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Experimental Research

Brain oxygen monitoring: in-vitro accuracy, long-term drift and response-time of Licox- and Neurotrend sensors

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Summary

Background. Oxygen tension sensors have been used to monitor tissue oxygenation in human brain for several years. The working principals of the most frequently used sensors, the Licox (LX) and Neurotrend (NT), are different, and they have never been validated independently for correct measurement in vitro. Therefore, we tried to clarify if the two currently available sensors provide sufficient accuracy and stability.

Method. 12 LX oxygen tension sensors and NT sensors were placed into a liquid-filled tonometer chamber. The solution was kept at $37 \pm 0.2\,^{\circ}C$ and equilibrated with five calibration gases containing different O_2- and CO_2-concentrations. After equilibration, readings were taken for each gas concentration (accuracy test). Afterwards, the sensors were left in 3% O_2 and 9% CO_2 and readings were taken after 24, 48, 72, 96 and 120 hours (drift test). Thereafter, a 90% response time test was performed transferring sensors from 1% to 5% oxygen concentration and back, using pre-equilibrated tonometers.

Findings. All Licox oxygen probes [12] were used for this study. Two of 14 Neurotrend sensors did not calibrate, revealing a failure rate of 14% for NT. Oxygen tension during the accuracy test was measured as follows: 1% O_2 (7.1 mmHg): LX 6.5 ± 0.4, NT 5.3 ± 2.3 mmHg, 2% O_2 (14.2 mmHg): LX 12.9 ± 0.6, NT 12.1 ± 2.2 mmHg, 3% O_2 (21.4 mmHg): LX 19.8 ± 0.7, NT 19.4 ± 2.4 mmHg, 5% O_2 (35.8 mmHg): LX 33.4 ± 1.0 mmHg, NT 33.5 ± 2.9 mmHg, 8% O_2 (57.0 mmHg): 53.8 ± 1.5, NT 53.6 ± 3.3 mmHg. After 120 hours in 3% O_2 (21 mmHg), LX measured 19.8 ± 1.9 mmHg, NT 17.9 ± 4.7 mmHg. 90% response time from 1% to 5%/5% to 1% oxygen concentration was $129 \pm 27/174 \pm 26$ sec for LX, $55 \pm 19/98 \pm 39$ sec for NT.

Conclusions. Both systems are measuring oxygen tension sufficiently, but more accurately with LX probes. NT sensors read significantly lower pO_2 in 1% O_2 and show an increasing deviation with higher oxygen concentrations which was due to two of twelve probes. A slight drift towards lower oxygen tension readings for both sensors but more pronounced for the NT does not impair long-term use. NT measures pCO_2 and pH very accurately.

Keywords: Licox; Neurotrend; pO_2; drift; accuracy; response time; in vitro.

Introduction

Catheter probes designed to measure partial pressure of oxygen (pO_2) in human brain tissue have been in use for the last several years. They might support clinicians to receive an extended overview about pathophysiological conditions during critical episodes in neurological and neurosurgical diseases additionally to routine monitoring of ICP. Following head injury, pO_2 measurement in injured brain tissue has been evolved to a reliable method to monitor cerebral oxygenation, which can be substantially compromised due to reduced cerebral blood flow, brain swelling or increased brain metabolism [4, 22, 23, 26]. Furthermore, it is described to survey cerebral oxygenation for treating increased intracranial pressure [11, 18, 21, 24, 26, 27]. The risk for cerebral ischemia due to reduced cerebral blood flow can also be monitored by this method following subarachnoid haemorrhage [2, 5, 7, 9, 10, 17] and stroke [6, 19]. Two currently available systems are based on different technologies: an electrochemical pO_2-sensor (Licox, LX) and a fluorescent pO_2-sensor (Neurotrend, NT). However, until now no study clarified the in vitro performance of these clinically applied sensors. But before these catheters are used to measure physiological and pathophysiological conditions in brain tissue, data from in vitro studies should be generated testing three important sensor requirements: reading of accurate absolute values, low drift over time and quick response to changes. Since this has not be done before, this study describes the in vitro characteristics

of both analysed catheter probes investigating the accuracy, drift and response-time test.

