Thermal Probe for Neurological Examination

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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 heat 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 continues with a prototype designed last semester. The prototype consists of a resistive heating element on a handle and an analog temperature control circuit. Future work includes adding a timer to the prototype that alerts the user after the device has been in contact with a person's skin for five seconds. We need to choose a suitable material for both the probe surface and device housing. In the future, we would also like to digitalize the prototype, which in turn would add safety features specified by the client.

Problem Statement

Doctors are now finding it necessary to test patients experiencing pain or numbness for neurological damage and warm/heat sensitivity. Currently, there is no available portable device that a physician can use to apply hot sensations to a patient's skin. A device that heats up to target temperatures of 38°C and 45°C 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.

Background

Injuries and diseases affecting peripheral nerves, the spinal cord, or the brain can be diagnosed with heat and cold sensitivity testing. The severity of an injury or disease can be determined in part 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 Ad-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 in the hot range and 38°C is in the warm range (Konietzny, 1984). Temperatures above 50°C cause 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 a thermal warm/heat 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 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 use such an attachment.

Welch-Allyn Power Handle

The Welch-Allyn ophthalmoscope/otoscope power handle contains a 3.5 V rechargeable Nickel-Cadmium battery. The handle is made of stainless steel and textured to insure 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. The collar must be turned roughly one-quarter turn to reach the full battery potential. 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.

Prototype Solution

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

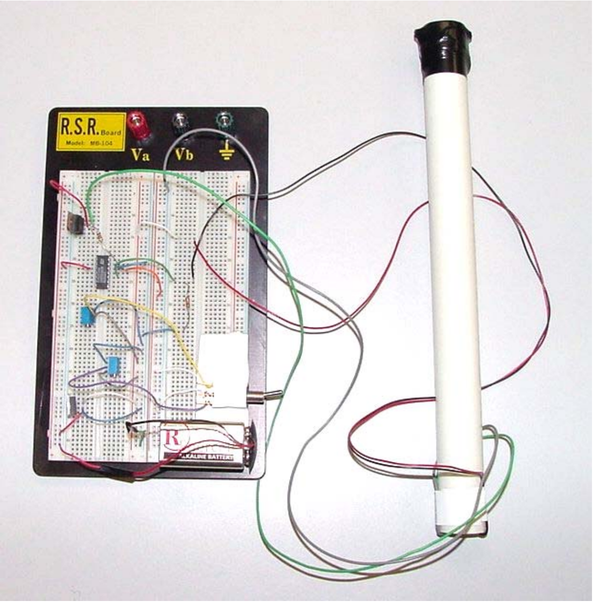

Figure 2. *The prototype device from last semester. The temperature control circuit is on the breadboard and the resistive heating element is at the top of the fiberglass pipe handle.*

The prototype consists of a resistive heating element 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 W 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 of the heating resistor changes, the voltage across the thermistor also changes. In the circuit, this voltage could be compared to reference voltages calibrated at specific temperatures. If the temperature of the resistor is higher than the target temperature, then no current will flow to the resistor (i.e. the probe will no longer heat up).

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 help prevent a physician from inadvertently burning a patient through excessive contact time.

Heating Element

The heating element is the most important part of the device. Based on research done in previous semesters, resistive heating seems to be the simplest, most inexpensive solution. 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 voltage times the current through the resistive element ($P = VI$). Because most of the power is dissipated by heat, regulating the current through the resistor allows accurate control of temperature.

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 cylindrical resistor on the back of the probe material 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 and resistant to corrosion. We will use a metal probe surface with high thermal conductivity to maximize 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 we have not yet determined the thickness of the metal.

Temperature Control

In the final design, we will use a thermistor to measure the temperature of the probe. The change in voltage caused by a temperature change 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 a small analog-to-digital converter and an integrated circuit (IC) would also 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 display the actual temperature on a liquid crystal display (LCD).

Timer Control

To prevent possible burns, a timer will be built into the device. 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. Alternately, we could 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.

Figure 2 shows an example analog timer circuit. When the physician first applies the probe to the patient's skin, the switch at B closes. After five seconds, the voltage reaches a level that causes a buzzer or light to alert the physician to remove the probe. The switch then closes at A and the capacitor would discharge through a small resistor (R_{small}), resetting the timer for another application to the patient. If we used a digital control circuit, we would use the clock circuitry to run a digital timer.

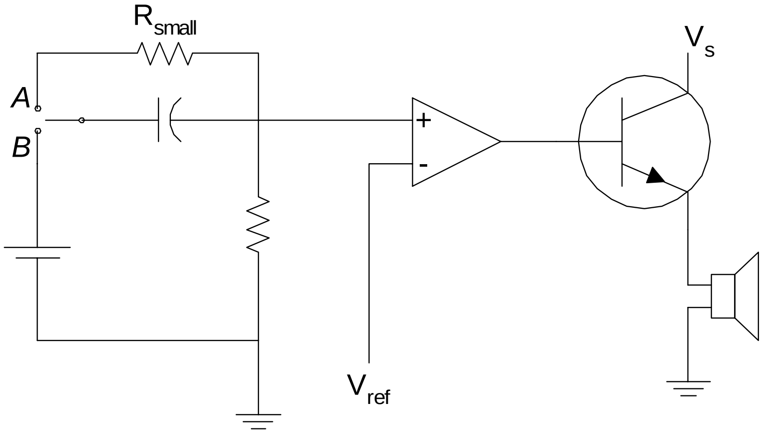

Figure 3. *An analog timer circuit. In this circuit, the resistors, capacitor, and reference voltage (V_{ref}) would be set so that the physician would be alerted five seconds after the switch was closed to B.*

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 relatively simple and inexpensive to manufacture. This design would be more flexible than a digital circuit 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. It may be possible to design the circuit with other safeguards.

