Analysis of Insulating Properties of Skin (Rodent)

BME 200/300

Client: Dr. Caroline M. Alexander

Advisor: Dr. Justin Williams

Team Members:

Team Leader: Caelen Nickel

Communicator: Charles Maysack-Landry

BWIG: Tayler Carlson

BWIG: Caden Binger

BPAG: Annika Syslack

BSAC: Bryan Heaton

Date: 10/11/2023

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 between two heat-conducting plates so that the skin is heated by pulses of 37℃ 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. Testing and its analysis has not yet been completed.

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Introduction

Motivation

Rodents such as mice and rats are essential parts of testing in many research labs and research and development settings. Rodents provide physiological models for the testing of medical devices, pharmaceuticals, and biologics. Therefore, much of 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, with implications in 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 [3]. Additionally, 4 million people die due to obesity a year [3]. The treatment and prevention of this, along with potential oncology implications lead to skin insulation and metabolism research being vital.

This product is a biomedical device that allows for conduct of this research and quantification of skin thermodynamic properties. The ability to measure the changes in temperature over a rodent skin sample shows heat permeability relative to genetic engineering, the environment, and/or diet of the rodent.

Existing devices and Current Methods

Figure 1: Omega Infrared Camera for thermal measurement [4]

Effective and non-invasive temperature measurement is often performed using infrared sensors or cameras, such as the Omega Infrared Camera illustrated 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 in the relevant project using rodent skin samples. Despite the benefits of infrared imaging, 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 was ultimately useless when calculating the thermal conductivity of a sample.

Figure 2: Thermtest MP-1 [5]

The Thermtest MP-1 is a commercially available technology that functions similarly to the intended product as outlined by the client requirements and preliminary designs. This device heats samples from one side, with computer controls allowing for customizable heat settings. On the other 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, abiding by what the client requires. However, this competitive design costs $30,000, as described by the client after receiving a quote.

Problem Statement

In order to monitor and quantify rodent skin thermodynamics, a biomedical device which can sense skin thermal insulation from a patch of ex-vivo mouse skin is necessary. An easy to use, reusable device will be developed to detect changes in temperature from the dorsal side of the skin when under periodic pulsations of heat. Eliminating evaporative cooling on the skin will help improve the accuracy of the measurements which will be taken within a specified sensitivity. The temperature results will be displayed graphically for ease of interpretation. Overall, this device will improve efficiency in the testing of rodent skin in a cost effective manner.

Background

Biology and Physiology

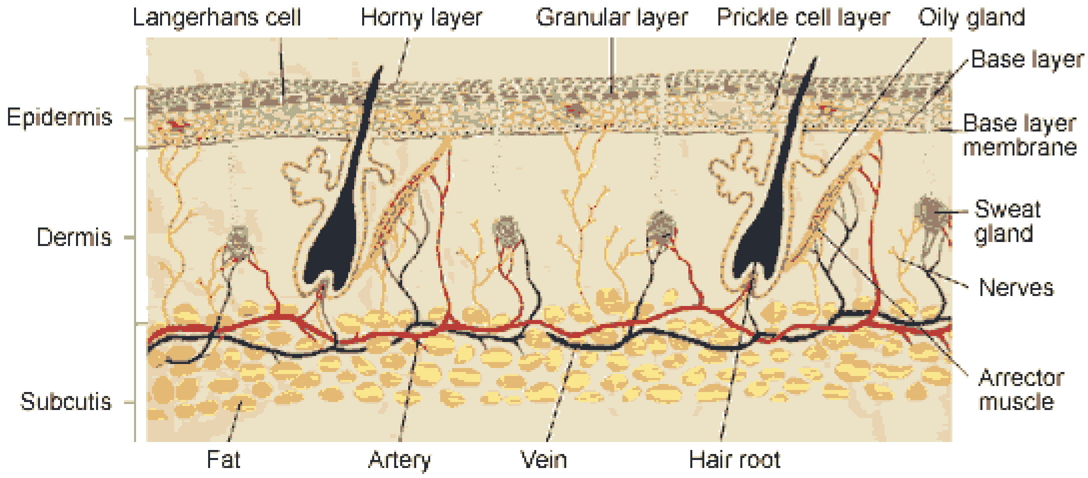

Figure 3: Detailed illustration of skin anatomy [6].

