Thermal Probe for Neurological Examination

May 4, 2001

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Biomedical Engineering 301 – Spring 2001
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Abstract

To help diagnose neurological disorders, a portable thermal probe is needed to determine if a patient has a loss of temperature sensation in a specific area of the body. The device will attach to the Welch Allyn ophthalmoscope/otoscope handle, which is already widely used in medical examining rooms. We brainstormed a number of design paths and chose a final solution that involves a newly designed prototype. The prototype consists of a resistive heating element on a handle and a digital circuit to control temperature. Future work includes adding a timer to the prototype that alerts the user after the device has been in contact with a subject's skin for five seconds. We also need to choose a suitable material for the device housing.

Problem Statement

Doctors are now finding it necessary to test patients who experience pain or numbness with warm/heat sensitivity for neurological damage. Currently, there is no portable device that a physician can use to apply hot sensations to a patient's skin. Physicians investigating sensory loss could use a device that heats up to warm and hot target temperatures of 38°C and 45°C respectively as a prescreening process before a more rigorous quantitative sensory test is performed. This device should be convenient to use and safe to apply to patients.

Background

Injuries and diseases affecting peripheral nerves, the spinal cord, or the brain can be diagnosed in part with heat and cold sensitivity testing. The severity of injury or disease can be determined by the temperature threshold at which a patient first senses the heat or cold (Hilz, *et al.*, 1999). Patients suspected of having a neurological sensory disorder often undergo quantitative sensory testing. In this procedure, the patient is exposed to sensory stimuli (vibrations, changing temperature, etc.) that gradually increase in magnitude. The patient responds to the stimuli and the amount of sensory loss may be quantified. Unfortunately, this type of test takes 30 to 60 minutes and must be performed in a lab with specialized equipment.

In a clinical setting, heat and cold sensations may be used to help diagnose patients suspected of neurological damage. A quick, convenient method of temperature sensation testing could be used to prescreen patients before undergoing quantitative sensory testing. Currently available devices that heat up to known temperatures for heat sensitivity testing are bulky and inconvenient, so generally only cold sensation testing is performed because ice and tap water are readily available.

Physiology of Temperature Sensation

Cold is sensed via myelinated Aδ-fibers and heat is sensed via unmyelinated C-fibers. Testing with only cool tap water and cold ice water is inadequate (Susser, *et al.*, 1999) because damage to the heat-sensing fibers may be overlooked. For sensory testing, 45°C is considered to be a hot temperature and 38°C is considered to be a warm one (Konietzny, 1984). Temperatures above 50°C can cause pain and skin burns with very short contact times, so no heat sensitivity testing is done above 50°C.

Thermal sensitivity thresholds have relatively little to do with increasing age (Merchut & Toleikis, 1990). In mammals, temperature sensitive neurons from the skin transmit signals to the hypothalamus where they are processed. Warm-sensitive neurons are affected by the physical state of lipids, changes in protein conformation, and membrane skeleton activity (Vasilenko, 1994).

Our client, Dr. Backonja, would like to have a small device to use in his clinic for heat sensitivity testing. The surface of thee thermal probe should reach the target temperatures of 38°C and 45°C relatively quickly and should be safe to use. (See Appendix A for a list of client and design requirements.) While not required, a thermal warm/heat probe may be designed as an attachment for Welch Allyn ophthalmoscope/otoscope handles. Because these handles are readily available at clinics and hospitals, many physicians could easily use such an attachment.

Welch Allyn Power Handle

Welch Allyn, Inc. makes several models of power handles for clinical use. The Welch Allyn ophthalmoscope/otoscope handle used for this design contains a 3.5 V rechargeable Nickel-Cadmium (NiCd) battery. The handle is made of stainless steel and textured to ensure good grip. The lower portion of the handle can be removed and plugged into an electrical outlet for recharging. A picture of the handle is shown in Figure 1.

Figure 1. A picture of the Welch Allyn convertible power handle [“3.5v,” 2000].

The ophthalmoscope and otoscope heads are secured to the top of the handle through a mechanism that requires pushing the head down and rotating clockwise. Voltage is delivered to the top of the handle by depressing the button on the collar and rotating the collar clockwise. Turning the collar adjusts a rotary potentiometer inside the handle, providing a source resistance from 0 to 5 Ω. The circuit uses the outer casing of the handle and locking mechanism as the negative terminal and the spring-loaded pin at center of the locking mechanism as the positive terminal.

