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Accuracy and stability of temperature probes for intracranial application

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Abstract

Intracranial temperature measurement may play a pivotal role for prognosis and treatment of neurological and neurosurgical patients. For reliable clinical application, accurate temperature readings are therefore necessary. We present an independent in vitro study investigating the accuracy and stability of three temperature probes. Eight Neurovent-P Temp (RN), eight Licox temperature sensors (LT) and eight Neurotrend sensors (NT) were placed into a water bath. The temperature was increased in 3 °C increments from 30 to 42 °C before (accuracy test day 0) and after (accuracy test day 5) a long-term stability test run at 37 ± 0.2 °C. The accuracy tests revealed deviations of <0.25, <0.2 and >0.4 °C for the RN, NT and LT probes, respectively, when compared to the reference measurement by a precision Pt100 temperature measuring instrument. All sensor types showed stable readings over the course of 120 h. The high variability of LT probes was due to a malfunctioning Licox monitor. Excluding these values reduced deviation below 0.21 °C the standard deviation at each temperature step was below ±0.08 (RN, NT) and ±0.12 (LT), laying within the range provided by the manufacturer (RN, NT: ±0.1; LT: ±0.2). In general, RN, NT and LT temperature measurement is reliable, but malfunctioning parts may lead to false interpretation of temperature readings. Therefore, validation of temperature probes to a reference temperature prior to clinical use is recommended.

Keywords: Temperature sensor, drift, accuracy; Neurotrend, Licox; Neurovent-P

1. Introduction

A constant brain temperature is critical for normal brain function. Reduced brain temperature due to controlled hypothermia has been shown to be neuroprotective following hypoxia, ischemia and traumatic brain injury (TBI) [e.g. (Agnew et al., 2003; Quinones-Hinojosa et al., 2003; Suehiro et al., 2003)]. In contrary, injury-induced decreased brain temperature has been associated with poor outcome in severe head-injured patients which is partially due to reduced cerebral blood flow (CBF). In both cases, monitoring of intracranial temperature is crucial and can be used to guide therapy or to detect regional ischemic events leading to a therapeutical intervention in patients with e.g. subarachnoid hemorrhage (Metz et al., 1996; Nara et al., 1998; Schwab et al., 1998; Soukup et al., 2002a). The temperature gradient between brain and core is mostly +0.3 and +2 °C (Mellergard, 1995; Rumana et al., 1998; Schwab et al., 1997; Tokutomi et al., 2003). In patients with poor prognosis following head injury (Soukup et al., 2002b) or prior to brain death (Fountas et al., 2003) core temperature is seen to exceed brain temperature. Thus, core body temperature does not reflect reliably brain temperature and cannot be used to guide therapy (cooling, detection of ischemia) after TBI. In many intensive care units, brain temperature is recorded by means of multi-parameteric neuromonitoring and several companies introduce new monitoring probes combined with a temperature sensor. Despite the information about the specification of temperature sensors provided by the manufacturer for their product, there is no independent confirmation and especially no long-term stability data available. Therefore, we report in this study about the accuracy, reliability and long-term stability of current commercially available temperature probes constructed for intracranial application.

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2. Materials and methods

2.1. Temperature probes

For each of four experimental setups, two new Neurovent-P Temp ICP probes with integrated temperature measurement (RN, Rehau AG, Rehau, Germany), two new "Licox" temperature sensors (LT, Integra Neuroscience Limited, Hamphire, UK) and two new Neurotrend sensors which passed the calibration process (NT, Codman Neurotrend Multiparameter sensor, Codman&Shurtleff, Raynham, USA) were used. The technical basis of the temperature probes LT and NT is a thermocouple element. In this probe, a small temperature-dependent voltage is generated at the junction of a pair of insulated wires of different metal (thermocouple effect). Accurate readings are obtained by referencing the generated voltage against another thermocouple whose temperature is controlled. In RN a thermistor works on the basis of a polycrystalline semiconductive resistor with negative temperature coefficient. The manufacturers report an accuracy of ±0.1 (NT, RN) and ±0.2 °C (LT) at body temperature.

The RN thermistor element (∅ 0.5 mm, length 5.5 mm) is located along with a pressure transducer at the tip of a 2.3 mm diameter catheter. In the NT, three optical sensors (pH, pCO_2, pO_2) and a thermocouple which is located most distally from the tip of the probe are integrated. The complete NT catheter probe is 17.5 mm in length and 0.5 mm in diameter. The LT temperature probe is one single thermocouple probe with a diameter of 0.8 mm. Data of all catheters as well as the used monitors and interfaces (cables) were provided by each manufacturer.