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 relatively 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 probably not heat up at all.

Using an IC would make the circuit more complex however. 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.

Management Plan

In the short-term, we plan to repair last semester's prototype device and use it to test the Welch-Allyn battery and the method of resistive heating. We will test both a new and a relatively old battery to see if battery age has an effect on the heating ability. If neither battery works, 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.

The next phase of the design will involve constructing and testing the elements of the heat probe. We will test the thermal capacity 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. This will help us determine the optimal thickness and material type for the probe. If we cannot find a suitable commercially available resistor, we will construct a flat coil resistor made of Ni-Chrome wire to heat the probe. The flat coil resistor will have to be affixed to the probe material in such a way as to maximize thermal transfer.

The final aspect of our design will be to improve the safety of the device. We may choose to continue with an analog circuit design, in which case failsafe measures will have to be built in. Using a digital control circuit may make it easier to ensure safety; however, it may be difficult to implement.

A prototype digital device may end up having two separate power supplies: one for the heating element and the other for the digital circuit. This would make it easier to implement the digital control because we would not need to use a special low-power IC.

Conclusion

So far this semester we brainstormed a number of paths to take and chose to continue with last semester's prototype. The prototype consists an analog temperature control circuit that transfers heat to the probe surface using a resistive heating element. The temperature at the probe surface is measured using a thermistor. To continue, it is first necessary to get the prototype working. Once it is working correctly, we can begin testing probe materials, and choose a material based on its heating and cooling times. We would then add a timer and hopefully digitalize the circuit.

Appendix A – Product Design Specifications

Thermal Probe for Neurological Examination

Version 7a: February 21, 2001

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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. Alternately, some mechanical method of preventing burns may engage after five seconds. 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 fairly 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 should 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 probe portion of the device that is to get hot (the thermal probe) should 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.
Aesthetics, Appearance, and Finish:	The device will most likely be black in color, similar to the ophthalmoscope head, and it should not have any sharp protrusions. The device should be pleasing to the eye. Device housing should be non-slippery.

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 very 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.

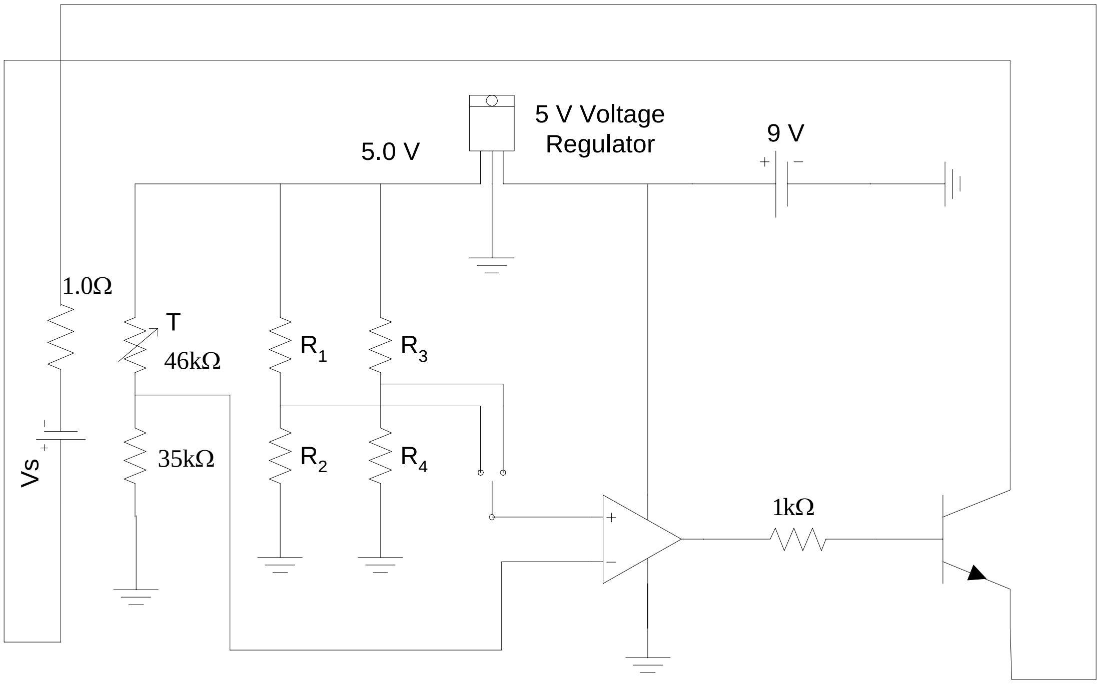

Figure 1-A. *The circuit diagram for the prototype from last semester. The circuit runs on a 9 V battery, while the heating element (the 1.0Ω resistor near the left of the diagram) is on its own separate voltage source, Vs.*

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, 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 a negative temperature coefficient type, 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 1 mm 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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