device was also shown to be sensitive enough to measure the temperature difference between varying skin sample thicknesses. In addition to its proven sensitivity, it was determined that the device could consistently maintain the targeted temperature required by the client, as seen with the Heating Element Verification. However, it is recognized from this test that there are improvements to be made, as discussed in Future Work. Through the described tests, the device is clearly able to mitigate the effects of evaporative cooling, is sensitive to changes in temperature from variable sample thickness, and is roughly reaching the target temperature. These positive results of the device are in addition to the fact that the total cost for fabrication was about $80, meaning it was cost effective compared to competing designs per the client's request.

B. Ethical Considerations

The research that this device is designed to facilitate would not be possible without the use of animal testing. This particular form of testing is becoming widely accepted through the increased regulation and continued research associated with it. As highlighted by the *Journal of Medical Ethics and History of Medicine*, the entire design process must be carefully constructed in order to preserve the intended purpose of the experiment when animal testing is involved [24]. The final design includes ergonomics and components that may either negatively or positively impact ethical criteria that have been laid out. According to the Public Health Service Policy which directly covers the animal rights associated with rats, mice, and birds, there are four different categories that must be considered in order to justify animal testing:

1) There must be a justification for this research and there must be a given estimate of how many animals will be used.
2) There must be procedures in place that maintain respect for the animals in both their pre-mortem and post-mortem states.
3) There must be a proposed alternative to make sure that the line of action is completely necessary.
4) There must be proof that this research isn't being done elsewhere [25].

The device in its current iteration is directly responsible for estimation and maintaining respect of the post-mortem rodents laid out above in the ethical standards. The area of skin that can be properly measured is determined by the size of the heating element and thermistor temperature sensor associated with the design. Additionally, once this sample size is established, it is possible to estimate the amount of rodents that will be needed to properly complete the testing protocols associated with this research.

Furthermore, the device should maintain the integrity of the ex-vivo skin gained from the rodents. Researchers involved in the testing process should be able to add the skin to this device easily without disrupting the sample. Even though this skin sample will be heated up, it is important that it remains intact once it is removed from the heating element.

Research claims and future operations will be based on the measurements this device conducts and thus has the responsibility to be accurate. Any inaccuracies in the device could lead the client and other researchers to make false claims that have the potential to be far reaching throughout the medical community. Therefore, rigorous testing and verifications must be performed in order to eliminate any sources of error, as discussed below.

Thorough testing would involve the use of actual skin samples to confirm that the device works in its intended application. However, to access such samples, euthanization of a rodent is required as described previously in this section. This bears moral weight and is dependent on the proper following of protocols and regulations governing euthanization and non-survival surgeries. This testing must be considered as a final verification and should not be repeated or otherwise performed in high volumes except for the use of data collection.

C. Sources of Error

Though there were several achievements in the final design, there are still sources of error that require attention. For the temperature readings on the skin samples, testing showed the samples must be taped between the heating element and each thermistor in order to get a consistent temperature reading. This could pose potential problems with the integrity of the samples as the skin is relatively thin and complex in its structure, and using tape during data collection could affect this system as well as resulting data. Also, the temporary and quite rudimentary nature of the tape method can cause inconsistencies in the thermistor-skin-heating element interface.

The heating element requires upgrading, as the device has been shown to heat up rapidly. The heating curve induced by the powered heating element is severe in amplitude and has a small period. As a result of this rapid heating curve, not only is it hard to visualize data, but the Arduino microcontroller encounters difficulty in temperature modulation. Before the sampling frequency of the Arduino allows for a response, the heating element can reach temperatures of 70 ℃. This temperature could damage the sample and inherently alter the data collection, while simply being dangerous to work with.

The materials utilized to construct the circuit were relatively low cost, which makes the circuit less stable than is sufficient. For example, to allow for prototyping, alterations, and cost effectiveness, a breadboard was used in the circuit design. Breadboards are very useful, but do provide unstable and more temporary connections. This lack of stability can cause inaccuracies in the data, increases the risk for short circuiting, and renders the device more fragile. In addition, these inexpensive components possess higher tolerances, meaning that their experimental values have an increased likelihood of being different from their defined values as posted in the product specifications. This is especially referring to the resistors, whose value can deviate 5% from their label. Because the resistance values are essential to the circuit calculations, inaccuracies in temperature measurement likely arise from this. These inaccuracies in the functioning of the device can affect the data in which the lab seeks to collect. As a result, future work should address these errors in order to produce a more accurate and better functioning device before its use in research.

D. Future Work

Moving forward, the design team plans to revise the final prototype and incorporate additional testing. The following are alterations that need to be made to the final design as a result of testing, results, and evaluation, along with additional testing:

- Redo circuit calculations to account for component tolerances
    - As mentioned in the Sources of Error section above and discussed in the Electrical Background, many electrical components, namely resistors, have tolerances. These deviations of experimental resistance from posted product specifications cause error.
    - Measure experimental resistance using a digital multimeter and substitute these resistance values into circuit calculations where posted resistance values were.
    - The addition of a filter would help eliminate noise, which Figure 14 displays.
- Create a printed circuit board (PCB) of the final breadboard circuit
    - Breadboards are useful for electrical circuit fabrication, but they are intended to be for temporary designs, proof of concept, testing, etc.
    - PCB connections are soldered, making them more stable and decreasing the likelihood of errors in circuit function and accuracy as a result of connections being interrupted, which has happened through the verification and testing process.
    - Compared to a breadboard, a PCB is much more condensed, allowing for the device electronics to be smaller and thus have a product with a smaller footprint. This is expected to increase the device's ease of use as it is better able to fit in the lab space.
- Purchase and incorporate a higher quality heating element into the next design iteration
    - Replace the current, low-cost heating element which experiences rapid heating that is too severe for use on skin samples.
- Implement a mechanism for applying the thermistors and heating element to the skin sample

- The design process focused on the instrumentation aspect of the design; however, after testing and client feedback, a design process for the interface between the device and skin samples is necessary.
- A conductive metal plate design with embedded thermistor(s) would firmly hold the sample to the heat source and thermistors, while ensuring that evaporative cooling cannot occur.
- This would increase ease of use and provide a more consistent contact for heating element and thermistors on the sample.