Ethical Issues

There are a limited number of ethical issues surrounding our design project. First, the device would be tested on human subjects in order to make sure the probe reaches optimal temperatures. It is necessary to supply the subjects with complete information regarding the purpose of the device and the risks of being involved in the study. In order to conduct human testing, the researchers are required to write a protocol on how and why the testing will be conducted. The University of Wisconsin Health Sciences Human Subjects Committee must also approve the protocol before testing can commence.

The purpose of our design project is to test patients who experience pain or numbness for neurological damage. This involves applying heat to the suspected damaged area. In the process of applying heat to the patient, a component in the device has the possibility of malfunctioning. In this case, the device could heat above the desired temperature and potentially burn the patient. The timer could also fail, resulting in the probe being held on the skin for too long. This could also cause the patient to be burned because a hot surface is in contact with the skin for a long period of time. We hope to minimize, these potential problems by making our final design digital. In this case, if one element in the device fails, the whole device will fail and no heat would be produced.

Previous Prototype

This project is a continuation from previous semesters. The previous team built a prototype, but little testing was done due to time constraints. Figure 2 shows the device that was built last semester.

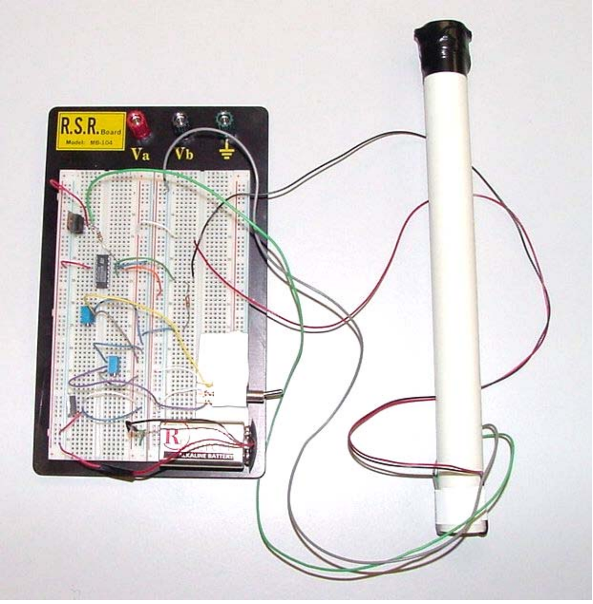

Figure 2. The prototype device from last semester. The temperature control circuit is on the breadboard and the resistive heating element is at the top of the fiberglass pipe handle.

The prototype consists of a modified resistor for heating on a handle and an analog temperature control circuit on a breadboard (see Appendix B for a circuit diagram). The heating element is a 1.0 Ω power resistor encased in aluminum. A small hole was drilled in the casing and a thermistor (a component whose resistance changes with temperature) was glued into place with metal-filled epoxy.

As the temperature in the immediate environment changes, the temperature of the thermistor also changes. In the circuit, this causes a change in resistance resulting in a change in voltage across the thermistor that could be compared to reference voltages calibrated to specific temperatures. If the temperature of the thermistor were higher than the target temperature, then no current will flow to the power resistor (i.e. the probe would no longer heat up).

The previous prototype when obtained was not functioning properly. Part of the semester was spent attempting to fix the prototype to use as a proof-of-concept model. After several weeks of little progress on this route, we decided to pursue a new design and built a new prototype from scratch.

The current prototype solution contains the same general heating approach used previously with a power resistor coupled to an aluminum contact surface, a thermistor coupled to the contact surface to monitor temperature, and a digital control circuit to control the current to the power resistor and ultimately the heat emitted.

Alternate Solutions

The design of the device involves three distinct subcomponents: the heating element, a temperature control circuit, and a timer control circuit. After the heating element and battery, the temperature control circuit is the most important component because it allows the device to reach specific target temperatures without burning patients. The timer circuit would alert a physician of prolonged heat exposure, indicating the device should be removed to avoid inadvertently burning a patient.

Heating Element

Besides resistive heating, another way to heat and cool is by using Peltier thermoelectric devices. Peltier heaters create a temperature difference when an electric current is passed through a junction of dissimilar semiconducting materials. Figure 3 shows the theory and normal configuration of a Peltier thermoelectric device.