Materials and methods

For each of six experimental setups, 2 new electrochemical oxygen tension sensors (Licox, CC1.SB Catheter pO_2 microprobe, Integra NeuroSciences Ltd., Hamphsire, UK), 2 new "Licox" temperature sensors (LT, Integra Neuroscience Ltd., UK) and 2 new fluorescent sensors which passed the calibration process (NT, Codman Neurotrend Multiparameter sensor, Codman&Shurtleff, Raynham, USA) were used. The Clark-type LX-sensors used in this study have a diameter of 0.45 mm, a pO_2- sensitive sensor length of 5 mm and a surface area for measuring pO_2 mentioned in the literature between 7.1 and 15 mm^2 [4, 13]. The NT sensor used in this report integrates three optical sensors (pH sensor is anchored to the tip of the sensor, followed by pCO_2- and pO_2-sensor) and a thermocouple in one catheter probe. The complete NT catheter probe is 17.5 mm in length, 0.5 mm in diameter, and individual optical fibres are 0.175 mm in diameter (data provided by manufacturer).

The catheter probes were placed into a closed container filled with a tonometer solution (1000 g distilled water, added 1.91 g $NaHCO_3$ and 14.01 g Na_2SO_4). The solution was kept at $37 \pm 0.2\,^{\circ}C$ in a waterbath throughout the complete monitoring time and equilibrated with five highly precise calibration gases (certified after DIN 51895, ISO 9001, Linde Gas AG, Bottrop, Germany), containing different O_2- and CO_2-concentrations (Table 1). For the accuracy test, the tonometer solution was equilibrated with each gas concentration for 30 minutes. After each equilibration period, sensor readings were taken for 20 minutes. After measurements for each gas concentration were finished, all sensors were left in one gas concentration (calibration gas #3 with 3% O_2 and 9% CO_2) and readings were taken after 24, 48, 72, 96 and 120 hours (drift test). For determination of 90% response time, the sensors were placed into a tonometer which was pre- equilibrated with calibration gas #1 (1% O_2, 5% CO_2). After an equilibration period of 15 minutes, sensors were transferred to a second tonometer pre-equilibrated with calibration gas #5 (8% O_2, 16% CO_2). After additional 15 minutes of equilibration period, sensors were placed back to calibration gas #1. Sensor readings were taken every 10 seconds over the complete response time test. The time taken to reach 90% of the signal change of the sensor measured after 15 minutes equilibration time was calculated (90% response time).

Table 1. *O_2 and CO_2 concentrations (%) in the calibration gases (gas #1–#5). Relative measurement deviation (±%) are related to the concentration of each gas. pO_2, pCO_2 are calculated assuming 1013 mbar barometric pressure, pH calculation please see method section*

Calibration gas #	% O_2 conc.	mmHg	%CO_2 conc.	mmHg	pH
1	1.01 (±2%)	7.13	5.02 (±1%)	35.78	7.347
2	1.99 (±2%)	14.18	6.97 (±1%)	49.68	7.205
3	3.00 (±2%)	21.38	9.04 (±1%)	64.44	7.092
4	5.02 (±1%)	35.78	11.94 (±1%)	85.11	6.971
5	8.00 (±1%)	57.03	16.00 (±1%)	114.05	6.844

Bath temperature at the time of sensor readings was measured by a precision measuring instrument (P555, temperature probe PT100, Dostmann electronics GmbH, Wertheim, Germany). NT measures temperature within the same catheter and automatically corrected pO_2 for temperature, while LX requires an additional temperature probe.

Barometric pressure [hPa] recorded every minute (Institute of physics of atmosphere, Johannes Gutenberg-University Mainz, Germany) was converted to [mmHg] by the following constant: 760 mmHg $*$ 1.333224 = 1013.25 hPa. After subtracting the partial pressure due to water vapour (47.6 mmHg), the partial pressure was calculated depending on oxygen concentration in each gas by the following equation:

$$\begin{aligned}\text{Partial pressure [mmHg]} = ((&\text{Barometric pressure [mmHg]}\\ &- \text{water vapour [47.6 mmHg for 37 °C]})\\ &* \text{oxygen concentration [mmHg]})/100\end{aligned}$$