Conclusion

Currently, there is not a cost effective and accurate device designed to measure the thermodynamic properties of ex-vivo rodent skin, particularly thermal conductivity. The client, Dr. Caroline Alexander of the UW-Madison Carbone Cancer Center, tasked the team to design a device that will sufficiently measure the insulative properties of rodent skin without taking into account the effects of evaporative cooling. The device that the team constructed is a 3D printed electronics box containing a circuit capable of controlling a heating element and measuring the ventral and dorsal surface temperature of skin samples.

Upon deliberating with the client, a device that was sensitive enough to measure small changes in insulative properties while providing pulses of heat to the skin sample was essential for the client's research. The team constructed the circuit required to control such a device before implementing a heating element in the design. The 3D printed box was later designed and fabricated to enclose the existing circuitry. Extensive testing of the prototype was conducted to ensure the device functions properly, does not measure the effects of evaporative cooling, and that the device is sufficiently sensitive to small changes in insulative properties. The prototype created by the team was effective at heating and measuring the temperature of the skin samples but failed to produce a smooth, linear heating environment. There are also acknowledged sources of error due to component inaccuracies.

In the future, the team can improve the quality of the components used to fabricate the device. This would include a higher grade heating element capable of heating the skin samples in a more controlled manner, a printed circuit board to contain the circuitry in contrast to the current breadboard design, and a more in-depth design process for the thermistor application to the skin. All of these changes would greatly improve the existing prototype and ensure client satisfaction for use of the device in research.

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Appendix A - Testing Protocols

Testing for the device was devised to follow a set of 6 intended protocols. These protocols would ensure that each component of the assembled device was functioning as planned and would provide a thorough measure to the client that the assembled device would be sufficient in its intended purpose. The team assigned multiple categories of importance for the functionality of the device, which are as follows:

1. Ensuring significant sensitivity in all installed parts such as the thermistors and Arduino output
2. Validating the heating element was functioning properly
3. Determining significant difference in the data collected by our device versus the current solution that uses infrared temperature measurement.

This last category was especially important as it would indicate the assembled device did a sufficient job in ignoring the effects of evaporative cooling.

The protocols were intended to follow a specific order as to ensure tests dependent on certain functioning aspects of the design would not be hindered by non-functional components. The protocols are as follows:

1. Validating Arduino for the collection of temperature data
2. Ensuring the functionality of the thermistors
3. Ensuring sufficient sensitivity in the implemented thermistors
4. Ensuring sufficient sensitivity in thermistors via acetone catalyzed lipid breakdown
5. Validating Arduino for the control of the heating element
6. Determining significant difference in the measurement of thermodynamic data

While these protocols laid out a great basis for the testing of the assembled device, upon discussion with the client the team decided to focus their efforts on gathering statistical data testable via hypothesis testing rather than ensuring functionality of each component individually. After completing initial testing similarly to the component testing outlined in the protocols, the team devised tests that could be confirmed significant by statistical analysis. These included tests on the assembled device with differing numbers of layers of a synthetic substitute and testing the evaporative cooling ignorance of the device as discussed in the sixth protocol above.

<u>Protocol 1: Validating Arduino Program for the Collection of Temperature Data</u>

This protocol is meant to ensure that the arduino program is collecting and outputting the correct temperature data when heated to a known temperature with a known functional heating element. This provides a solid base for the rest of the tests as the program can be used to read temperature data for the remainder of the testing process.

Materials:

1. Infrared thermometer
2. Assembled device
3. Computer (for running Arduino IDE/ thermistor data interpretation)

Procedure:

1. Collect the infrared infrared thermometer and assembled electronic device.
2. Ensure that the heating element is at room temperature with nothing on it.
3. Place the infrared thermometer so that it is directed at the surface of the heating element.
4. Begin heating the heating element.
5. Simultaneously monitor the temperature measured by the infrared thermometer and the thermistor in the heating element.
6. Turn off the heating element once the heating element has reached 34° Celsius.
7. If the thermistor has been verified to be functional, you can conclude the functionality of the arduino program for the collection of temperature data with the following:
    a. If the temperature measurements from the infrared thermometer align with that of the arduino program temperature output, the arduino program is functional in collecting temperature data.
    b. If the temperature measurements from the infrared thermometer do not align with that of the arduino program temperature output, the arduino program is not functional in collecting temperature data.

Protocol 2: Ensuring the Functionality of the Thermistors

This protocol ensures that the installed thermistors on the assembled device are functional in collecting accurate temperatures. This test again utilizes a known functional heating element and a functional infrared thermometer to cross-check the data from the thermistors to ensure they are functional.

Materials:

1. Infrared gun
2. Assembled device
3. Computer (for running Arduino IDE / thermistor data interpretation)

Procedure:

1. Obtain a heating element identical to the one used in the assembled device.

2. Ensure that the arduino program for the transformation of the thermistor data into temperature is functional.
3. Obtain the heating gun to use as a valid source of thermodynamic data collection.
4. Ensure that the heating element is at room temperature with nothing on its surface.
5. Handle the infrared thermometer so as to record the surface temperature of the heating element.
6. Begin heating the heating element.
7. Begin recording the temperature of the heating element with the infrared thermometer.
8. Simultaneously monitor the thermodynamic data output from the arduino gathered by the thermistor.
9. Ensure that the measurements from the infrared thermometer and the thermistor are equivalent throughout the whole heating process.
10. Once the heating element has reached 34° Celsius, stop data collection and turn off the heating element.
    a. If the temperature readings from the infrared thermometer and thermistor are equivalent throughout the heating process, the thermistor is functional.
    b. If the temperature readings from the infrared thermometer and thermistor are not equivalent throughout the heating process, the thermistor is not functional.

<u>Protocol 3: Ensuring Sufficient Sensitivity in the Implemented Thermistors</u>

This protocol is a simple check of the thermistor output to verify that the thermistor output is in increments of a tenth of a degree Celsius or smaller. This test ensures that the device measures temperature data in sufficiently small increments for the client's research.