The skin, apart from being the largest organ in the human body and its first line of defense against the outside world, is a complex system with detailed anatomy and physiological effects. One of the functions of skin is temperature regulation, allowing heat to be dissipated from the body into the surroundings [6]. Control of afferent blood flow allows for the magnitude of heat transfer across skin to be modulated, and this is visible when a person undergoing physical exertion becomes more vascular. 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 of the skin, but by the structure of the skin itself. As 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 [7]. 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 [8]. Skin lamellae regulates the heat transfer to and from the environment as it is closer to the surface of the skin [9]. 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 [10]

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 [1][10]. 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, 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 [10]. 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 your skin [11]. The absorption of heat by the liquid sweat removes this thermal energy from the body, thus cooling the body [12]. This exact process also occurs when heating a tissue sample. As tissue is exposed to heat, water within the sample will heat up and evaporate, removing energy from the system and into the environment. The result is that the sample is cooled, and measurement of how a material interacts with heat is affected.

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 37℃ 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 in. piece of copper costs $24.99, whereas aluminum costs $12.19 for a 12x12 in 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].

Client Information

The client Dr. Caroline Alexander is a Professor of Oncology 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 37℃ 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 for which has already been established within the laboratory. For example, the device should fit within the designated area well. Due to the size of the skin sample, 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 A**.

Preliminary Designs

Heating Element

Wall Power Heating Element

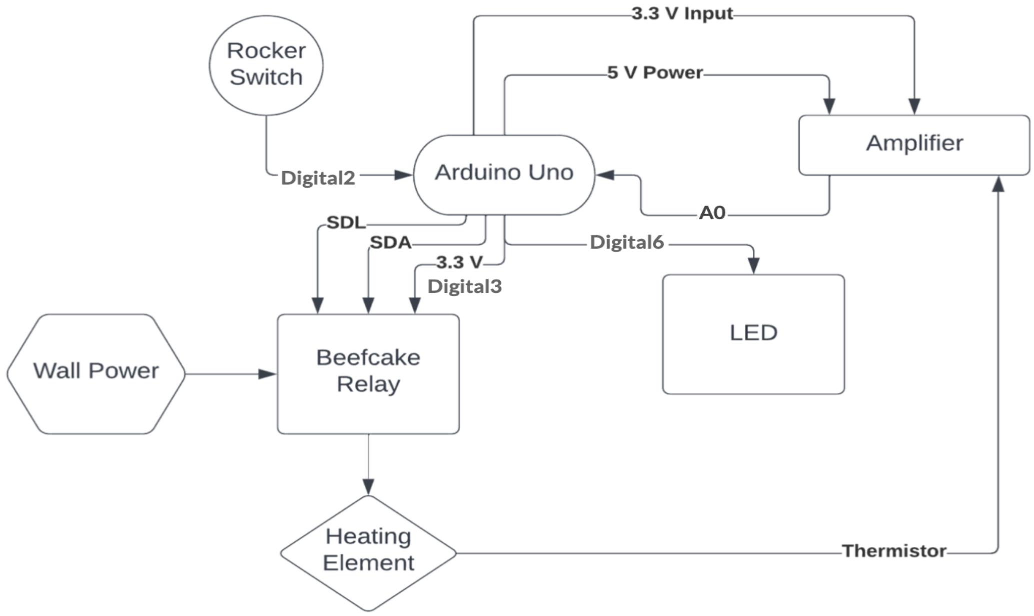

Figure 4: A hardware block diagram showing the components and flow of a heating element circuit which uses wall power.

A heating element design centered on wall power being the primary power source would be constructed in a way represented by the block diagram. A beefcake relay would be incorporated in order to process the wall power and send it to the heating element, pending power from the Arduino microcontroller. A rocker switch and thermistor circuit both control the Arduino. If the rocker switch is in the off position and/or the thermistor circuit detects a temperature greater than 37℃, the Arduino microcontroller and downloaded code would instruct the beefcake relay to not send wall power to the heating element, thus turning it off.