The pH of the buffer solution was calculated as follows:

$$\text{pH} = 7.203 - \log(\%CO_2/7) - 0.007146$$

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) as

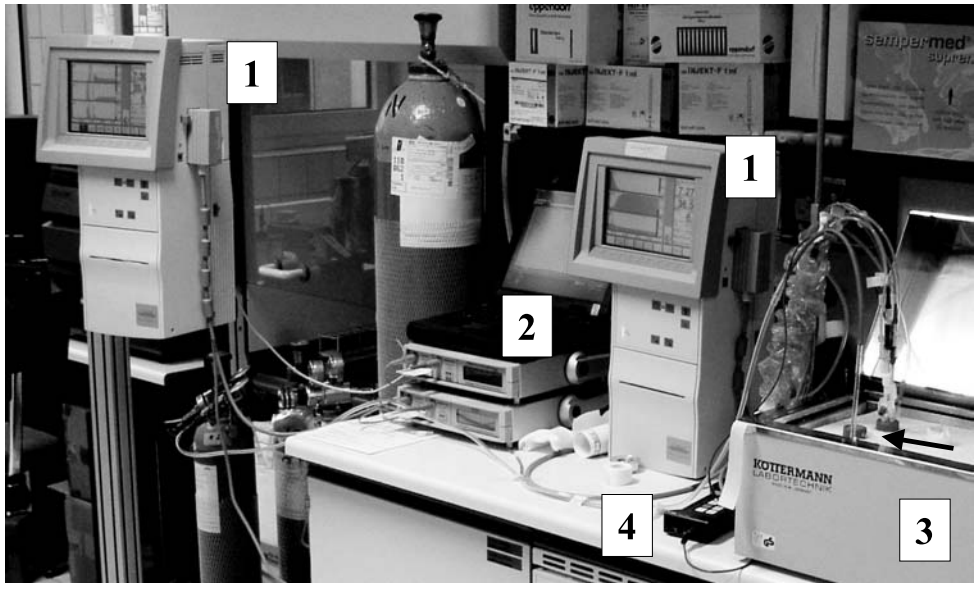

Fig. 1. Setup of the in-vitro experiment shows the waterbath (*right, 3*) and two PC collecting data from the Neurotrend (*1*) and Licox monitors (*2*) via ICU-Pilot®. A PT100 temperature probe was used as reference to monitor the waterbath temperature (*4*). Note that the sensors are mounted in two tonometers (arrow) which are bubbled continuously with predefined gas mixtures

shown in Fig. 1. Data are presented as means ± standard deviation. Statistical analysis (Mann-Whitney-U-Test) 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. All authors confirm that both experimental setup and data analysis was not influenced by any company, even if this study was financially supported by Codman& Shurtless, Raynham, USA, distributor of the Neurotrend sensor.

Results

Accuracy of pO_2 readings

Two of 14 NT probes were rejected due to a failed calibration procedure. 12 NT probes with a successful calibration were further analyzed. No technical failure was found in all 12 Licox sensors calibrated during the manufacture process. For each LX probe a chip card containing the calibration data was inserted into the Licox monitor. Figure 2 shows the pO_2 readings for both the LX and NT sensor probe in the tonometer solution bubbled with the five different calibration gases. In calibration gas #1 and #2 (low oxygen concentrations), measurements of NT and LX were 1.8–1.9 mmHg and 0.6–1.1 mmHg, respectively, lower than the pO_2 calculated by O_2-concentration of calibration gases. For higher oxygen concentrations (gas #3–#5), deviations further increased slightly for both NT and LX (Table 2). pO_2 measured in calibration gas #1 (1%/7 mmHg pO_2) was significantly different between NT and LX ($p<0.01$; Table 2). In calibration gases #2–#5 no statistically significant difference

