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Intracranial temperature and pressure measurement: In vitro temperature sensing characteristics of the dual sensing element *

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Abstract— **A pressure sensor has been used to measure temperature concurrently. We have designed, and characterized the measurement of temperature from the same sensor to allow simultaneous monitoring of intracranial temperature and pressure. The temperature measurement has a sensitivity of 85.08 mV/°C across the measurement range 20-45 °C. The time constant of the temperature sensor is 150 ms. We have evaluated the accuracy of the temperature measurement and the long term drift of 13 sensors over 28 days. The mean difference of the temperature measurements from the reference measurements was less than 0.2 °C.**

I. Introduction

Post traumatic hyperthermia is commonly seen in patients of traumatic brain injury (TBI) and is known to have a negative impact on patient recovery [1, 2]. In the acute phase following an insult, even small elevations in brain temperature can result in perturbations in the metabolic, inflammatory, circulatory and neural functions of the brain which ultimately lead to brain damage [3]. A recent study of the effects of mild hyperthermia in rats with mild TBI found significant increases in contusion volume and neuronal damage in the brains of rats held at 39 °C for 15 minutes prior to trauma and again at 39 °C for 2 hours following trauma [4]. Elevated brain temperatures, in excess of 40 °C, have been shown to cause damage to neural cells, glial cells and endothelial cells as well as cerebral microvessels [5].

The main aim of the early treatment of TBI is to avoid or limit the extent of secondary brain injury [6] and, to this effect, rigorous control of normothermia is recommended [7]. Increasingly, emphasis is being placed on the value of intracranial temperature monitoring for patients of traumatic brain injury. Patient outcomes are improved when brain temperature is used to guide therapeutic management [8].

The European Brain Injury Consortium (EBIC) guidelines advocate the use of invasive temperature measurement in all TBI patients requiring ventilation, stating the importance of maintaining normothermia [8]. Therapeutic hypothermia has been suggested to improve TBI patient outcomes [9, 10] and, during such therapy, brain temperature monitoring should be used to control the cooling [11]. It is also beneficial to monitor brain temperature during the rewarming period, in order to control the rate of warming and to prevent sudden increases in temperature which may lead to increased intracranial pressure (ICP) [3, 12].

Raised ICP is another common secondary factor of TBI and while the relationship between intracranial temperature and ICP is complex, increases in ICP have been associated with elevated intracranial temperature [13]. Raised ICP, also, has profound effects on the patient outcome and the importance ICP monitoring in TBI patients is well recognized. Guidelines provided by the Brain Trauma Foundation recommend the placement of an ICP monitor in "all salvageable patients" suffering from a substantial TBI [7]. In such cases the benefits of an invasive monitoring device are deemed to outweigh the risk. A single intracranial sensor which measures temperature, in addition to pressure, would provide valuable information for critical care monitoring and therapeutic intervention.

Recent studies highlight the importance of measuring brain temperature throughout the critical period following TBI for the reason that rectal temperature (Tr) and tympanic temperature (Tt) measures may lead clinicians to underestimate brain temperature when the brain is susceptible to secondary insults [13, 14]. In hyperthermic TBI commonly brain temperature is significantly elevated with respect to core body temperature [13] and has been shown to be between 0.5 °C to 1 °C higher than rectal temperature (Tr) [15, 16]. In some severe cases, however, the reverse is true with brain temperatures lower than core temperatures [14, 17]. Tympanic temperature (Tt) has been shown to differ significantly from brain temperature with a mean gradient of 0.64 °C [14]. The temperature gradient between the cortex and central brain can be as great as 0.9 °C and thus the location of the implanted probe is an important consideration when taking intracranial temperature measurements [18].

Several commercial intracranial temperature sensors are available. Some function as stand-alone temperature sensing devices while others form part of a multimodal measuring device. In those devices that measure multiple parameters the temperature sensor is an independent element, usually a thermistor or thermocouple. Stand—alone temperature sensors include the Neurotrend temperature probe (Codman&Shurtleff), a thermocouple element with reported accuracy of 0.1 °C and the Licox temperature sensor (Integra Neurosciences) a thermocouple element of 0.8 mm diameter with reported accuracy of 0.2 °C.