Battery Power Heating Element

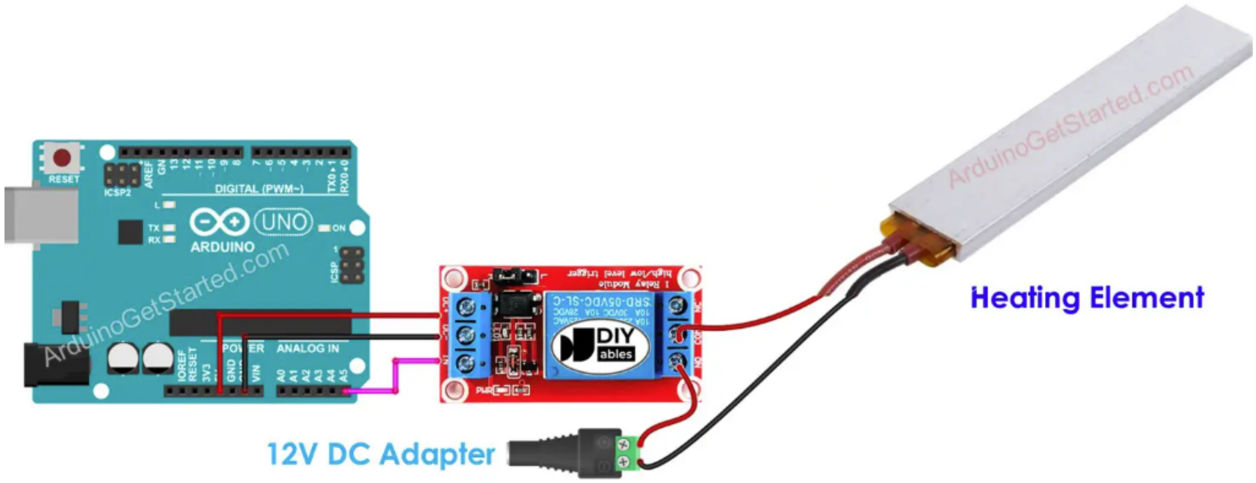

Figure 5: A modified Fritzing diagram showing the battery incorporated into circuit design [20].

This design includes a battery that powers the heating element, controlled by an Arduino microcontroller as in the wall power heating element design. Not shown in the diagram is the feedback system utilizing a thermistor circuit to ensure the heating element does not heat past 37℃, which would be identical to the block diagram made for said wall power design.

Temperature Sensor

Thermistor Temperature Sensor

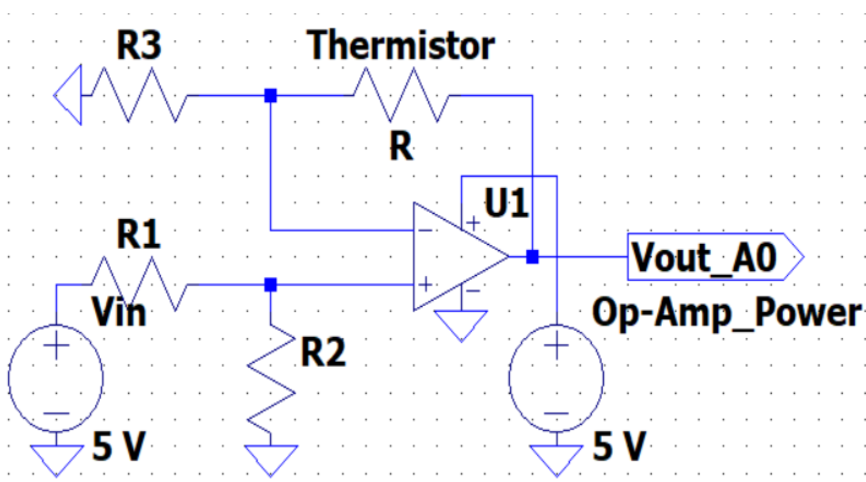

Figure 6: This LTSpice schematic shows the circuit design incorporating a thermistor that would be used in the thermistor temperature sensor design.