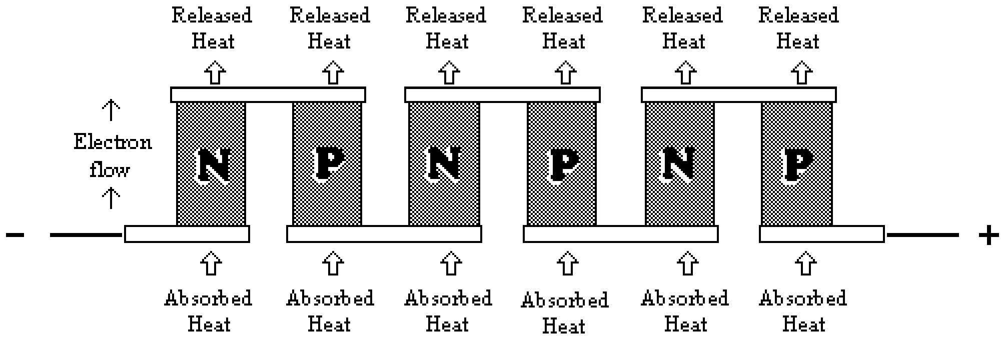

Figure 3. Thermoelectric heat pump. N-type and P-type semiconductor materials pump heat with and against the flow of electrons through them, respectively [“Frequently,” 2000].

These devices are typically used for cooling items as computer processors or portable refrigerators. Peltier heaters are difficult to find in the small size desired and with appropriate control mechanisms. Because Peltier devices act as a heat pump, one would have to warm the cool side to pump heat to the warm side. Peltier devices are not very useful in heating applications; instead, resistive heating is the simplest and most direct solution [Beebe, 2001; Föll, 2000].

By passing current through a resistor, heat can be generated in order to reach the two target temperatures. The power dissipated is equal to the resistance times the current squared through the resistive element ($P = I^2R$). Because all the power is dissipated as heat, regulating the current through the resistor allows accurate control of temperature. Since the power dissipated is dependent upon resistance and the purpose of the device is to generate heat, it is important the power resistor only minimally change resistance with temperature change.

There are a number of different types of resistors that could be used to produce the necessary heat. Most resistors are cylindrical in shape, so one method would be to place a large cylindrical resistor on the back of the probe material, with its long axis parallel to the plane of the probe surface, and rely on the probe material to disperse the heat over the probe surface. Another method of resistive heating would be to use a known length of Ni-Chrome wire (nickel-chromium alloy) to provide resistance. The Ni-Chrome wire could be formed into whatever shape is needed to maximize the contact between the resistor and the probe material, resulting in even dispersal of heat over the probe surface.

The probe surface must be easy to clean, corrosion resistant, and thermally conductive. Various metals and plastics are currently used for clinical devices, but since the surface must be thermally conductive, metals are preferable to polymers. Copper has the best thermal conductivity of the common metals, but poses some problems with surface oxidation reactions and sterilization. Aluminum is less reactive than copper and also has high thermal conductivity to allow efficient heat transfer between the heating element and probe and between the probe and skin.

The probe surface will be circular with an area of 4.0 cm^2, but the thickness of the metal will be determined through experimentation. The thermal mass of the probe should be low enough so that target temperatures can be reached quickly. It should also be high enough so the surface temperature will not decrease rapidly when the probe is applied to the patient's skin or when the device is turned off momentarily during a thermal sensitivity examination.

Temperature Control

A thermistor may be used to measure the temperature of the probe. A thermistor coupled closely with the probe surface will allow for a nearly direct way to monitor the temperature of the surface. The change in resistance due to a change in temperature could be used in an analog or digital circuit to control temperature. Last semester, an analog circuit was designed that could be adjusted to different temperatures.

Using an analog-to-digital converter and an integrated circuit (IC) would allow for convenient temperature control. The IC could be used to turn off the power to the resistor once the probe surface reached the target temperature and could also be programmed to light a diode corresponding to the appropriate temperature or to display the actual temperature on a liquid crystal display (LCD).

Timer Control

To prevent possible burns, a timer will be built into the device. In the prototype, this timer will not be responsible for turning off the power to the heating element; instead, once the probe has been applied for five seconds, the physician will be alerted by a sound or light. Because the probe will retain some heat after the power is shut off, the only sure way to stop heating the skin is to remove the probe. It will be left up to the operator to remove the probe from the skin after five seconds have elapsed.

The timer would be activated by a small switch that could take several forms. The switch could be one or several small buttons located next to the probe surface, or the probe surface itself could act as a button. It would also be possible to use a design with two electrodes that would close the circuit once the device was brought into contact with the skin. Because we do not want the physician to push the device into the patient's skin, any method used must require little pressure for activation.

A series RC circuit could be used as a timer, with the capacitor connected to the cathode of the battery. The timer switch would start to charge the capacitor, causing the voltage between the elements to decrease exponentially with a time constant determined by the values of R and C. After five seconds, this voltage reaches a threshold voltage, causing a comparator's output to flip, causing a light or speaker to activate and alerting the doctor to remove the probe from the patient's skin. This type of timer would probably not be very accurate so a different approach is preferable.