2.2. Study protocol

For each running series, a set of three types of probes (six sensors in total) was placed into a water bath (Haake R3, Fison, Germany). The probes were fixed in a round plastic tube which allowed quick temperature exchange and minimised water turbulence. The water bath temperature was monitored by means of a precision temperature measuring instrument (P555, temperature probe PT100, Dostmann electronics GmbH, Wertheim, Germany) over the complete monitoring time. This temperature reading was considered as reference temperature for all probes and throughout the study.

For each experimental setup, the catheter probes were first placed into a water bath consisting of a buffer solution (pH 7.4) which was initially kept at 37 ± 0.2 °C. Afterwards, the water bath was cooled down to 30 °C by adding cold buffer solution and readings of all sensors were taken after temperature reached a stable state. Thereafter, using a stepwise increment of 3 °C, temperature readings of all probes were taken at 33, 36, 39 and 42 °C water bath temperature on day 0 (accuracy test day 0, see Fig. 1). For each temperature step, one reading for all sensors was taken simultaneously after equilibration of temperature was obtained according to the reference probe reading (within 5 min). For testing the stability of temperature readings, sensors were left in the water bath at 37 °C for 120 h (stability test). Thereafter, the accuracy test from 30 to 42 °C in 3 °C increments was repeated (accuracy test day 5) (Tables 1 and 2).

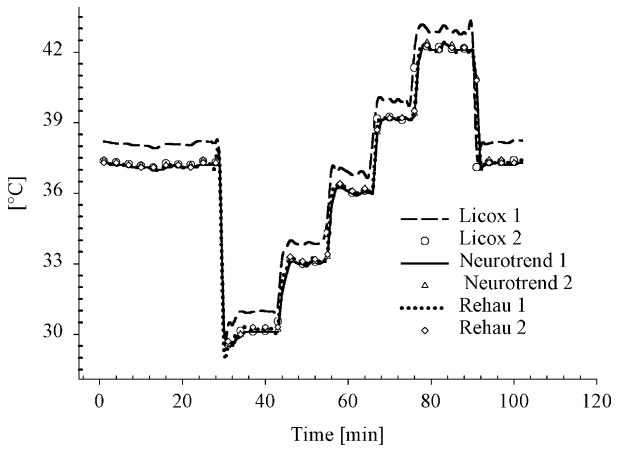

Fig. 1. Example of online measured temperature values collected by ICU-Pilot software (CMA/Microdialysis, Sweden) from two Licox, two Neurotrend and two Neurovent-P Temp sensors. Water bath temperature was increased from 30 to 42 °C in steps of 3 °C. Note the quick response to temperature changes by all probes and the consistently higher reading of one Licox sensor (Licox 1).

2.3. Licox sensors

LT catheters revealed unexpectedly larger deviations from the target temperatures compared to the other sensors. Therefore, six LT temperature sensors were further evaluated to pin-down the source of the variation. All three hardware parts, the Licox temperature sensors (probes #1–6), Licox monitors (monitors 1 and 2) and connecting cables (wires A

Table 1
Accuracy test of temperature measurement on day 0

Ref temp	RN	LT	NT
30.05 ± 0.03	30.29 ± 0.06	30.56 ± 0.45*	30.19 ± 0.08
32.97 ± 0.03	33.16 ± 0.05	33.46 ± 0.46*	33.10 ± 0.05
35.99 ± 0.04	36.15 ± 0.06	36.47 ± 0.44*	36.09 ± 0.07
39.00 ± 0.04	39.19 ± 0.03	39.54 ± 0.47*	39.18 ± 0.06
42.00 ± 0.03	42.13 ± 0.05	42.54 ± 0.44*	42.19 ± 0.06

A reference temperature probe (Ref temp; PT100 sensor) was placed in a water bath together with three types of temperature probes (RN: Rehau Neurovent-P Temp, LT: Licox temperature sensor, NT: Neurotrend) which are clinically used for multi-parameteric neuromonitoring in patients. They were exposed to increasing water temperature ranging from 30 to 42 °C. Data are displayed in degree Centigrade and as mean ± S.D.. At each temperature step, a one-way ANOVA on ranks with post-hoc testing of the reference temperature probe against all other temperature probes was used for statistical analysis. Note that all ANOVAs were significant at $P < 0.01$. Asterisks (*) indicate post-hoc tests between reference probe and all other probes ($P < 0.05$).