Multi-parameter monitoring probes include the Camino 110-4BT (Integra Neurosciences), a 1.35 mm fiber optic pressure and temperature sensor with reported accuracy of 0.3 °C in the measurement range 30 °C to 40 °C, the Neurovent-P Temp ICP probe (Rehau) with 0.5 mm diameter

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by 5.5 mm length thermistor element and reported accuracy of 0.1 °C, the Neurotrend Multi-parameter sensor (Codman&Shurtleff), of 0.5mm diameter comprising a thermocouple (distal to the tip of the probe) with reported accuracy of 0.1 °C and each of a pH, a PCO_2, and a PO_2 optical sensor.

A recent study reported development of a temperature sensor for integration with a multi-modal smart catheter [19]. In this study the authors demonstrated a time constant of 180 ms, a resolution of 0.06 °C and a mean accuracy of 0.1 °C after 5 days of continual recording from 20 sensors.

We report the development of temperature measurement from a commercially available 2 French (0.67 mm) ultra-miniature pressure sensor tip catheter. The same sensing element is used to measure both pressure and temperature. The ability of the single sensor to detect two important physiological measures is beneficial in applications such as TBI where the information gained from temperature and pressure monitoring is valuable and where the small dimensions of the sensor are of merit.

The Millar solid state pressure sensor is a silicon chip with two diffused piezoresistive strain gauges, each connected to a resistive wire. One side of the gauge is coupled to a moveable diaphragm which is in contact with the measurement environment. When the pressure experienced by the sensor changes, the diaphragm moves in response to the change and one resistive wire stretches with respect to the other causing a differential change in resistance.

Temperature variations, experienced by the sensor, cause the values of both piezoresistive elements to move in the same direction. This behavior offers the ability of the sensor to detect temperature at the same time as making conventional pressure measurements. The sensor was connected to a custom built circuit that amplifies the temperature related change in gauge resistance.

II. Design

A. Principle of Temperature Measurement

The resistances of the two piezoresistive elements of the Millar solid state pressure sensor increase with an increase in temperature. It is by this mechanism that temperature measurements are made from the Millar sensor.

B. Circuit Development

The Millar strain sensor is a half bridge. A circuit was designed and built to detect changes in the resistance of the sensor elements caused by changes in temperature.

The sensor was connected as the high side of a Wheatstone bridge circuit with the low side formed from two resistors with a ppm rating of 5. The common mode voltage across the full bridge was used as the measure of temperature. Common mode voltage increases proportionally with an increase in environmental temperature. This relationship is approximated by a linear model, as illustrated in Fig 2.

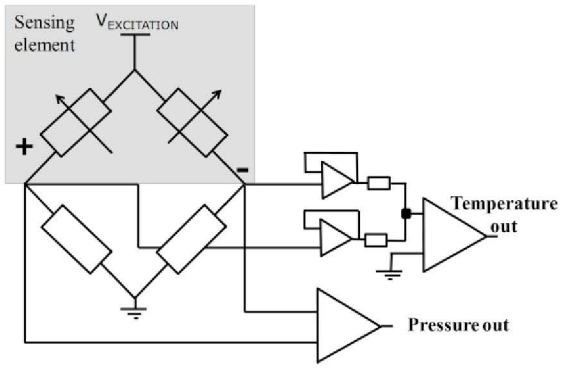

Figure 1. Schematic illustrating the method used to obtain temperature measurement from the Millar pressure sensor. Temperature is a common mode output while pressure is a differential output.

A summing circuit added the voltages of each side of the bridge and this was subtracted from a reference level to accommodate amplification. Suitable amplification (201 times) was introduced to map the temperature range 20 °C to 45 °C to an output voltage of 0 to 2.4 V.

C. User Interface

Data from the Millar sensors and reference probe were logged using a program written in LabVIEW, via National Instruments USB 6210 data acquisition cards (with stated accuracy of 88.5 μV). Using the linear equations established during calibration, temperature calibration coefficients for each sensor were entered into the program to allow voltage output from the temperature circuits of the Millar probes to be converted into temperature measurements.

Provision was made for continual measurements to be taken via a while loop with user control (via the user interface) of the measurement frequency as well as the number of terms used in averaging. Voltage and temperature data from the Millar sensors, as well as temperature data from the reference sensor, were output to a spreadsheet file with each execution of the loop.