Materials:

1. Infrared gun
2. Assembled device
3. Computer (for running Arduino IDE/ thermistor data interpretation)

Procedure:

1. Ensure that the assembled device is assembled correctly.
2. Begin testing with the thermistor on the heating element.
3. For this thermistor, locate the output from which you can see the recorded temperature.
4. Ensure that the heating element is at room temperature.
5. While observing the output for the recorded temperature from the thermistor on the heating element, begin heating the heating element to 34° Celsius.

6. Ensure that the thermistor includes readings to the tenth of a degree Celsius or smaller.
    a. If the temperature readings are in increments of 0.1° Celsius or smaller, the thermistor is sufficiently sensitive in its readings of thermodynamic data.
    b. If the temperature readings are in increments larger than 0.1° Celsius, the thermistor is **not** sufficiently sensitive in its readings of thermodynamic data.
7. Repeat this process with the thermistor located on the heat measurement plate.
    a. For the purposes of this test, there does not need to be a sample in the device.

Protocol 4: Ensuring Sufficient Sensitivity in Thermistors via Acetone Catalyzed Lipid Breakdown

The fourth protocol ensures that the assembled device will measure sufficiently small changes in thermodynamic properties such that the device will be useful in the client's research. It is known that acetone wipes break down the lipids on the skin samples and increase the thermal conductivity of the sample. Using subsequent passes of acetone wipes on the skin samples then measuring the temperatures of each, it is possible to ensure that the assembled device measures these changes in thermal conductivity. This change in thermal conductivity is sensitive enough to ensure the device is applicable to the client's research.

Materials:

1. Assembled device
2. Ex-vivo rodent skin sample
3. Computer (for running Arduino IDE/ thermistor data interpretation)
4. Acetone wipe

Procedure:

1. Gather the assembled device, a sample of ex vivo rodent skin, and an acetone wipe.
2. Locate the temperature output from the thermistors.
3. Ensure the heating element on the assembled device is at room temperature.
4. Place the sample of skin on the heating element, such that the dorsal side is face up.
5. Record the initial temperature of the dorsal side of the skin from the heat measurement plate.
6. Begin heating the skin until the heating element reaches 34° Celsius.
7. Record the change in temperature from the final temperature measured by the heat measurement plate and the initial temperature recorded previously.
8. Remove the sample from the heating element. Let the skin and the heating element cool to room temperature.

9. Retrieve the acetone wipe.
10. Wipe the dorsal surface of the sample of rodent skin. Do ***one pass*** with the acetone wipe.
11. Repeat steps 2-8 with the wiped sample. Ensure that you have recorded the change in temperature of this sample.
12. Again, wipe the dorsal surface of the sample of rodent skin. Only do ***one more pass*** with the acetone wipe.
13. Repeat steps 2-8 with this doubly wiped sample. Ensure that you have recorded the change in temperature of this sample.
14. Ensure that the temperatures measured with 0, 1, and 2 passes of the acetone wipe are significantly different from one another.
    a. If the measurements are significantly different, the thermistors are sufficiently sensitive.
    b. If the measurements are not significantly different, the thermistors are NOT sufficiently sensitive.

Protocol 5: Validating Arduino Program for the Control of the Heating Element

The fifth protocol tests the more intricate measures of the arduino program associated with the assembled device. The arduino program is designed to turn off upon the heating element reaching a desired temperature as specified in the code. This test ensures that the arduino program can be turned on and off as desired and specified by different temperatures being reached by the heating element. The test calls for usage of a known functional heat measuring device to be cross checked with the arduino output then ensuring that the heating element turns off as desired.

Materials:

1. Assembled device
2. Computer (for running Arduino IDE/ thermistor data interpretation)

Procedure:

1. Gather the assembled device and ensure it is connected to the arduino program.
2. Ensure that the heating element is at room temperature with nothing on it.
3. Set the arduino program to turn off the heating element upon reaching a temperature of 34° Celsius.
4. Obtain a heating gun as a valid source of thermodynamic data collection.
5. Place the heating gun so as to point at the surface of the heating element.
6. Set the arduino program to turn on the heating element.
7. Monitor the heating gun until the surface temperature of the heating element reaches 34° Celsius.

8. If the heating element turns off upon reaching 34° Celsius as monitored by the infrared thermometer, the arduino program is functional for the control of the heating element.

Protocol 6: Determining Significant Difference in the Measurement of Thermodynamic Data

The sixth protocol details the most important test for the functionality of the device. The protocol calls for data collection using the assembled device and the infrared thermometer on as many skin samples / available skin as possible. These samples will be summarized into means, standard deviations, and sample sizes then analyzed using a variety of hypothesis testing methods. Upon ensuring that the infrared thermometer and assembled device measure statistically significant differences in thermodynamic data collection, there is a strong implication that the assembled device is sufficient in ignoring the effects of evaporative cooling.

Materials:

1. Many samples of ex-vivo rodent skin
2. Infrared gun
3. Assembled device
4. Computer (for running Arduino IDE, thermistor data interpretation, and statistical analysis)

Procedure:

1. Gather multiple samples of rodent skin.
    a. The larger the number of samples for the experimental group, the better. This will increase the quality of the hypothesis test later on.
2. Obtain a heating element capable of producing heat pulses of 34° Celsius.
3. Upon completion of setting up the heating plate and ensuring it is functioning properly, begin testing the skin samples with the infrared thermometer.
4. Place the skin sample on the heating element, ensuring the element is still turned off.
5. Gather the initial temperature of the dorsal side of the rodent skin. Record this value. *
6. Upon placing the rodent skin on the heating element, begin heating the underside of the skin to 34° Celsius.
7. Once this temperature is achieved by the heating element, record the temperature of the dorsal side of the sample using the infrared thermometer. Record this value. *
8. Subtract the final temperature observed from the initial temperature. Record this value. *
9. Place this sample aside, ensuring that it is well marked for further analysis.
10. Repeat steps 4 through 9 for each sample of rodent skin.

11. After heating each sample and recording temperatures using the infrared thermometer, repeat steps 4 through 10. The only difference in this iteration is that recording the temperatures of the skin will be with the assembled device.

Table 4. Sample data table prepared for the data collection outlined in this testing protocol, where the difference in temperature would be found for each sample.