Table 2
Accuracy test 5 days after placing probes in a water bath at 37 ± 0.2 °C

Ref temp	RN	LT	NT
30.06 ± 0.03	30.26 ± 0.05	30.49 ± 0.38*	30.18 ± 0.04
32.99 ± 0.04	33.14 ± 0.06	33.40 ± 0.42*	33.11 ± 0.06
36.00 ± 0.04	36.15 + 0.07	36.45 ± 0.43*	36.13 ± 0.08
39.02 ± 0.03	39.16 ± 0.04	39.50 ± 0.43*	39.18 ± 0.07
42.01 ± 0.04	42.14 ± 0.04	42.49 ± 0.43*	42.18 ± 0.06

The accuracy test was performed exactly as on day 0 (see Table 1, method section). All Data are displayed in degree Centigrade and as mean ± S.D.. At each temperature step, a one-way ANOVA on ranks with post-hoc testing of the reference temperature probe against all other temperature probes was used for statistical analysis. Note that all ANOVAs were significant at $P < 0.01$. Asterisks (*) indicate post-hoc comparison between reference probe and other probes ($P < 0.05$).

and B), were permutated and temperature was measured in a 35 °C water bath. For each measuring condition, data were collected every 20 s for 5 min and provided as mean ± S.E. deviation in Table 3.

2.4. Data collection and analysis

Data of all monitors connected to the sensors were transferred via RS-232 ports to a RS-232/USB Hub (Edgeport, InsideOut Networks, Austin, Texas, USA) and collected in a time-locked PC using a data collecting software (ICU-Pilot, CMA Microdialysis, Solna, Sweden). Data are presented as mean ± S.D.. Statistical analysis (one-way ANOVA with post-hoc analysis, Mann–Whitney *U*-test, Pearson- and Spearman correlation) was performed by SPSS Software (Release 11.0.1, SPSS Inc., Illinois, USA). A *P*-value of <0.05 was considered to be statistically significant for one-way ANOVA and Mann–Whitney *U*-test and $P < 0.01$ for Pearson- and Spearman correlation.

3. Results

3.1. Accuracy tests

At 37.03 ± 0.03 °C reference temperature, RN measured 37.15 ± 0.06 °C, LT 37.55 ± 0.49 °C ($P < 0.05$ versus reference temperature) and NT 37.14 ± 0.09 °C. The accuracy tests for 3 °C temperature increments from 30 to 42 °C are shown in Fig. 1 and Table 1 (day 0) and in Table 2 (day 5). Initially, deviation from the reference probe reading was <0.25 °C for RN and <0.2 °C for NT sensors in the temperature range between 30 and 42 °C, while the deviation for LT probes was >0.5 °C with a high standard deviation. A one-way ANOVA on ranks revealed a significant effect ($P < 0.01$) for all temperature increments. Post-hoc analysis showed a significant difference ($P < 0.05$) at all temperature steps between the reference temperature and the LT sensors only. For the second accuracy test after 120 h in the water bath, statistical analysis showed a significant deviation for the LT sensors only. Temperature deviations concerning the accuracy test on day 5 were <0.2 °C for RN and NT and still >0.4 °C for LT with high standard deviation.

3.2. Stability test

Comparison of temperature readings from each sensor on day 0 (accuracy test 0) with measurements after 120 h in the water bath (accuracy test 5) revealed no significant drift in temperature readings, indicating high stability for all three sensor types: LX temperature measurement slightly decreased at 0.08 ± 0.03 °C, while temperature readings increased in NT sensor at 0.01 ± 0.03 °C and RN 0.005 ± 0.07 °C. The temperature readings from all probes correlated significantly with the reference temperature using a Pearson correlation ($r^2 = 0.99$, $P < 0.001$) as well as using a Spearman rank correlation ($r^2 = 0.977$ for RN, $P < 0.01$; $r^2 = 0.970$ for LX, $P < 0.01$; and $r^2 = 0.974$ for NT, $P < 0.01$).

Table 3
Six LT probes were connected to each of two LT monitors (LT monitors 1 and 2)