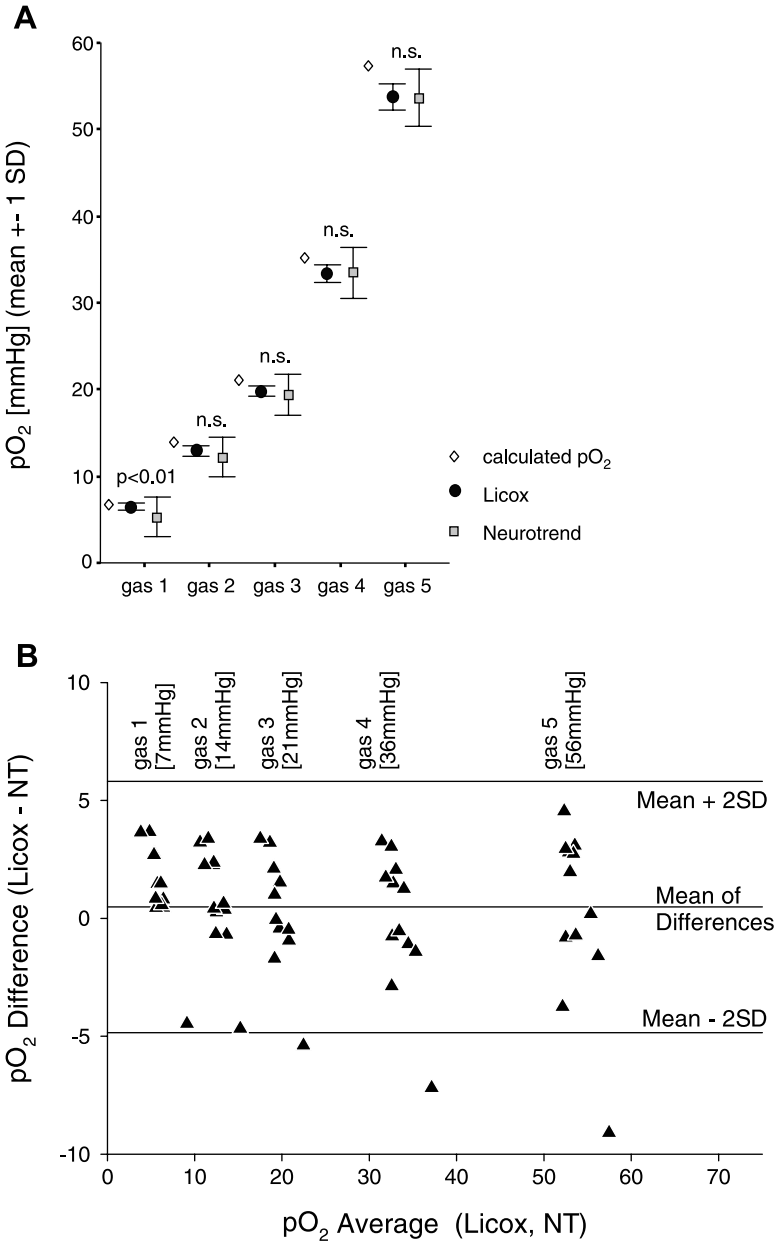

Fig. 2. Distribution of measured pO_2 concentrations [mmHg] in comparison with the expected/calculated oxygen values (A) and comparison of the two oxygen measurement methods by a Bland-Altman plot (B) using different test gases (gas 1–5). In the upper graph (A), an accuracy test of Licox (*LX*) and Neurotrend (*NT*) pO_2 probes (correctly calculated pO_2 is represented by ◊, see Table 1) was performed in five different high precision calibration gases. Data of LX and NT are shown in mean ± standard deviation. In the lower graph (B) the differences of LX and NT oxygen readings are plotted against the mean of LX and NT values (12 pairs/gas concentration). This plot indicates that at each calibration gas the NT measuring method is comparable to the 'gold standard' of LX, although NT sensors read lower values at low oxygen concentrations and show a high variability between probes at high oxygen concentrations

Table 2. *Results of accuracy test with absolute values of pO_2 in all five calibration gases measured by LX and NT sensor probes ($pO_{2\ meas}$) compared to the calculated partial pressure ($pO_{2\ calc}$) corrected by local barometric pressure. $pO_{2\ diff}$ represents the difference between the calculated and measured pO_2 corrected to the time dependent local barometric pressure*

Gas	$pO_{2\ calc}$	$pO_{2\ meas}$		$pO_{2\ diff}$	
		LX	*NT*	*LX*	*NT*
1	7.11 ± 0.24	6.47 ± 0.43	5.27 ± 2.30	0.64 ± 0.45	1.84 ± 2.30
2	14.02 ± 0.49	12.90 ± 0.56	12.15 ± 2.28	1.11 ± 0.55	1.87 ± 2.29
3	21.13 ± 0.75	19.79 ± 0.66	19.43 ± 2.39	1.34 ± 68	1.71 ± 2.41
4	35.37 ± 0.12	33.38 ± 1.00	33.46 ± 2.89	1.99 ± 0.97	1.91 ± 2.92
5	56.37 ± 0.19	53.82 ± 1.52	53.63 ± 3.27	2.55 ± 1.51	2.73 ± 3.32

$pO_{2\ calc}$, $pO_{2\ meas}$ in [mmHg].

was found. The difference between the partial pressure in the tonometric solution corrected for the local barometric pressure and the measured partial pressure by LX and NT are shown in Table 2.