The thermistor is a variable resistor that responds to changes in temperature with corresponding changes in temperature exhibiting a linear relationship. 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 Gain = 1 + ($R_{Thermistor}$ / R3).

Thermocouple Temperature Sensor

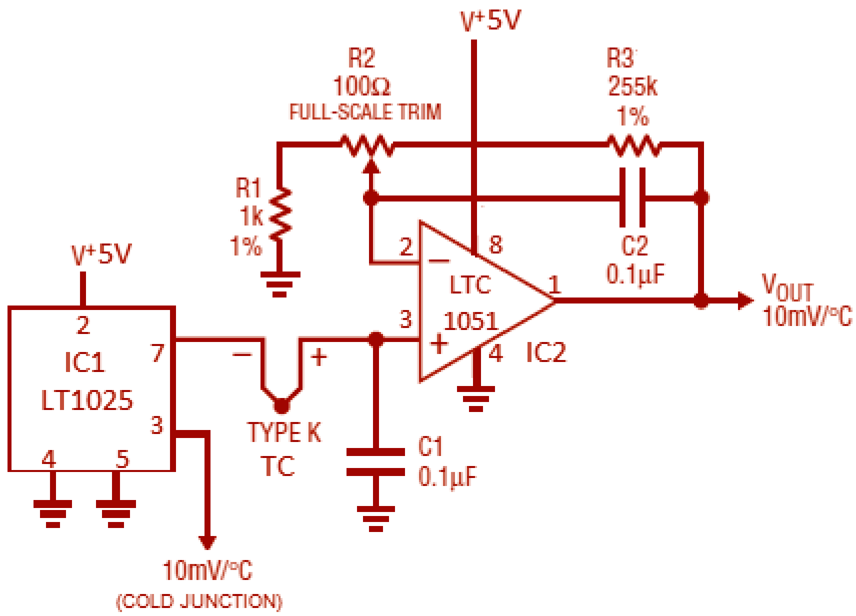

Figure 7: This generated circuit schematic shows the circuit design incorporating a K-type thermocouple that would be used in the thermocouple temperature sensor design.

To use a thermocouple in a temperature sensor circuit, an additional amplifier LT1025 is necessary. The voltage output of the thermocouple is sent into an non-inverting operational amplifier circuit similar to the thermistor circuit, however also requiring the use of a filter to mitigate noise.

Thermopile Temperature Sensor

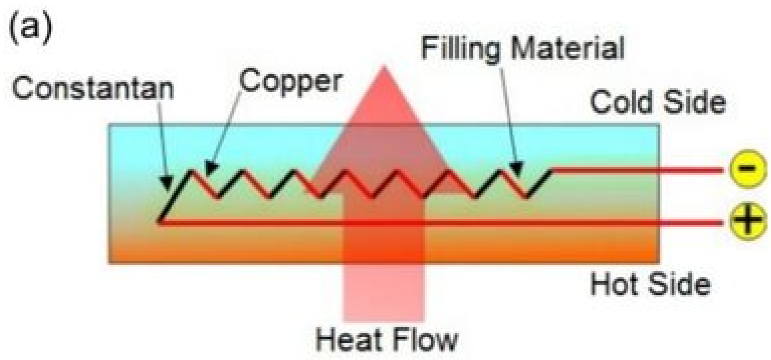

Figure 8: An illustration of a thermopile, featuring multiple thermocouples in series [21].

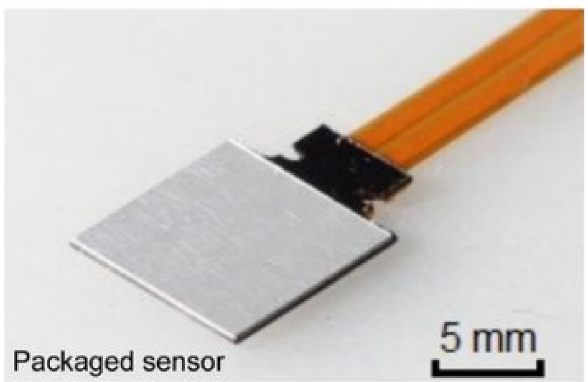

Figure 9: Flat plate design thermopile that would be incorporated into the thermopile temperature sensor circuit [22].