	Sample #1	Sample #2	Sample #3	Sample #4
Initial Temp. (℃)				
Final Temp. (℃)				
Δ Temp. (℃)				

To determine whether or not our device is sufficient in ignoring the temperature-altering effects of evaporative cooling, run a matched pairs hypothesis test for the difference in means between skin samples heated and measured with the infrared thermometer versus skin samples heated and measured with the assembled device. Use a bootstrap hypothesis test in this protocol. This is the safest option as normality of the sample data cannot be assumed, especially with relatively small sample sizes (<30).

The hypothesis test will be run with the following hypotheses:

H_0: $\mu_{infrared} - \mu_{thermistor} = 0$

H_A: $\mu_{infrared} - \mu_{thermistor} \neq 0$

The samples of rodent skin come from a random sample of a much larger population of skin samples. For this hypothesis test, Use an α value of 0.05.

For the hypothesis test,

1. If not installed already, ensure that R and RStudio are installed on your computer. These are necessary tools for running bootstrap hypothesis tests.
2. Provided here is a code skeleton for this bootstrap testing case.
3. Once copied into RStudio, find the second chunk (bits of code denoted by the triple apostrophe and curly brackets).

4. In the first two lines of the second chunk, there are two different empty vectors heat_gun_delta_T and assembled_device_delta_T.
5. In the empty sets of parentheses denoted by c() following these variable names, enter the data collected from the procedural portion of this protocol as numbers separated by commas. This data will include the change in temperature values for the infrared thermometer (heat_gun_delta_T) and the assembled device (assembled_device_delta_T). **Ensure that the data is entered such that the first index of each vector is data from the same skin sample, the second index the data from the second skin sample, etc.**
6. Once the data has been entered into this chunk, run the chunk by pressing the green check mark in the top right corner of the area denoted as described previously.
7. After running this chunk, the bootstrap test is ready to be run. Run the next chunk in RStudio, that starts with bootstrap=function()...
8. The decimal value outputted into the terminal is the p-value for the experiment.

Performed Protocols

<u>Ensuring Sufficient Sensitivity in Thermistors via Tegaderm Layer Testing</u>

Materials:

1. Minimum 8 layers of Tegaderm
2. Assembled device
3. Computer (for running arduino program, thermistor data interpretation, and statistical analysis)

Procedure:

1. Gather Tegaderm and separate into individual sheets
2. Ensure the heating element is turned off and at room temperature
3. Begin testing with 0 layers of Tegaderm placed on the heating element (control)
4. Allow the heating element to heat for 10 seconds while gathering temperature data from the dorsal thermistor
5. Record the temperature data
6. Repeat steps 4-5 with 1, 2, 4, and 8 layers of Tegaderm placed on the heating element, stacked one on top of the other.
7. After data collection for each group is complete, run an ANOVA test for the data in MATLAB, with the null hypothesis being that the mean temperature for each group is the same and the alternative hypothesis being that at least one mean temperature is different.
8. Analyze the p-value in context of the test with an ã value of 0.01.

Determining Significant Difference in the Measurement of Thermodynamic Data

Materials:

1. Infrared gun
2. Assembled device
3. Hand or other exposed skin
4. Computer (for running Arduino IDE, thermistor data interpretation, and statistical analysis)

Procedure:

1. Upon completion of setting up the full thermistor circuit and ensuring it is functioning properly, begin measuring the temperature of the surface of your hand with the infrared thermometer and thermistor simultaneously.
2. Collect data for 10 seconds, taking a video of the digital display of the infrared thermometer in order to collect its data.
3. Export the Arduino serial monitor into MATLAB and enter the data points from the infrared thermometer into an array in MATLAB

Table 5. Sample data table prepared for the data collection outlined in this testing protocol, where the difference in temperature would be found for each sample.

	Trial #1	Trial #2	Trial #3	Trial #4
Initial Temp. (℃)				
Final Temp. (℃)				
Δ Temp. (℃)				

To determine whether or not our device is sufficient in the avoidance of measuring the temperature altering effects of evaporative cooling, run a two-sample hypothesis test for the difference in means between skin measured with the infrared thermometer versus skin measured with the assembled device. Use a one sided student t-test in this protocol. This is a great option as normality of the sample data can be assumed with relatively large sample sizes (>30).

The hypothesis test will be run with the following hypotheses:

H_0: $\mu_{infrared} - \mu_{thermistor} = 0$

H_A: $\mu_{infrared} - \mu_{thermistor} \neq 0$

The samples of rodent skin come from a random sample of a much larger population of skin samples. For this hypothesis test, Use an α value of 0.05.

For the hypothesis test,

1. If not installed already, ensure that R and RStudio are installed on your computer. These are necessary tools for running hypothesis tests.
2. Provided here is a code skeleton for this testing case.
3. Once copied into RStudio, find the second chunk (bits of code denoted by the triple apostrophe and curly brackets).
4. The numbers entered into the code are sample values and are meant to be changed. Interpretation of the variable names should be done as follows:
    a. **heat_gun_mean**: the mean final temperature of the infrared thermometer measurements
    b. **Assembled_device_mean**: the mean final temperature of the assembled device's measurements
    c. **heat_gun_sd**: the standard deviation of the final temperature measurements gathered from the infrared thermometer.
    d. **assembled_device_sd**: The standard deviation of the final temperature measurements from the assembled device.
    e. **n_heat_gun**: the number of trials done for thermodynamic data collection with the infrared thermometer
    f. **n_assembled_device**: the number of trials done for thermodynamic data collection with the assembled device.
5. Once the data has been entered into this chunk, run the chunk by pressing the green check mark in the top right corner of the area denoted as described previously.
6. After running this chunk, the t-test has been run. The decimal value outputted into the terminal is the p-value for the experiment.