III. Experimental Results

Calibration data were obtained by placing the thirteen Millar sensors in a water bath held a constant temperature for 40 minutes at each of 30 °C, 33 °C, 36 °C, 39 °C and 42 °C. The temperature of the bath was measured using the reference probe; GE Sensing CSP60BA103M-H/2-90, a 4-wire Thermistor Probe (calibration traceable to IST-90) interfaced to Fluke 1504 Digital Thermometer Readout (calibration traceable to NIST) with a combined accuracy of at least 0.004 °C. Voltage output from the temperature sensing circuit of each Millar probe was recorded along with the reference temperature.

A. Sensitivity

The Millar sensors display strong linearity with respect to temperature demonstrated by a correlation coefficient of 0.9999. The sensitivity of the sensors is 85.08 mV/ °C as shown in Fig 2.

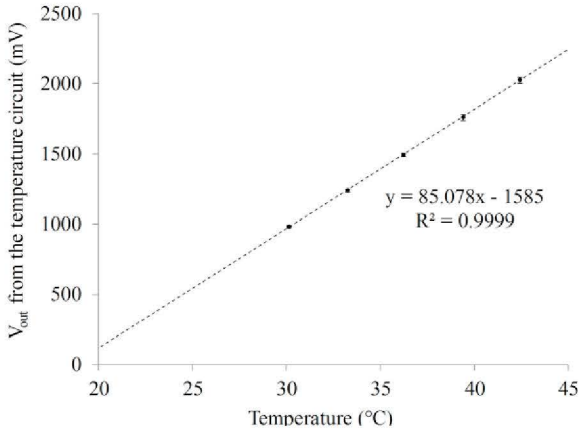

Figure 2. Sensitivity of the Millar sensor to temperature within the measurement range 20 °C to 45 °C. Common mode voltage across the sensor bridge plotted against sensor environment temperature. The sensors exhibit a linear relationship with changes in temperature.

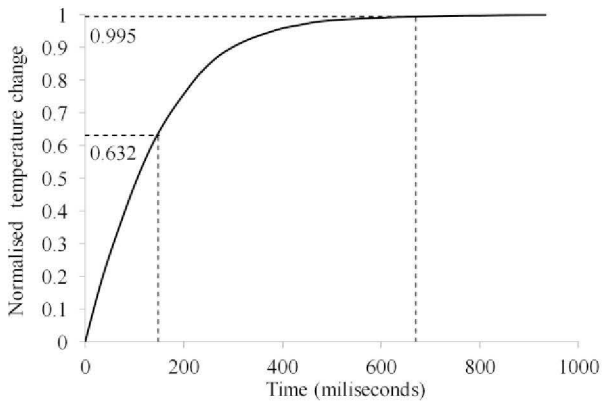

Figure 3. Time response: The Millar sensors were moved from a water bath held at 21°C to a water bath held at 41°C. The time constant was found to be 150 ms while the response time was found to be 670 ms.

B. Time Response

The time response of the sensors was determined by transferring the Millar sensors from one temperature bath held constant at 21 °C to another temperature bath held constant at 41 °C. The temporal response of the sensors was described by both response time and time constant. The response time is the time it takes for the sensor to measure within 0.5 % of its final asymptotic temperature following a step change. The time constant is the time it takes for the sensor to measure 63.2 % of its final asymptotic value. The response time of the Millar sensor's temperature response was found to be 670 ms and the time constant was found to be 150 ms. Fig 3 demonstrates the sensor's temporal response to the step change in temperature.

C. Accuracy and long-term drift

13 sensors were held in a water bath controlled to 38 °C for 28 days and data were recorded. The LabVIEW program was configured to take temperature readings every second and record the 20 point moving average continually at 10 minute intervals.

The temperature measurement taken from each sensor was compared to the measurement from the reference temperature sensor. Fig 4 shows the drift characteristics of the 13 sensors over the 28 day period. Table 1 demonstrates the error in the temperature measurement for each sensor at the end of day 5, 10, 15, 20, 25 and 28.

The accuracy of a clinical thermometer is specified in BS EN 12470 the international standard governing the performance criteria of clinical thermometers. Part 4 specifies that a clinical thermometer should have a maximum permissible error of 0.2 °C within the required measuring range of 25 °C to 45 °C [20].