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 [22].

Preliminary Design Evaluation

Design Matrix

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*, while only 10 on the *Temperature Sensor Design Matrix* 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*.

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*.

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*. 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*.

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*. For the *Temperature Sensor Design Matrix*, 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 in 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* as the design team expects more of the device to be purchasable. The weight for the *Temperature Sensor Design Matrix* 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

Safety:

The wall powered heating element scored a 2 in safety because of the fact that an outlet is required to power the device, creating risk of electrical problems such as 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.

Accuracy:

The wall powered heating element design scored a 4, slightly higher than the battery powered design because electronics experience shows that wall power is a more reliable source of energy and would allow for fewer electrical connections. Electrical connections always pose the risk for energy loss and increase the likelihood that output voltage is lost, which would make the temperature of the heating element appear less to the Arduino microcontroller in the feedback circuit. This would cause errors in heating temperature, most likely heating samples above 37℃ and compromising 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 may require a 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 heat source for many repeated trials would require a significant portion of the budget.

Ease of Fabrication:

The wall powered heating element scored a 4 over the battery powered element as the design team has more experience with creating circuits using wall power. Although wall power introduces safety concerns, the group feels more comfortable navigating these issues than the ones introduced by batteries, such as recharging or replacing them and finding the correct voltage. Overall, a battery capable of powering the heating element offers the need for more electrical connections that must be made as well.

Temperature Sensor

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. The thermopile temperature sensor design received a weight of 1 in this category because thermopiles would be capable of measuring evaporative cooling even when in direct contact with the samples, which would take thermodynamic factors into account that the researchers are 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 design team has the most experience with thermistors and though we also have enough experience with thermocouples, thermistors have been used in design and are inherently much simpler. The thermistor circuit does not require the use of an additional amplifier and filters as the thermocouple and thermopile would, and thus has fewer components and would be easier to fabricate.

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 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.

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. A thermocouple is only slightly larger than a thermistor, but requires more wires and electrical components as mentioned, therefore expanding the scale of the design unnecessarily. Thermopiles are series connections of thermocouples, therefore are larger components but 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 the circuit. Thermopiles scored a 3 in safety as well for this reason.

<u>*Proposed Final Design*</u>

Based on the evaluation of the design matrices, it has been 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*, winning in 3/5 criteria and the thermistor temperature sensor scoring highest in the *Temperature Sensor Design Matrix*, winning in 4/5 criteria.

The wall powered heating element was found to be favorable by the design team because there is more familiarity with the necessary components that go into constructing the instrumentation, such as a beefcake relay. In addition, these components are more cost effective, especially when considering that batteries are expensive and still not without their inaccuracies in electric potential generation. 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 design team has also worked with thermistors in the past and possesses many of the components that are used in conjunction with the thermistor, enabling for greater ease of fabrication.

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 37℃ or off if it is above 37℃. On the dorsal (top) 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 37℃ heat applied to the skin is the essential data which the researchers need, so it will be displayed.

Fabrication/ Development Process

Materials

The final proposed design will consist of electronic components contained within an exterior container. As decided in the design matrices and corresponding evaluation, the materials necessary for the electrical circuits will feature 2 thermistors, a beefcake relay, a rocker switch, and 2 operational amplifiers. This equipment is available through the BME Design Lab as it is used in spring BME 201 courses. However, the purchase of thermistors that are more accurate or more optimally sized/shaped is a possibility. All wires, resistors, breadboards, LEDs, and the Arduino microcontroller are possessed by the design team due to previous instrumentation courses.