LT probe	Ref temp	LT monitor 1		LT monitor 2	
		Wire A	Wire B	Wire A	Wire B
#1	34.95 ± 0.10	35.89 ± 0.06	36.25 ± 0.12	35.42 ± 0.08	35.41 ± 0.09
#2	35.04 ± 0.01	35.77 ± 0.03	35.86 ± 0.04	35.13 ± 0.03	34.98 ± 0.02
#3	34.99 ± 0.05	35.82 ± 0.03	35.92 ± 0.04	35.12 ± 0.04	35.12 ± 0.02
#4	34.94 ± 0.00	35.64 ± 0.04	35.97 ± 0.03	34.97 ± 0.04	34.88 ± 0.06
#5	34.86 ± 0.08	36.24 ± 0.05	35.94 ± 0.05	35.17 ± 0.05	34.97 ± 0.03
#6	34.82 ± 0.03	35.92 ± 0.02	35.93 ± 0.06	35.05 ± 0.04	34.96 ± 0.03
All (1–6) connecting wire A	34.93 ± 0.06	35.88 ± 0.20		35.14 ± 0.16**	
All (1–6) connecting wire B		35.98 ± 0.14		35.05 ± 0.19##	

Additionally, connection wires (A and B) were interchanged. Temperature readings (°C) of each probe (#1–6) on each LT monitor are shown (average of 15 values taken during 5 min). Note that LT monitor 1 showed temperature readings in mean 0.96–1.05 °C higher compared to the reference temperature, whereas monitor 2 showed 0.12–0.21 °C higher temperature readings. Symbols indicate a significant difference between temperature readings from monitor 1 and from monitor 2 using connecting wire A (** $P < 0.01$) or connecting wire B (## $P < 0.01$). There were no significant differences between the readings from the two wires when connected to monitor 1 as well as to monitor 2, Statistical analysis was performed by means of Mann–Whitney *U*-tests.

3.3. Licox sensors

To find an explanation for the higher variability found with LT sensors, six of six LT probes were randomly connected to each of the two LT monitors (LT monitors 1 and 2) and tested at a reference temperature of 34.93 ± 0.06 °C. Furthermore, connection wires (A and B) were additionally switched. LT monitor 1 showed temperature readings of the single probes 0.7–1.38 °C (on average 0.95–1.05 °C) higher than the reference temperature, while deviations were <0.5 °C (on average 0.12–0.21 °C) if sensors were connected to LT monitor 2 (Table 3). The connecting wires A and B had no significant effect on the temperature readings.

4. Discussion

In this experiment, temperature measurements with RN and NT probes have been reliable in physiological range of 30–42 °C. Similar results have been found for the RN probe previously (Morgalla et al., 1999). The temperature probe of the Paratrend 7 sensor which is comparable to the NT showed a good correlation to a reference temperature probe ($P < 0.0001$) (Zauner et al., 1995). In our study, temperatures measured with the NT probe also correlated significantly with the reference temperature ($r^2 = 0.99$; $P < 0.01$) and remained stable over 120 h. Identically to our findings, slightly higher readings (0.1–0.3 °C) were found for the Paratrend 7 probe (Zauner et al., 1995). The readings from the LT sensors were also stable over time, but in contrast to the other probes LT sensors showed high deviations of temperature readings compared to the reference temperature. Such a deviation could be caused by three factors: a technical malfunction of probes, LT monitors and/or connecting wires. The very small difference in temperature readings comparing the two accuracy tests and between the two wires indicates that the connection to the monitors as well as the sensors themselves were working properly and showing accurately temperature changes. Thus, we concluded that one of the two monitors provided by the manufacturer for this study seems to be calibrated incorrectly, leading to increased temperature readings. This became only obvious because two monitors were used simultaneously in this in vitro experiment. An analysis of measurements from the correctly working LT monitor indicated a small deviation from the reference temperature comparable to the other sensors (see also Table 3). This result is, however, critical in terms of handling of high quality instruments in a clinical setup, suggesting routine validation to an independent reference probe at regular intervals.

A slight deviation of all parameters towards higher readings (0.1–0.2 °C) was found when comparing to the reference temperature. The manufacturer of the RN, NT and LT sensor reports accuracy of ±0.1 °C (RN, NT) and of ±0.2 °C (LT). Our in vitro data showed that the standard deviation of all types of temperature sensors was well within this given range (RN, NT: ±0.08; LT: ±0.12). The RN and NT probes show a slightly higher deviation from the reference temperature which might either be caused by the calibration by the manufacturer, a shift of the reference temperature probe towards lower readings due to thermal diffusion or by slightly higher readings of the other temperature sensors itself. It is known, that measured temperature decreases depending on the depth of the sensor introduced into the medium (Stone et al., 1997). Therefore, it is recommended to insert probes to a sufficient depth, which might be at least 1.5–2 cm as also proposed by Stone et al. (1997). In a clinical setup it is therefore important to insert sensors to comparable depths in each patient. In conclusion, all tested, clinically used temperature systems showed sufficient reliability and accuracy if calibration is correct, and therefore, could be applied to guide therapy or support prognosis in neurological and neurosurgical patients.

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