After equilibration in constant gas concentrations, partial pressure measurement of oxygen was more heterogeneous in NT compared with LX, leading to higher standard deviations (Fig. 2, Table 2). This was not due to the reduced numerical data delivered by the NT monitor (integer numbers) compared with LX (rational numbers). The higher heterogeneity of the NT persists also after rounding the rational numbers of LX. Mainly two NT sensors (16.7%) added to the higher standard deviation of NT probes. The Bland-Altman plot indicates that both methods are comparable in low oxygen concentrations, but with a tendency of lower readings by NT. At high oxygen concentrations NT measurements deviate more from the ones recorded by Licox (Fig. 2B).

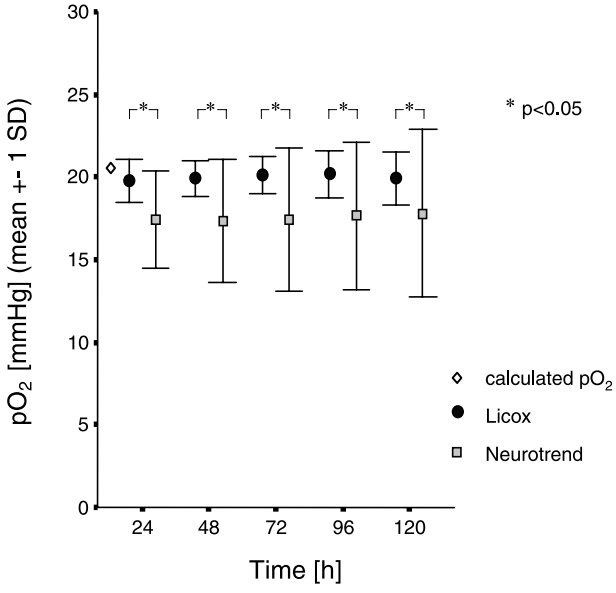

Fig. 3. Stability test over 5 consecutive days for Licox and Neurotrend sensors. Drift of pO_2 [mmHg] was measured over time in probes equilibrated in tonometric solution with calibration gas #3 (calculated: 21.13 ± 0.75 mmHg pO_2, depending on atmospheric pressure)

Drift of pO_2

Measurements for both sensors left in calibration gas #3 (3% O_2) were taken after 24, 48, 72, 96 and 120 hours (Fig. 3). The differences between the real pO_2 corrected for local barometric pressure and the measured pO_2 is summarised in Table 3. Absolute pO_2 measured by NT is 3.2–4.1 mmHg lower than pO_2 calculated by O_2-concentrations depending on atmospheric pressure in the tonometer (pO_2 of 21.13 ± 0.75 mmHg). LX sensors measured 1.0–1.4 mmHg lower pO_2 (Table 3)

Table 3. *Results of drift test with measurement of pO_2 every 24 hours for five days (time) by LX and NT sensor probes ($pO_{2\ meas}$) compared to the calculated partial pressure ($pO_{2\ calc}$) corrected by local barometric pressure. $pO_{2\ diff}$ represents the difference between the calculated and measured pO_2 corrected to the time dependent local barometric pressure*

Time	$pO_{2\ calc}$	$pO_{2\ meas}$		$pO_{2\ diff}$	
		LX	*NT*	*LX*	*NT*
24 h	21.1 ± 0.06	19.7 ± 1.3	17.6 ± 3.0	1.4 ± 1.3	3.7 ± 2.9
48 h	21.2 ± 0.08	19.9 ± 1.0	17.1 ± 3.2	1.3 ± 1.0	3.8 ± 3.7
72 h	21.2 ± 0.09	20.2 ± 1.0	17.3 ± 3.9	1.1 ± 1.0	3.7 ± 4.3
96 h	21.2 ± 0.1	20.1 ± 1.3	18.0 ± 4.3	1.0 ± 1.3	3.5 ± 4.5
120 h	21.2 ± 0.1	19.8 ± 1.9	17.9 ± 4.7	1.3 ± 1.6	3.4 ± 5.1

$pO_{2\ calc}$, $pO_{2\ meas}$ in [mmHg].