On the electronics-sample interface, material decisions are important in order to avoid affecting results and causing inefficiencies. As mentioned and outlined in the Product Design Specifications (**Appendix A**), the device will heat to standard body temperature of 37℃, and therefore the materials used should be resistant to temperatures of at least 40℃. Many materials comply with this requirement, allowing for the use of metals and hard plastics. In order to minimize heat loss, a material that is thermally conductive is required. For the proposed final design, copper or aluminum foils will be ideal to separate the heating element and thermistor from the sample as they withstand temperature changes in the required magnitude, are thermally conductive, and can be sanitized easily [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℃ [15].

The exterior of the product will contain all of the electrical components, only having the heating element surface and thermistor temperature sensor accessible. Since the design should invoke a professional finish, a hard plastic (PLA) for prototypes and stainless steel for the final design will be used for the exterior.

Methods

Fabrication of the proposed final design will be done incrementally, starting with prototype iterations. The design team will order all electrical components necessary to construct the heating element circuit and temperature sensor circuit. The majority of such components are already possessed as a result of previous coursework. From here, it is important that the circuits are constructed and tested prior to fabrication of the structure, interfaces, and exterior of the device. Then, the breadboard(s), Arduino microcontroller, and beefcake relay can be installed into the container that the device operates within. Lastly, the separation between the heating element and thermistor temperature sensor will be fabricated using the materials discussed, and other connections from outside of the device, such as the rocker switch, wall power cord, and indicator LED will be made via fabrication of cutouts in the exterior.

Testing

No testing has been performed at this time, as the design team is still in the process of creating a prototype of the design. However, intended testing will be done both as a part of the fabrication of the device and to ensure its proper functioning.

As outlined in the final proposed design, thermistors will be used to regulate the heating element temperature and sense the dorsal temperature. A thermistor circuit outputs a voltage that is linearly related to the temperature that the thermistor is exposed to. In order to convert this voltage to a temperature, the thermistor must be tested to make a calibration curve. A calibration curve is a graphical representation of the relationship between resistance and temperature of the thermistor, and it is made by measuring the resistance using a multimeter while a known temperature is applied to the thermistor. The equation that is derived from this curve is essential to the Arduino code and overall accuracy of the device, so multiple trials measuring the resistance in heat controlled water baths will be performed. The water baths will be heated on a hot plate, with thermometers verifying the temperature value that the measured resistance corresponds to.

Once the proposed final design is fabricated, the prototype iterations and final design will be tested for accuracy and safety. First, the temperature of the heating element will be measured using a thermometer, ensuring that the device heats samples at the desired 37℃ temperature. It is important that the Arduino correctly modulates the heating element, and this testing will also verify the correct functioning of the circuit. The final thermistor circuit will be tested in a similar method as the formation of the calibration curve, by exposing the thermistor temperature sensor to water baths of known temperature values and ensuring the results the device displays are within the specified accuracy. Again, this will also be a conclusive test to ensure that the circuit functions correctly. Once this testing is completed, feedback from the client and researchers working on applicable projects will be important in determining if the product functions as intended against the final Product Design Specifications. The researchers will numerically rank the device's performance in the categories outlined in the design matrices, as well as provide qualitative feedback.

Results

There are no testing results available at this time, as the design team is still in the process of creating a prototype of the design.

Discussion

Once a prototype is fabricated and tested, the results will be considered within the design team and with the client to decide how the design should be modified or if a different design is necessary. Any adjustments of the design should be diligently fabricated and tested in a similar way to the original design to analyze for improvement. Following any adjustments, said testing will be performed until the design meets the client's requirements.

As a research device that is used to conduct animal testing, heavy ethical considerations apply. This device is intended to measure the thermal insulation of ex-vivo mouse skin, meaning that mice will have been recently euthanized and had their skin surgically removed in order to perform the testing. While the device does not influence this process or pertain to the well being of the rodents, its involvement in the ethically hot topic of animal testing cannot be ignored. Laboratory protocols outlining the use of this device must also include information on the safe handling and ethical treatment of animals for testing. The nature of the research that this device performs has implications in improving the health of rodents bred in captivity, in addition to that of humans. Results of this research on the modulation of rodent metabolism by skin insulation could allow for genetic, environmental, and diet modifications that increase the rodents' metabolic rates, thus improving their overall health.