Appendix B - Calibration Curve Testing

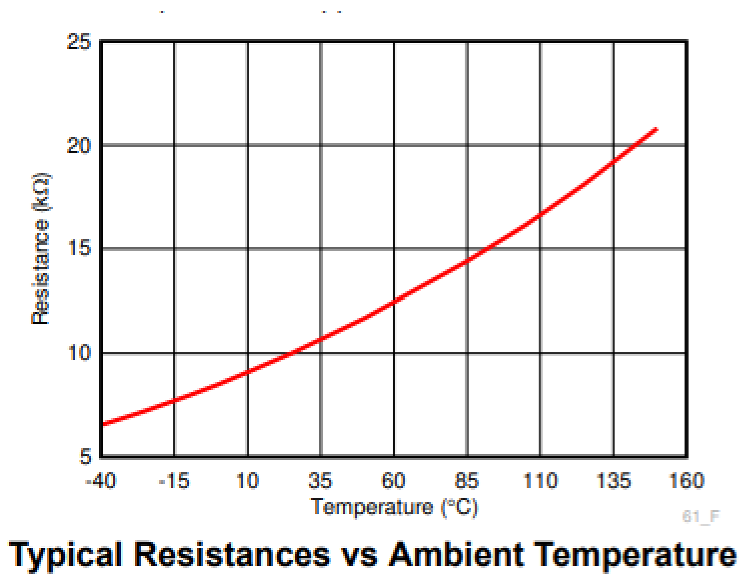

Figure 16. Graph showing the estimated resistance of the thermistor relative to temperature per the vendor Digikey

In order to derive an equation that models the relationship shown above in Figure 16, calibration curve testing had to be performed. This testing entailed measuring the resistance of the thermistor at different ambient temperatures. For this temperature measurement, a digital thermometer, an analog thermometer, and a K-type thermocouple were all used and averaged to mitigate any errors particular to one device. Using this method and the data from it, Table 6 below was constructed. As the product specifications for the thermistor stated that within the targeted range, the thermistor exuded a perfect linear relationship, 3 data points were deemed sufficient.

Table 6. Experimental data collected from calibration curve testing, relating thermistor resistance to ambient temperature.

Resistance (Ω)	Temperature (C)
9380	18
9440	19
9680	22

Graphing this data shown in Table 6 yielded the graph below in Figure 17. Microsoft Excel enabled the application of a linear trendline, and this equation was provided as shown in the top of Figure 17.

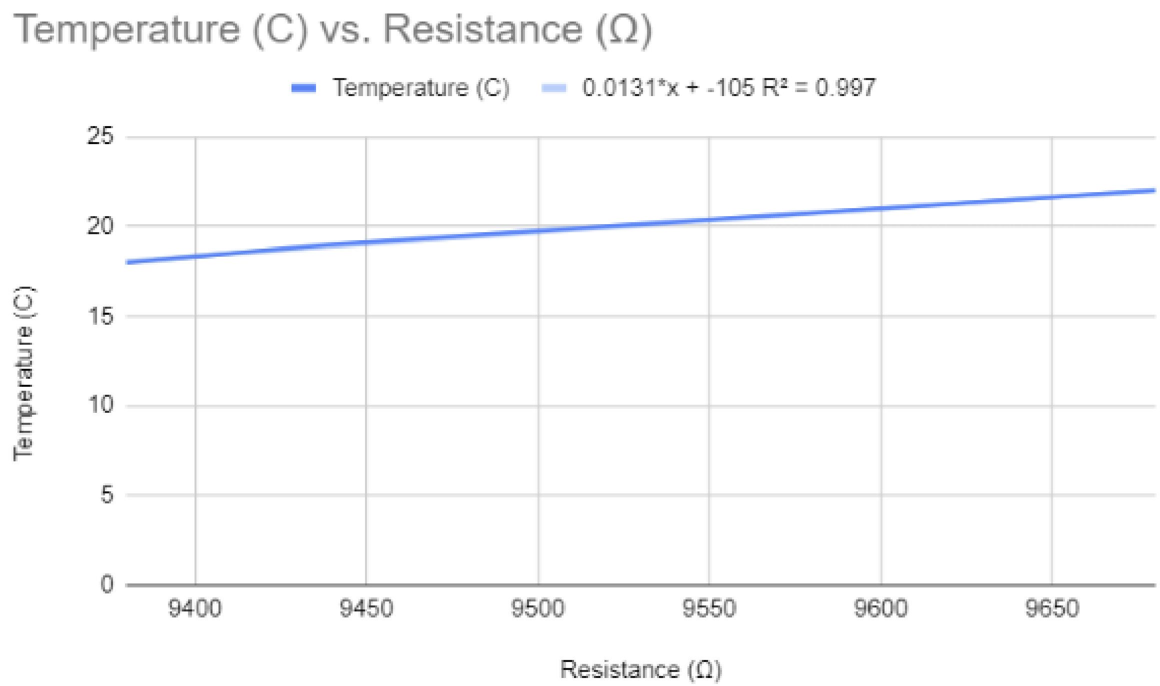

Figure 17. Plot of experimental data relating thermistor resistance to ambient temperature in Table 6. Shown is the derived equation used in circuit calculations.

Then, to confirm that circuit calculations were correct, the output voltage of the thermistor circuit was measured using an oscilloscope in the Makerspace. This voltage value was compared to the ambient room temperature using the same method as previously described. In order to test more data points, the output voltage of the thermistor circuit was measured using a digital thermometer, while temperature was recorded using the same method. However, to get alternative temperature values, the thermistor circuit was placed outside and adjacent to a space heater on two different settings.

Table 7. Experimental data collected from verification of the calibration curve, relating circuit output voltage to ambient temperature.

Voltage (V)	Temperature (C)
0.34	13.61
0.43	56.67
0.39	37.21
0.31	-0.72

Graphing this data shown in Table 7 yielded the graph below in Figure 18. Microsoft Excel enabled the application of a linear trendline, and this equation was provided as shown in the top of Figure 18.