Table 4. *Results of accuracy test with absolute values of pCO_2 and pH in all five calibration gases measured by NT sensor probes ($pCO_{2\ meas}$, pH_{meas}) compared to the calculated partial pressure ($pCO_{2\ calc}$, pH_{calc}) corrected by local barometric pressure*

Gas (% pCO_2)	$pCO_{2\ calc}$	$pCO_{2\ meas}$	pH_{calc}	pH_{meas}
5.02	35.36 ± 0.14	35.38 ± 1.78	7.347 ± 0.021	7.36 ± 0.06
6.97	49.15 ± 0.20	49.48 ± 2.11	7.205 ± 0.018	7.23 ± 0.07
9.04	63.77 ± 0.27	63.69 ± 2.25	7.092 ± 0.012	7.11 ± 0.06
11.94	84.23 ± 0.33	84.88 ± 3.30	6.971 ± 0.008	7.00 ± 0.07
16.00	112.80 ± 0.43	112.98 ± 3.11	6.844 ± 0.008	6.86 ± 0.06

$pCO_{2\ calc}$, $pCO_{2\ meas}$ in [mmHg].

Table 5. *Results of drift test with measurement of pCO_2 and pH each 24 hours over five days (time) measured by NT sensor probes ($pCO_{2\ meas}$, pH_{meas}). The calculated partial pressure ($pCO_{2\ calc}$) is corrected by local barometric pressure, calculation of pH_{calc} see text*

Time	$pCO_{2\ calc}$	$pCO_{2\ meas}$	pH_{calc}	pH_{meas}
24 h	63.70 ± 0.17	64.03 ± 2.35	7.094 ± 0.015	7.13 ± 0.06
48 h	63.79 ± 0.24	63.77 ± 2.75	7.096 ± 0.018	7.15 ± 0.06
72 h	63.98 ± 0.26	63.46 ± 3.10	7.098 ± 0.020	7.16 ± 0.07
96 h	63.89 ± 0.41	63.19 ± 3.04	7.100 ± 0.020	7.19 ± 0.08
120 h	63.80 ± 0.46	63.02 ± 3.13	7.101 ± 0.080	7.19 ± 0.05

$pCO_{2\ calc}$, $pCO_{2\ meas}$ in [mmHg].

and pO_2 readings were significantly different between LX and NT after 24 hours and this difference remained over the next 96 hours ($p < 0.05$). NT sensors showed a more heterogeneous distribution of pO_2 and this deteriorated over time. LX sensors showed a very stable measurement of pO_2 throughout the drift test and even after 120 h a low standard deviation was fond (Fig. 3).

90% response time to pO_2 changes

90% response time after changing sensors from calibration gas #1 to calibration gas #5 was 129 ± 27 sec for LX and 55 ± 19 sec for NT. After 15 minutes equilibration, pO_2 readings of LX were 1.5 mmHg lower (54.9 ± 1.9 mmHg) and of NT 5.9 mmHg lower (50.5 ± 7.0 mmHg) compared with the calculated pO_2 in the tonometer solution. After transferring sensors from calibration gas #5 back to gas #1, LX needed 174 ± 26 sec and NT 98 ± 39 sec to reach 90% of the total signal change. After equilibration in calibration gas #1, mean pO_2 readings were 7.1 ± 0.7 mmHg for LX and 4.4 ± 4.3 mmHg for NT sensors.

Accuracy and drift of pCO_2 and pH

Since LX does not measure pCO_2 and pH, data of both parameters concerning accuracy and drift are shown for NT only. The difference between pCO_2 in the tonometer solution (corrected for barometric pressure) and pCO_2 measured by NT was less than 1 mmHg for all CO_2 concentrations in the calibration gases. Differences of calculated and measured pH were less than 0.05 units (Table 4). There is no significant drift over 120 hours for both pCO_2 and pH measurement (Table 5).

Discussion

Clinical studies have shown for LX sensors a low zero-drift of 1.1 ± 0.9 mmHg, a high "good data quality" of 95% and a low sensitivity-drift of 1.4 ± 1.3 mmHg [15]. However, until now there exists no in vitro analysis of the NT sensor along with the LX sensor focussing on the technical properties of both sensors. Therefore, we used a standardised setup to evaluate both sensors and to minimise methodical errors: high precision gases were used to minimise deviation in gas concentrations, partial pressure reference values for oxygen and carbon dioxide were corrected to external barometric pressure, darkening of the tonometer excluded external light influences to the fiberoptic probes and buffer temperature in the tonometer was kept constant to 37 ± 0.2 °C. NT sensors packed in the pouch which is pre-filled with the first calibration gas were taken out immediately before the calibration process because they should not be left outside the pouch for hours before calibrating due to compromised pO_2 accuracy. However, both sensors measure pO_2 slightly lower compared with the reference value (calculated by oxygen concentration and barometric pressure). Furthermore, pO_2 readings between both sensors are significantly different for low