A digital timer could be made from a counter that would be reset when the trigger depressed and would send a signal after a number of counts equal to five seconds has occurred.

Comparison of the Solutions

The analog temperature control circuit (Appendix B) would be a convenient method of controlling the power supplied to the heating element. The circuit is simple and inexpensive to manufacture and would allow us to optimize the heating, temperature control, etc. However, the design would become unsafe if any of the components were to fail. Failure of a resistor in the circuit could lead to uncontrolled heating of the probe surface.

Using a digital circuit instead of an analog circuit has advantages and disadvantages. The IC could be programmed to control both the timer and probe temperature. It would also be simple to use the IC to display the temperature to an LCD. This design would potentially be safer than an analog circuit; if a circuit component failed, the probe would not heat up at all. The digital design would also be more accurate and therefore safer than the analog circuit.

Using an IC would make the circuit more complex. Troubleshooting would be more difficult, although some problems could be fixed with different programming. The rechargeable battery of the Welch Allyn handle only provides 3.5 V, so it would be necessary to find a low power IC or to use a separate power source for the IC. Overall, if implemented successfully, a digital design will yield a safer and more accurate device.

Resistive heating, upon review of information, appears to both be more feasible and easier to use than a Peltier thermoelectric device. This will allow for a direct way to supply heat dependent upon the resistance (which is dependent upon length) of the Ni-Chrome wire.

The probe surface, which must be sanitary, should maintain its physical characteristics while staying thermally conductive. For placement upon the skin, ethanol wiping of a metal surface is typically a sufficient cleaning method. Aluminum will stand up well to such a maintenance procedure.

Chosen Design

Because of safety considerations, as well as ease of troubleshooting and altering the design, a digital control design was chosen. The Welch Allyn battery will be used to provide power for the heating element. The heating element is implemented as a flat coil of resistive wire.

Battery

When we tested the properties of the NiCd battery in the Welch Allyn handle, we noticed that the battery drains quickly and has three plateau levels for the voltage and power it supplies. Figure 4 is a plot of power output from the NiCd battery versus time for 2 and 5 Ω resistors.

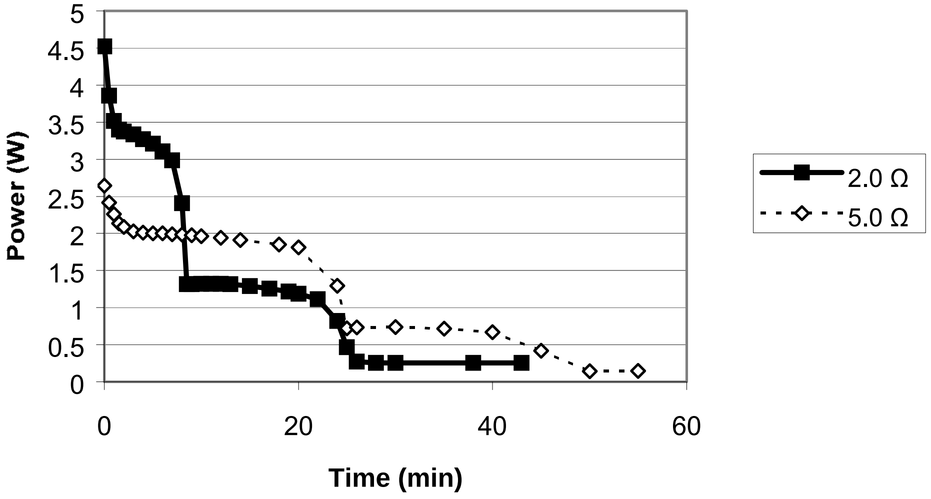

Figure 4. Power output versus time for the 2 and 5 Ω resistors with the Welch Allyn battery.

This drop in voltage and power would greatly change the time it takes to reach the target temperature (if it could be reached at all). To get a better power output, we built a 5 Ω heating element. One important fact to note is that the battery used for this testing was at least 14 years old. A new battery would be more stable and would allow for more power to be obtained per charge.

Heating Element

We wanted to create a heating element that would produce all of its heat close to the probe to avoid wasting energy. We researched available elements, but could not find ones that were inexpensive and would suit our design. To build the element, we created the flat coil from Ni-Chrome wire shown in Figure 5.