The accuracy of all 13 sensors remained within the limits required by BS EN 12470-4 for the first 15 days. The mean temperature difference on day 15 was 0.08 °C. During the remainder of the test the accuracy of four sensors drifted outside of the requirement: By day 20, one sensor; by day 25, three sensors; and by day 28, four sensors had exceeded an error of 0.20 °C. The mean temperature difference on the 28th day was found to be -0.12 °C.

The results suggest that, as is, the sensors will be appropriate for acute monitoring and short term use of up to 15 days. If the sensor is to be specified for use up to 28 days those sensors with poorer drift characteristics will need to be identified and rejected. It may be possible to predict sensors with poorer drift characteristics by studying the pattern of drift over a five day period.

TABLE I. ERROR IN TEMPERATURE MEASUREMENT AT THE END OF DAY 5, 10, 15, 20, 25 AND 28

Sensor	Temperature Measurement Error (°C)					
	Day 5	***Day 10***	***Day 15***	***Day 20***	***Day 25***	***Day 28***
1	0.02	0.01	0.00	-0.01	0.03	0.04
2	-0.05	0.02	-0.02	-0.03	-0.05	-0.04
3	0.02	0.00	-0.05	-0.08	-0.07	-0.08
4	-0.06	-0.05	-0.15	-0.20	-0.21[a]	-0.22[a]
5	-0.02	-0.01	-0.07	-0.10	-0.10	-0.10
6	-0.04	-0.04	-0.09	-0.11	-0.15	-0.15
7	-0.02	-0.02	-0.07	*-0.14*	-0.16	-0.15
8	-0.09	-0.11	-0.18	-0.20	-0.23[a]	-0.25[a]
9	-0.01	0.00	-0.04	-0.08	-0.10	-0.11
10	0.02	0.04	0.02	0.00	-0.01	0.01
11	-0.09	-0.10	-0.18	-0.23[a]	-0.27[a]	-0.28[a]
12	-0.01	0.01	-0.03	-0.04	-0.03	-0.03
13	-0.09	-0.08	-0.13	-0.17	-0.20	-0.21[a]
mean	**-0.03**	**-0.03**	**-0.08**	**-0.11**	**-0.12**	**-0.12**
max	**-0.09**	**-0.11**	**-0.18**	**-0.23[a]**	**-0.27[a]**	**-0.28[a]**
min	**-0.01**	**0.00**	**0.00**	**-0.01**	**-0.01**	**0.01**
std dev	**0.02**	**0.04**	**0.02**	**0.00**	**0.03**	**0.04**

a. Error exceeds limits specified by BS EN 12470-4 Standard for Clinical Thermometers

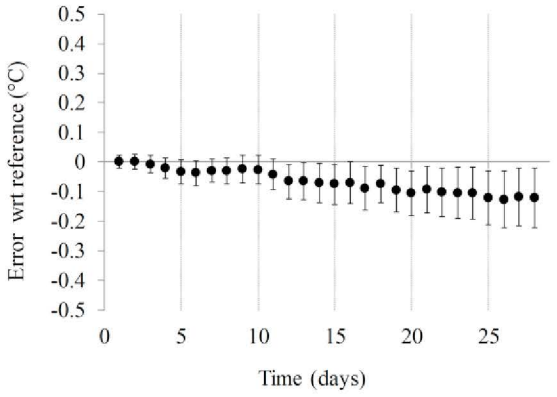

Figure 4. Long term drift: Mean error in the temperature measurement of 13 sensors compared to the reference sensor over 28 days.

IV. Conclusion

In this work we have developed and characterized temperature measurement from a commercially available clinical pressure sensing catheter. Temperature measurements made with the pressure-temperature sensing catheter are accurate and reliable within the range 20 °C to 45 °C. Our bench testing has demonstrated that the temperature measurement of the sensor is appropriate for acute and short-term monitoring of up to 15 days. Drift testing over 15 days demonstrated errors of less than 0.2 °C when the sensors were compared to the NIST-traceable reference probe. Future work will involve developing methods to identify sensors with poorer drift characteristics in order to select those which will maintain an accuracy of ± 0.2 °C over a 28 day period. Future work will also involve the implantation of a miniaturized circuit within a telemetry device into a rat in order to study the in vivo characteristics of the temperature sensor.

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