pO_2 (1% oxygen), but there is no statistically significant difference for higher O_2 concentrations. Therefore, we suggest that differences in 1% O_2 concentrations (barometric pressure corrected pO_2 7.1 ± 0.2 mmHg) with deviation of pO_2 readings of both sensors (NT 1.8 ± 2.3 mmHg and LX 0.64 ± 0.45 mmHg than expected pO_2) are mostly caused by the sensor and calibration technique. In the LX sensor, the electrochemical pO_2 sensor firstly described by Clark (2) consists of a cathode (gold) which is maintained at a negative potential relative to a reference anode (silver) and both electrodes are immersed in a potassium chloride electrolyte solution. Oxygen diffuses into this cell through a membrane selectively permeable for oxygen. A reduction of oxygen ($O_2 + H_2O + 4e^- \rightarrow 4OH^-$) at the cathode generates a current which can be calculated to a pO_2. The pO_2 also depends on the applied potential, the size and physical characteristics of the cell, and on the configuration of the electrodes [14]. In contrast, the fluorescent sensors (NT) work completely differently. For each sensor, light of specific wavelength illuminates a sample chamber containing a dye [for O_2-sensor: tris (4,7-diphenyl-1,10-phenanthroline) ruthenium II chloride; for CO_2- and pH-sensor: phenol red]. This incident light is completely or partially absorbed or remitted with a different wavelength. Since each analyse embedded in the dye absorbs characteristic wavelengths in preference to others, measurement of the intensity of the absorbed radiation intensity can yield a measurement of the analyse of interest. Similarly, the intensity of the remitted radiation can be influenced in a known manner by the analyte of interest (pO_2, pCO_2, pH). For pO_2 measurement, the intensity of the emitted fluorescent light is decreased (quenched) by oxygen [8, 16], and the quantitative relationship between the observed fluorescent intensity (I) and pO_2 is described by the Stern-Volmer equation ($I = I_0/(1 + k * pO_2)$, where I_0 is the unquenched intensity ($pO_2 =$ 0 mmHg) and k is the quenching constant [20]. Based on this relationship, one would expect that fiber-optic probes (NT) are more precise compared with Clarc-type electrode (LX) sensors [14] because they are calibrated immediately before usage and have a higher sensitivity for low pO_2. The Stern-Volmer equation implicates that the largest changes in intensity with changes in pO_2 occur at low values of pO_2, so that the method is most accurate at these low values of pO_2 [14]). However deviation of pO_2 measurements seen with the NT sensor are still within the claimed performance criteria specified by the manufacturer (NT measures pO_2 in a range from 10 to 160 mmHg, in vitro accuracy of ± 3.5 mmHg between 10 to 60 mmHg and $\pm 10\%$ between 60 to 110 mmHg, pO_2 drift $<0.5\%/h$). It remains unclear why these differences are not seen in the pCO_2 probe which also runs fiber-optically but measures much more precisely. However, in this study NT seems to be sensitive to much more technical influences such as calibration procedure, sensor size, diffusion of oxygen into the dye as well as optical accuracy of emitted and detected re-emitted light leading to higher inaccuracy at low oxygen concentrations and standard deviation compared with the LX sensor. The difficult calibration process of NT sensors in combination with the need of very accurate miniaturised catheter production might lead to a higher failure rate of NT catheters, which was 14% (2 of 14 NT sensors) in this study. The high accuracy of the LX sensor as found in this report is also described by Dings *et al.* [4] who found a mean of sensitivity error less than 1.1% with a maximal sensitivity error of -3.87 between 22–37 °C and a pO_2 range of 0–150 mmHg%. For low oxygen concentrations, we suggest a slightly higher sensitivity error: assuming that there is no zero display error, sensitivity error for LX is between -4.5% and 9.0%, and for NT between 4.8% and 25.87%. One reason for this difference might be that Dings *et al.* evaluated the LX sensors in 6% (42.7 mmHg at 760 mmHg atmospheric pressure and 47.6 mmHg water vapour) and 0% oxygen concentrations only without using a buffer solution and not correcting pO_2 for local barometric pressure.