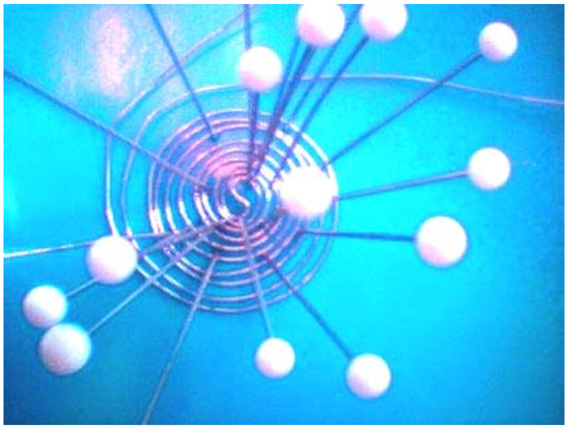

Figure 5. The Ni-Chrome resistive wire coil. In this figure, the coil is pinned to a rubber surface to help it maintain its shape.

The Ni-Chrome coil is the main component of a multi-layer element. A cross-sectional sketch of the heating element is shown in Figure 6.

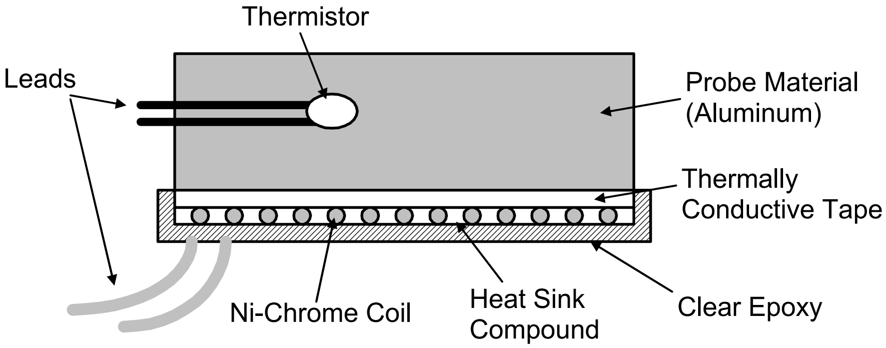

Figure 6. A cross-section of the heating element with labeled components. Note: The sketch is not to scale.

We made the probe of an aluminum disk with a thickness of 4.5 mm and a diameter of 23 mm. We drilled a small hole in the side of the aluminum disk for the thermistor. After placing the thermistor, this hole was filed with heat sink compound and then sealed with metal-filled epoxy. We attached heat sink tape to the reverse side of the aluminum disk and adhered the coil to it. Between the wire coils, we filled the gaps with heat sink compound to help even the thermal flux. Finally, we sealed the back of the entire probe with clear epoxy as an insulating layer.

Analog Control Circuitry

The temperature control will be achieved with a digital circuit. This digital circuit interfaces with a small analog circuit containing a thermistor to measure temperature. A NTC (negative temperature coefficient) thermistor changes resistance as a negative exponential in relation to temperature. We used this type of thermistor, bridged with a balancing resistor to ground. These two elements carry the full voltage of the control circuit power supply, and the voltage between them will be proportional to temperature. If the thermistor has a resistance $R(T_1)$ at temperature T, that voltage will rise linearly with temperature ($R^2 = 0.99$) in the range of temperature from T-20°C to T+20°C if the balancing resistor is set to $R(T_1)$. An analog-to-digital converter will read this voltage and give the digital circuitry an accurate digital representation of the probe surface temperature.

Digital Control Circuitry

The digital representation of the temperature will be an n-bit word. The number of bits necessary for this is dependant on the desired precision in reading the temperature. We have to consider thermistor temperatures from 15°C to 55°C, the minimum ambient temperature of the environment the probe will be used in, and the maximum temperature of the probe surface due to heating, with 5°C added to allow the circuitry to read voltage at 50°C without problems. If an 8-bit converter were used, the maximum temperature resolution would be $(55-15)/2^8 = 0.156$°C, and a 12 bit converter has a maximum resolution of $(55-15)/2^{12} = 0.01$°C. The actual resolution depends on how the temperature voltage fluctuates over the range of possible temperatures.

We will have our target temperatures stored in the circuitry as n-bit words equal to the n-bit word produced by the converter when the thermistor is at the target temperature. The target words will be inputs to a multiplexer. The operator will select the desired target temperature, and the circuitry will decode that into select inputs for the multiplexer. The selected target word and the converted temperature word will be inputs to a comparator. If the temperature is lower than the target, the comparator will output a high voltage. This voltage feeds into the base of a transistor, allowing current to pass to the heating element. If the temperature is higher than the target, the comparator will output a low voltage to the transistor and current will not be allowed to flow through the heating element. The block diagram of the digital control circuit is shown in Figure 7.