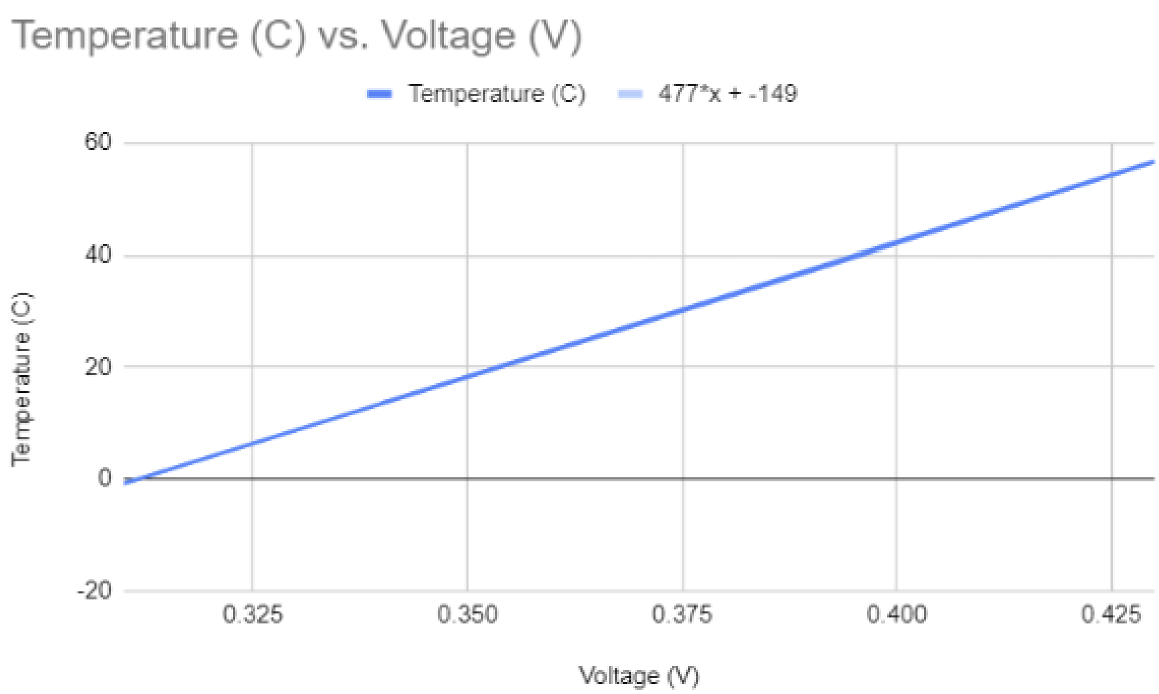

Figure 18. Plot of experimental data relating circuit output voltage to ambient temperature in Table 7. Shown is the derived equation used in circuit calculations implemented into Arduino code.

Appendix C - Expenses

Item	Material	Location	Qty	Total Cost	Website Link
1	3-D Printing- Box	UW Makerspace	1	$52.16	N/A
2	3-D Printing- Lid	UW Makerspace	1	$12.08	N/A
3	Thermistors (2)	Digi-Key	1	$8.93	https://www.digikey.com/en/products/detail/texas-instruments/TMP6131LPGM/10445064?so=83856311&content=productdetail
4	Operational Amplifier	Digi-Key	1	$7.84	https://www.digikey.com/en/products/detail/texas-instruments/LM358P/277042?so=83856158&content=productdetail
		Total Cost		**$81.01**	

Appendix D - SOLIDWORKS Drawings

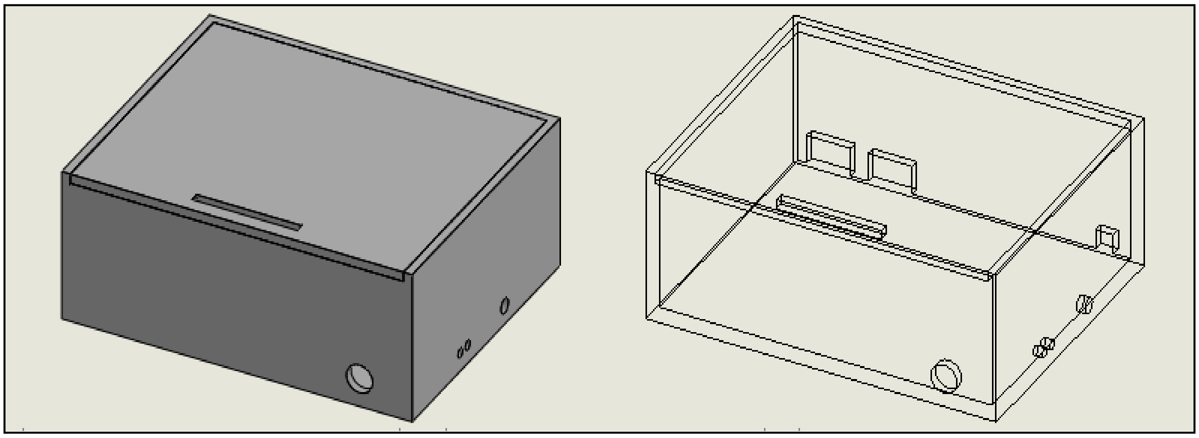

Figure 19. SOLIDWORKS generated isometric drawings of the electronics box, showing a colored illustration (left) and a wireframe illustration (right).

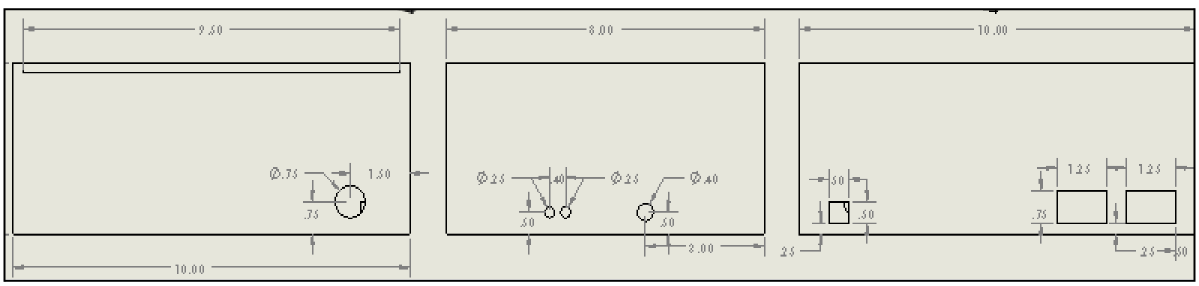

Figure 20. SOLIDWORKS generated drawings of the electronics box showing the dimensions of the three faces with holes for electronic connections.