In clinical practice, the sensitivity error of both sensors presumably is of minor importance, since accuracy and drift of both catheters sufficiently allow for differences between a critical pO_2 of 5–15 mmHg and a normal pO_2 of 20–50 mmHg [3, 12, 14, 22, 23]. This study shows, that several technical in-vitro preconditions of both oxygen tension measurement methods are be fulfilled. The Bland-Altman plot (Fig. 2B) indicates that both methods produce similar and reliable oxygen values over a broad range of oxygen concentrations, although there are greater variations between the NT sensors than between the LX sensors (see also Fig. 2A). However, there is still a lack of evidence whether the results are comparable during routine clinical use in the human brain. Furthermore, despite absolute readings of pO_2, the duration of low pO_2 should be taken into account along with the fact that a heterogeneous pO_2 distribution in brain tissue can result in variable pO_2 readings. As shown in this study, sensors measure pO_2 at low pO_2 increasingly differently compared with the expected

pO_2, e.g. less than 15 mmHg (calibration gas #1 and #2). Zauner *et al.* [25] presented an in vitro setup with using the Paratrend 7 sensor, which is a Clarc-type electrode in contrast to the fluorescent NT sensor. Probes were placed in an incubator filled with human packed cell units on 37 °C and bubbled with different concentration of gases. 7 Paratrend readings were compared with intermitted blood gas analysis above 18 mmHg. The maximal difference for pO_2 was less than 8 mmHg. However, these results are just valid for $pO_2 > 18$ mmHg. In addition, possible heterogeneous distribution of oxygen within the incubator as well as a possible inaccuracy of the blood gas analyser might cause additional bias. For this reason, we suggest that choosing highly precise calibration gases bubbled in a buffer solution as performed in this experiment allows very accurate calculation of pO_2 and therefore can minimise these variables. Moreover, the in vitro results of Zauner *et al.* [25] can not be adopted for the NT probe because of the completely different pO_2 sensor technology. Until now no comparable study exists analysing the accuracy of pO_2 sensors for application in human brain. Notably the frequently performed "100% inspired oxygen test" to check if the oxygen tension sensor is working properly should take into consideration a relatively high 90% response time of 129 ± 27 sec for LX sensor compared with 55 ± 19 sec for the NT sensor. This result reflects that both sensors are not directly comparable in clinical use. Clinical experience with LX probes suggests that a much quicker response time is achieved in brain tissue. The used in vitro setup in this study might not represent an ideal comparison for reaction time of the two probe types. The additional temperature measurement of NT with simultaneous temperature corrected pO_2, pCO_2 and pH measurements eliminates errors in pO_2 calculation. For LX, this has to be done either manually (1 °C steps on LX monitor) which yields a slight inaccuracy of pO_2 readings or by adding an additional temperature probe connected to the monitor. A recent study comparing different temperature probes revealed very precise temperature readings at a range of 30–42 °C for both LX and NT systems [1]. Although this study implies that in vitro the NT technology measures pO_2, pCO_2 and pH accurately enough in the physiological range (pO_2 7–57 mmHg, pCO_2 36–114 mmHg, pH 6.8–7.4), there is – in contrast to LX and Paratrend sensors-conflicting data of evidence that this new fiberoptic catheter technology is able to provide reliable monitoring data in clinical practice [9]. Thus, in vivo evaluation in animals is necessary to study sensor properties in physiological and pathophysiological conditions to further analyse its purpose as a cerebral monitoring tool in humans.

Conclusion

In vitro accuracy of LX and NT probes measuring oxygen tension seems sufficient in all tested oxygen and carbon dioxide concentrations, even if the NT sensor measured significantly lower in 1% O_2-concentration. Also for long-term use there is only a slight drift towards lower oxygen tension readings for both sensors, but more pronounced for the NT. pCO_2 and pH measurement performed by NT is very precise. Both sensors show a shorter response time to pO_2 increase compared with pO_2 decrease. For both directions, LX needs more time to reach a 90% response compared with NT.

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Comments

The authors have described a carefully designed in-vitro bench test study comparing the long-term zero drift and response time of the two main commercially available PO_2 sensor systems.

Such carefully controlled bench tests are useful as a method for comparing technologies, which might not either be practical or ethical in clinical studies. The authors have accurately defined the zero drift and response times of the two systems and have provided useful technical information to others wishing to use either technologies.

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This is a very useful and topical laboratory study, comparing static and dynamic accuracy of two tissue oxygenation sensors.

Dynamic properties of both sensors were compared- and this is of special values, when various 'dynamic autoregulation' indices have just been introduced based on the brain tissue oxygenation.

Laboratory setup was unable to simulate small and relatively fast changes in brain oxygenation, as they observed in practice and most probably provoked by fluctuation of rCBF- and this is a limitation of the laboratory dynamic test.

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