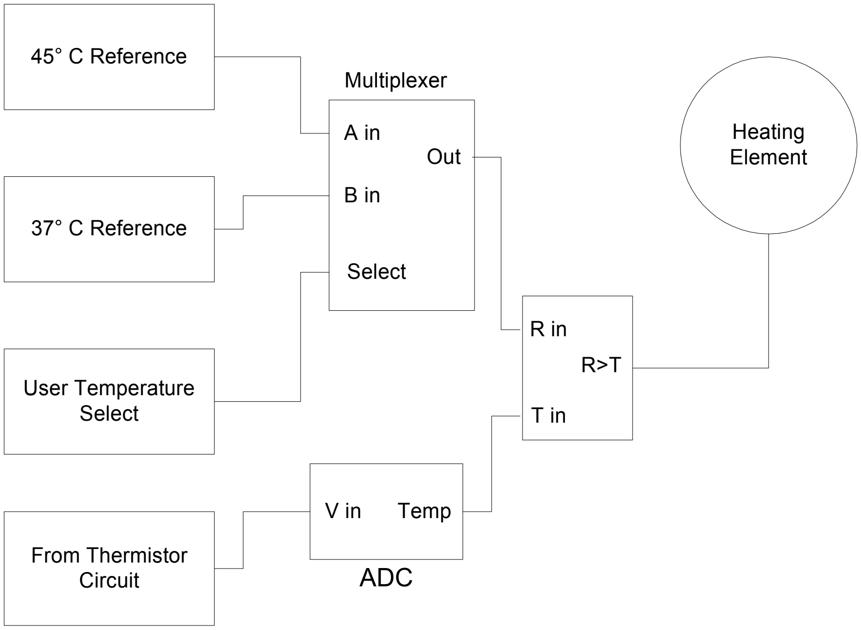

Figure 7. Functional diagram of the digital temperature control circuit.

The digital system needs a clock to periodically sample the temperature voltage. This clock can be used along with a counter to implement a timer to alert the doctor when the probe surface has been in contact with the patient's skin for 5 seconds. The end of the 5 seconds can be easily signaled with lighting a light emitting diode. A relatively small amount of digital logic will be need to be added to the major functional parts to make sure the system works correctly, and so the inputs that come from the outside of the device (e.g. buttons) will correctly communicate their intent to the digital circuitry.

Management Plan

We will test both a new and a relatively old battery to see if battery age has an effect on the heating ability. If it is ultimately determined that even the new source is not acceptable, we will have to look at using an alternate power source. If this were the case, we would ask Dr. Backonja for his preferences before deciding on an alternate power source.

Upon completing a prototype as a proof-of-concept, components of different modification may be tested in an attempt to improve the design. Included in this area are the thermal mass and conductivity of metals with differing thickness. By trying the device on ourselves, we can get an idea of how warm the probe feels at the target temperatures.

The final aspect of our design will be to improve the safety of the device. Using a digital control circuit will make it easier to ensure safety. There are still some analog components (such as the thermistor) that must be designed in such a way to eliminate possibly harmful occurrences such as heating above 50°C.

Decreasing the size of the circuit and finding suitable casing are issues to be taken up after the prototype has been fully tested. Human testing procedures must also be obtained to determine the effectiveness of the design in an actual clinical setting.

Conclusion

This semester we brainstormed a number of paths to take and chose to implement a new design. The prototype consists of a digital temperature control circuit that controls heat transfer to the probe surface using a resistive heating element. The temperature at the probe surface is measured using a thermistor. To continue further, it is first necessary to test the prototype and determine any necessary changes. Once it is working correctly, we can begin testing probe modifications, and choose modifications based on heating and cooling times. We could then add a timer and work on other safety issues with the design.

Appendix A – Product Design Specifications

Thermal Probe for Neurological Examination

Version 8: May 2, 2001

Andrew Hoyord, Bern Jordan, David Manthei,
Dana Mueller, and Paul Victorey

Function

Doctors are now finding it necessary to test patients experiencing pain or numbness for neurological damage and warm/heat sensitivity by applying hot sensations to their skin. A device that heats up to a “warm” and “hot” target temperatures could be used by the physician as a prescreening method before a quantitative sensory test is recommended. This device should be convenient to use, and safe to apply to patients.

Client Requirements

The product should:

- Be safe and not burn patients; i.e. the temperature must never rise above 50°C
- Heat up to target temperatures of 38°C and 45°C relatively quickly (±1°C)
- Maintain the target temperature through several successive tests on the same patient
- Have a probe surface with an area of 4.0 cm^2
- Indicate when the probe surface has reached the target temperature
- Indicate when the probe has been applied to a patient’s skin for five seconds
- Be convenient to use and easy to clean with alcohol and/or soap and water
- Attach to a Welch Allyn ophthalmoscope/otoscope handle or some other common clinical-setting power source

Design Requirements

Physical and Operational Characteristics

Performance: The probe surface should heat from room temperature to 38°C and 45°C (±1°C) within 30 seconds.