Metabolic rate and its results are a significant determinant in human health, thus impacting people in a multitude of ways. In the United States, diet-induced obesity is a major issue with many related health risks. Research that has the ability to prevent or treat diet-induced obesity would improve lives and mitigate the prevalence of related diseases. According to the client, applications of her research could even extend into the oncology field, with metabolism and obesity relating to tumor prevention. This device, therefore, has an ethical obligation to be accurate so that the researchers can collect quality data and make correct claims, while developing methods and products to assist people suffering from diet-induced obesity. Also, this device functioning as intended will make research in this area more efficient and cost effective, allowing researchers to conduct more research and spend money elsewhere, with the overall effect of elevating research in this area.

Future sources of error can be identified in the described testing, and are likely to occur in the temperature sensor readings and heating element temperature. The thermistors that are used in both of these components must be thoroughly tested to find the resistance at given temperatures. Even with this level of testing, the equations generated from calibration curves that the Arduino code uses are imperfect, more akin to a line of best fit rather than a direct conversion from voltage to temperature. As a result, there can be inaccuracies in the temperature sensor reading or control of the heating element, causing possible error. That being said, more thorough temperature testing and calibration provides more data, improving the fit of the temperature-resistance equation. In addition, many electrical components, namely resistors and thermistors, have an error associated with them. While the exact resistance value is given in the product specifications, there is often a 5% or 10% difference, known as tolerance. This can be addressed in the final design, as more expensive resistors are of a higher quality and have a much smaller tolerance. Also in the final design, soldering of connections in the circuit will ensure there are little to no interruptions in electrical current, increasing reliability and accuracy.

Conclusion

Metabolic rates are directly related and experimentally shown to be affected by the heat dissipation through the skin. As a result, metabolic rates can be influenced by particular genes, the environment, or diet as these factors alter the thermodynamic properties of skin. Due to changes in these elements, it is possible to increase metabolic rates, increasing the amount of nutrients consumed and the amount of heat that is produced. In order to perform research in this area, the insulative properties of rodent skin must be quantified. The purpose of this biomedical device is to provide researchers with the ability to accurately and efficiently heat rodent skin samples and obtain data on its insulative properties. In order to accurately measure the heat transfer across the skin samples, the effects from evaporative cooling must be ignored, instead focusing on heat conduction by the skin.

To address this, the proposed final design made up of the wall power heating element design and the thermistor temperature sensor design will be fabricated. These two components will make up the proposed final design, which allows the researchers to place samples of ex-vivo mouse skin on the flat surface of the heating element. The heating element will be powered by a 120 V wall outlet modulated by a beefcake relay and controlled by an Arduino microcontroller. A feedback circuit using a thermistor will ensure that the heating element is at the appropriate temperature. Meanwhile, a flat plate containing a thermistor will contact the dorsal side of the skin sample and measure the temperature. The thermistor will be part of a non-inverting amplifier circuit that will provide the Arduino microcontroller with a voltage output, which will be converted to a temperature value using a calibration curve equation. This temperature value will be important for the researchers' data collection and thus displayed.

The design team plans to acquire the remaining electrical components necessary in the circuits, then begin fabrication of the heating element circuit and feedback thermistor circuit, as well as the thermistor temperature measurement circuit. The completed electrical circuits will then be tested for accuracy and proper functioning, then the fabrication of the exterior compartment will commence. The final device design will undergo an additional round of testing as described previously, as well as used by researchers in order to receive qualitative and quantitative feedback.

In conclusion, the design team aims to fabricate and test a working prototype that accurately and efficiently measures the thermal insulation of rodent skin samples for research purposes. The team understands that this process will not be linear and will require continued research, constant client communication, and persistent teamwork.

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Appendix A - 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

Communicator: Charles Maysack-Landry

BWIG: Tayler Carlson

BWIG: Caden Binger

BSAC: Bryan Heaton

BPAG: Annika Syslack

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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