Appendix E - Arduino Code

```
int rpin = 2;
int bpin = 11;

float slope = 487.0;
float yint = -149.0;

void setup() {
  // put your setup code here, to run once:
Serial.begin(9600);
pinMode(rpin, INPUT);
pinMode(bpin, OUTPUT);
}
void loop() {
  // put your main code here, to run repeatedly:
int sensorValue = analogRead(A1);
int heatValue = analogRead(A5);

float voltageValue1 = sensorValue * (5.0 / 1023.0);
float temp_reading = (slope * (voltageValue1)) + yint;
float voltageValue5 = heatValue * (5.0 / 1023.0);
float heat_temp = (slope * (voltageValue5)) + yint;

Serial.print("temp_reading");
Serial.println(temp_reading);
Serial.print("heat_temp");
Serial.println(heat_temp);
delay(1000);

byte rOutput = digitalRead(rpin);
if (rOutput == LOW);
  digitalWrite(bpin, LOW);
  Serial.println("off");
  break;
if (heat_temp > 34.0) {
  digitalWrite(bpin, LOW);
    }
if (heat_temp < 30.0) {
  digitalWrite(bpin, HIGH);
    }
```

Appendix F - MATLAB Code

```
% Perform a one-sided t-test (less than)
[h_less, p_less, ci_less, stats_less] = ttest2(group1, group2, 'Tail', 'left');
% Display results for less than alternative
fprintf('One-sided t-test (less than) result:\n');
fprintf('   t-statistic: %.4f\n', stats_less.tstat);
fprintf('   p-value: %.4f\n', p_less);
fprintf('   Confidence interval: [%.4f, %.4f]\n', ci_less(1), ci_less(2));
% Determine if the null hypothesis can be rejected
if h_less
   fprintf('The null hypothesis (mu1 <= mu2) can be rejected at the 5%%
significance level.\n');
else
   fprintf('The null hypothesis (mu1 <= mu2) cannot be rejected at the 5%%
significance level.\n');
end
% Perform a one-sided t-test (greater than)
[h_greater, p_greater, ci_greater, stats_greater] = ttest2(group1, group2,
'Tail', 'right');
% Display results for greater than alternative
fprintf('\nOne-sided t-test (greater than) result:\n');
fprintf('   t-statistic: %.4f\n', stats_greater.tstat);
fprintf('   p-value: %.4f\n', p_greater);
fprintf('   Confidence interval: [%.4f, %.4f]\n', ci_greater(1),
ci_greater(2));
% Determine if the null hypothesis can be rejected
if h_greater
   fprintf('The null hypothesis (mu1 >= mu2) can be rejected at the 5%%
significance level.\n');
else
   fprintf('The null hypothesis (mu1 >= mu2) cannot be rejected at the 5%%
significance level.\n');
end


% Perform a multiple comparison test
```

```
group ={'Control', '1 Tegaderm Layer', '2 Tegaderm Layers', '4 Tegaderm
Layers', '8 Tegaderm Layers'};
data = [therm_control, therm_teg1, therm_teg2, therm_teg4, therm_teg8];
% Example data
group = {'GroupA', 'GroupB', 'GroupC', 'GroupD', 'GroupE'};
% Perform one-way ANOVA
[p, tbl, stats] = anova1(data, group, 'off');
% Display results
disp('ANOVA p-value:');
disp(p);
disp('ANOVA table:');
disp(tbl);
```

Appendix G - Product Design Specifications

PRODUCT DESIGN SPECIFICATIONS: ANALYSIS OF INSULATING PROPERTIES OF SKIN (RODENT)

Date: 09/15/2023

BME 200/300

Client: Dr. Caroline M. Alexander

Team Members:

Team Leader: Caelen Nickel

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Function:

The insulative properties of mouse skin prompt significant changes in the rodents' energy metabolism. Heat-permeable skin allows for increased heat dissipation, improving the metabolic health of mice and preventing diet-induced obesity. In order to explore these relationships by monitoring and quantifying skin insulation, a biomedical device which can sense said skin thermal insulation from a patch of ex-vivo mouse skin is necessary. An easy to use, reusable device will be developed to detect these measures within a specified sensitivity and display the results. This device will improve efficiency and accuracy in the testing of rodent skin.

Client Requirements:

1. The device must measure the heat transmitted through a sample of mouse skin as a way of quantifying insulative properties.
    a. Included in the device must be a heating element that uses pulses of 37℃ to heat the sample periodically.
    b. The temperature on the dorsal (top) side of the skin must be detected.
    c. The heat transmitted that is measured should only be a result of conduction and convection, not evaporative cooling.
2. The temperature measurements relative to time must be displayed to the researcher in a graphical form.
3. The device must be easy to use, reusable, and a cost effective alternative to competition.

Design Requirements:

1. Physical and Operational Characteristics:

a. Performance Requirements:

- The biomedical device will quantify the thermal insulation of mouse skin by measuring the temperature on top of the skin in relation to time.
- The device will provide a heat source to heat the skin from the bottom and sensors/circuitry for temperature measurement.
- The product will be reusable, allowing for the testing of multiple skins and able to be reset, calibrated, and sanitized.
- The researcher should have the ability to easily move and operate the device.

b. Safety:

- The device's heating element will be programmed to heat to specifically 37℃. Code and electronic hardware will ensure the heating element is off when the device is not in use.
- Electrical connections will be securely fastened to avoid short circuiting.
- The product must be kept in a dry environment away from liquids.
- The temperature sensor component of the device will allow for cleaning and sterilization after each use to prevent infection and contamination as laboratory protocols outline.

c. Accuracy and Reliability:

- To ensure the data collected is useful to the researchers, the device should record with a precision of 0.1℃ and be within 0.5℃ of the actual temperature within the range of 30-40℃.
- Data should be collected at a rate of 5 Hz.
- Per the client, the samples will be a maximum size of 4 x 6 cm and a minimum thickness of 0.05 mm.
- The device should maintain accurate performance after hundreds of repeated uses over the course of at least 5 years.

d. Life in Service:

- Both the heating element and temperature sensor will need to operate using skin that is with and/or without fur.
- The device will need to handle repeated use in quick succession. Each test is short, but many could be conducted at a time.
- The device will heat to standard body temperature of ≈37℃, so the materials used should be resistant to temperatures of at least 40℃.

e. Shelf Life:

- The average heating element has a lifespan of about 10 years, pending proper use and storage [1].
    - Heating elements have resistivity properties on their plates to make sure that they aren't damaged by samples while simultaneously making the surface easy to clean.
    - Based on the type of heating element and its electrical connections, non-corrosive features will increase the lifespan.
- Both plastic and copper are viable options to be used throughout the design. Both need to be able to withstand an increase in temperature as they will be near the heating element.