The heating element should use minimal power from the battery.

The device should be able to run for 30 minutes on a single charge.

Safety:	The probe temperature must not exceed 50°C in any event (including user abuse and circuit element failure) The risk of electrical shock to user and patient must be minimized. A five-second timer should be used to alert physician to remove device from patient's skin. To minimize pathogen transmission, the probe should be able to withstand frequent washing with soapy water and alcohol The probe must be free of sharp edges, rough surfaces, or spaces that would allow for pinching
Accuracy and Reliability:	The device should heat up to within 1°C of the specified target temperature. Once target temperature is reached, the temperature should remain constant until power is turned off. The five-second timer to limit patient contact should be accurate to within 0.1 s. With repeated use, the device should consistently attain target temperatures. Probe temperature (or temperature display) should not be dependent on battery strength.
Life in Service:	Device should be able to withstand frequent cleaning with soap water and alcohol. The device will be used on at most 15 patients per day, less than 4 minutes for each (max 60 minutes on per day). Two to ten years of use expected before replacement.
Shelf Life:	Indefinite if kept at room temperature free from high humidity and excessive dust.
Operating Environment:	The device will be used under normal indoor hospital/clinical conditions (20-25°C, 1 atm pressure, less than 60% relative humidity, and very little dust) by trained physicians. The probe will primarily be used on a patient's hands and feet. The skin may possibly be moist.

Ergonomics:	Size of probe should allow for full contact to the skin of the various areas of the body tested. Placement of operator controls should not cause undue strain in the hand, wrist, or fingers. Operation with only one hand is desired. The device will be kept relatively simple with as few buttons as possible. The buttons included will be clearly labeled as to what their specific function is. Any movable controls should only have slight frictional resistance. Controls should be adequately spaced apart and sized large enough to be recognized by touch.
Size and Shape:	The probe surface should be circular and 4.0 cm^2 in area. The entire device should roughly be the size of the normal head attachments to the battery pack (ophthalmoscope or otoscope heads). The size of any numerical display should be larger than 5 mm tall.
Weight:	The attachment should weigh no more than 225 g. The mass of the probe tip should be minimized to conserve battery power, yet large enough to maintain temperature when applied to the skin.
Materials:	All exterior materials must withstand alcohol and soap washing. The heated probe must be made of a non-corrosive material with high thermal conductivity. The body of the instrument should be made of a non-conducting material to prevent heat loss of the probe tip. Standard electrical components will be used for the circuitry.

Production Characteristics

Quantity:	One prototype device for client's use, possibly more if successful design.
Target Product Cost:	The attachment should cost no more than existing attachments for eye and ear testing which run $100-150. The prototype may cost up to $300.

Miscellaneous

Standards and Specifications:	FDA standards applying to electrical, and electrical medical devices if the device becomes mass-produced. If it is just an experimental device, it is necessary to obtain an NIH human subjects protocol. These standards are yet to be found out.
Customer:	Customer requirements listed above.
Patient Related Concerns:	Patients will be concerned with the safety of the device.
Competition:	This device will be used to prescreen patients before recommending quantitative sensory testing; a battery of sensory tests that checks for temperature sensitivity and other stimuli. There exist large AC powered heated probes used for the same type of neurological exam the device will be used for. There exists no competition from Welch Allyn (they are not interested in producing a thermal probe for neurological examinations).

Appendix B – Prototype Temperature Control Circuit

The prototype was designed to heat a small metal probe surface to a target temperature and regulate it so that it stayed at that temperature. With this being the only goal in mind, a 5-second timer and a temperature display were not included. The prototype circuit is shown in Figure 1-A.