    - Copper has many positive attributes because it is corrosion resistant, has an extremely high melting point, and is malleable [2]. Based on the project's requirements it should have an indefinite life span [3].
    - Plastic has a lower melting point than copper, but it is still well above 37°C. Most plastics have a shelf life of about three years [4].

f. Operating Environment:

- The device will be utilized and stored in a laboratory at room temperature, 20°C, and standard pressure, 1 atm.
- The presumed conditions for the device will be in an indoor laboratory setting, meaning the device will have limited exposure to dust, humidity, and corrosion.
- People handling and operating the device will be researchers and other laboratory staff.

g. Ergonomics:

- There are many different sizes of workbenches and laboratory space. Most workbenches range from 24-36 inches in width, 30-120 inches in depth, and 30-36 inches tall [5].
    - The device should fit easily on all laboratory workbenches and thus should be designed with small benches in mind (24 x 30 x 30 inches).
    - The device will need to be operated from an angle that allows for easy placement of the rodent skin. Depending on the height of the researcher and/or the laboratory work space, a chair or stool may be necessary to use. Accessibility to the heating element and other components will be included in the design.
    - Due to the heating element being incorporated into the design, it will be important to have an external power source nearby.

h. Size:

- The heating element should be able to accommodate a 2 x 4 cm patch of skin.
    - Most heating elements such as hotplates sold commercially include a wide range of dimensions with moderate sized hotplates ranging from 20.8 x 36 x 10 cm and large hotplates ranging from 28.8 x 43.8 x 20 cm [6].
    - Due to the size of the sample, a smaller heating element with dimensions such as 14 x 14 x 5 cm and a plate with a radius of 5 cm would be better equipped to fit the researcher's needs [7].

- The device will include a second component that presses down on the dorsal side of the patch of skin. A copper or aluminum sheet should be used in order to minimize heat adsorption [8].
    - Most cost-efficient copper sheets are sold 15 x 15 cm with a gauge of 18 [3].
    - The metal sheets should be fabricated to fit the size of the heating plate, equating to a radius of about 5 cm.

i. Weight:

- The device must be within certain weight criteria as those operating and transporting the device will ideally carry it at chest height close to their body for easiest transportation. According to legal guidelines, this means that laboratory staff should only carry a device that is 16 kg or less [9].
    - A relatively small copper sheet (15 x 15 cm, 18 gauge) will weigh a little less than 0.15 kg per sheet [3].
    - A relatively small heating element will weigh around 0.6 kg including the weight of the heating plate itself [7].
    - The device should weigh under 3 kg which is well within the given lifting requirements for the workplace.

k. Materials:

- The final product should be made of a rigid material enabling reusability and invoking a professional, clean look.
- The heating element will be made of a material that withstands frequent temperature changes and temperatures of 37℃, allowing for the use of most metals and hard plastics [10].
    - A material that does not absorb heat or act as insulation from the heating component to prevent heat loss and allow for greater efficiency is optimal, such as copper [11].
    - For prototypes, cost-effective plastics and resins compatible with 3D printers will be used. Such materials are safe in short-term use at 37℃ [12].

l. Aesthetics, Appearance, and Finish:

- The final appearance of this product should be a relatively small and space-efficient device.
- Controls and other user interfaces on the device should be simplistic and intuitive.
- The final product and all electrical circuitry should be contained in a sleek, well-constructed exterior that is professional and able to withstand laboratory use.

2. Product Characteristics:

a. Quantity:

- One fully functional design will be developed and manufactured for the client by the end of the semester.
  - Multiple iterations of prototypes will be essential in the design process.

b. Target Product Cost:

- A firm budget has not yet been provided. However, the total cost of the device should be affordable as the prices of current commercial alternatives was cited as a hurdle by the client.
  - The necessary variation of microprocessors to operate the electronic circuit range from $20-$30 [13].
  - For the measurement of heat, K-type thermocouples cost $5.50, and thermopiles can be purchased for under $40 [13].
  - Wires, resistors, and other minor electronic items cost under $1.00 per unit [13].
  - All stock metal and plastic for the final design of the product cost under $35 [3]. However, prototypes can be constructed using scrap material available in the UW-Madison TeamLab.

3. Miscellaneous:

a. Standards and Specifications :

- This device must comply with National Safety Standard IEC 61010-031 Ed. 20 b: 2015, which specifies specific safety standards that electrical devices must follow in order to be utilized [14].
  - Under IEC 61010-031, the device should be able to be utilized without risk of electrical shock and burn, excessive temperature and mechanical hazards [14].
- Most specifically, IEC 61010-2-010 Ed. 4.0 b:2019 discusses safety and accuracy of measurement surrounding devices that are heating materials, which should be easily applicable to the device as the temperature is not getting extremely hot [15].

b. Customer:

- The target customer for this product is our client and her laboratory staff. However, this device could be useful to other research labs or for materials testing.
- Laboratory staff will be the primary users of this device, so it should seamlessly integrate into the lab environment and work well with other devices they currently use.

c. Patient-Related Concerns:

- This device will be used for an ex-vivo research application on surgically removed samples of mouse skin, thus patient-related concerns are minimal.
- Prior to being used for animal testing with this device, the mice should be humanely euthanized according to lab protocols.
- Sterlilzation of the device between tests is necessary to uphold researcher health and safety.

d. Competition:

- The temperature sensor market is quite saturated with products like the Total-Range Traceable Thermometer [16], or the Extech TM500 [17].
    - Both models are thermocouple thermometers and are limited in their ability to automatically transfer data. More importantly, they are affected by surface evaporation.
- The main competition that is specialized in ex-vivo skin temperature measurement while ignoring evaporative cooling is the Thermtest Measurement Platform MP-1 [18].
    - This device pulses heat and automatically calculates thermal conductivity for samples of a minimum size 5 mm x 5 mm and a minimum thickness of 0.01 mm [18]. The limit for this device is that it’s out of the client’s budget.

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