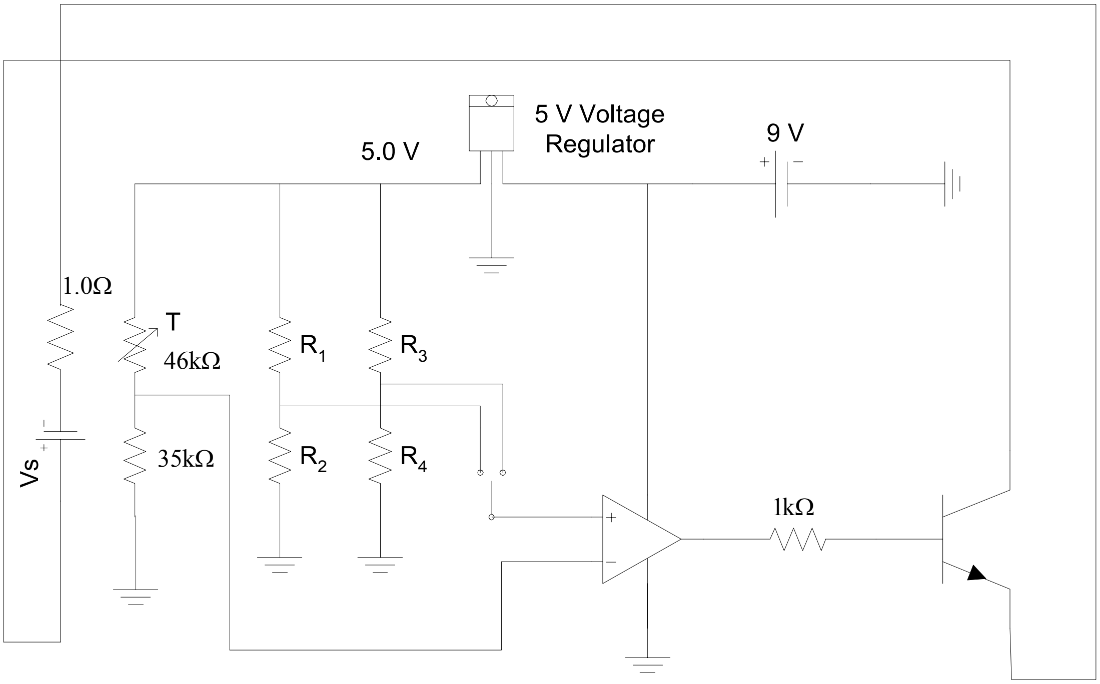

Figure 1-A. The circuit diagram for the prototype from last semester. The circuit runs on a 9 V battery, while the heating element (the 1.0Ω resistor near the left of the diagram) is on its own separate voltage source, Vs.

The theory of the control circuit was to allow current to flow through the heating resistor when the temperature of the probe surface was below the target temperature selected. The temperature of the probe was measured by a thermistor, and in the configuration above, which includes a Wheatstone bridge with potentiometers, the voltage at the negative input of the op amp will increase with a temperature increase. Reference voltages at the positive input of the op amp will coincide with the target temperature that each reference represents. The op amp will output a positive voltage when the reference voltage is higher than the voltage coming from the thermistor, and will output a zero voltage when the reference voltage is lower than the voltage coming from the thermistor.

When the op amp outputs a positive voltage, the NPN transistor will allow current to pass thru the heating resistor. When the op amp outputs a zero or negative voltage, the NPN transistor will not allow current to pass through the heating resistor. By this means, no heat is produced when the temperature measured is above the set target temperature.

The thermistor used is rated at 46 kW at room temperature, and is an NTC type (negative temperature coefficient), so the resistance is inversely proportional to temperature. The resistor chosen to balance the thermistor was 35 kW, because this was around the expected thermistor resistance at working temperatures. A 9 V battery was chosen to power the regulatory portion of the circuit and an AC/DC converter was chosen to power the heating element. The DC converter can supply 12 V at up to 1500 mA, which provides more than enough power to heat the probe surface quickly. The DC converter was a good power supply for the heating element because it could supply ample power but not die out like a battery could. The 12 V could be attenuated to some voltage Vs to achieve a lower power input to the heating element. The 9 V battery was easy to work with and, along with the 5 V regulator, could provide a constant voltage to the control elements.

The heating resistor used in the prototype was a 1.0 W power resistor that was encased in aluminum. This metal was intended for mounting the resistor, but the mounting material was removed and the thermistor was embedded in the remaining aluminum. A tiny (less than 1mm in diameter) glass encapsulated bead thermistor was placed into a hole drilled into the aluminum casing and glued into place with metal-filled epoxy to create good thermal contact between the thermistor and the metal that is heated by the heating resistor. The power resistor was then mounted to the end of a short length of fiberglass pipe. The pipe allowed for easy handling of the probe surface.

The reference voltages utilize a trim-pot circuit element, which is equivalent to two resistors in series, with a lead between the two resistors. Turning an adjustment screw changes the relative resistance of both equivalent resistors; either raising or lowering the voltage at the middle depending on which way the screw is turned.

The control circuit was built on a pre-fabricated breadboard to make building, testing, and troubleshooting easier. This meant that the entire prototype was much larger than the volume that the final design would fit into.

Appendix C – References

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