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Photoplethysmographic Measurements from Central Nervous System Tissue

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Abstract. A new system for measuring the oxygen saturation of blood within tissue has been developed, for a number of potential patient monitoring applications. This proof of concept project aims to address the unmet need of real-time measurement of oxygen saturation in the central nervous system (CNS) for patients recovering from neurosurgery or trauma, by developing a fibre optic signal acquisition system for internal placement through small apertures. The development and testing of a two-wavelength optical fibre reflectance photoplethysmography (PPG) system is described together with measurements in rats and preliminary results from a clinical trial of the system in patients undergoing neurosurgery. It was found that good quality red and near-infrared PPG signals could be consistently obtained from the rat spinal cord (n=6) and human cerebral cortex (n=4) using the fibre optic probe. These findings justify further development and clinical evaluation of this fibre optic system.

1. Introduction

Noninvasive arterial blood oxygen saturation measurement by pulse oximetry is widely recognized as one of the most important technological advances in clinical monitoring [1]. Although generally reliable, the use of transmission pulse oximeter probes is limited to peripheral parts of the body such as the finger, toe or ear lobe.

1.1. Reflectance pulse oximetry probes

An attempt to measure blood oxygen saturation at other sites than the periphery has previously been made by Kyriacou *et al* with the development of a reflectance opto-electronic oesophageal pulse oximeter [2]. The measurement of arterial oxygen saturation using the principle of reflectance pulse oximetry, which measures the intensity of light backscattered from the tissue, was first described by Mendelson and Ochs [3]. Studies using the reflectance oesophageal pulse oximetry system have shown that measurable PPG signals and SpO_2 values can be detected in the oesophagus of healthy adult patients during anesthesia. The oesophageal blood oxygen saturation (SpO_2) values showed good agreement with results from commercial finger pulse oximetry probes and CO-oximetry. A further study in patients undergoing cardiac surgery showed that reliable oesophageal SpO_2 readings could be

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obtained during periods when finger probes failed due to poor peripheral perfusion [4]. Despite its successful performance, the size of the oesophageal probe limits its application in areas such as a brain or other small cavities.

A number of internal monitoring applications require further miniaturization, indicating the need for coupling of the light sources and photodetector to optical fibers. In addition to enhanced accessibility to a wider range of internal sites, optical fibers have the advantage for patient safety of complete electrical isolation. Optical fibers are already used for many clinical applications including oximetry, most notably for measuring the oxygen saturation of whole blood within large blood vessels [5]. Externally applied optical fiber pulse oximeters are used routinely to monitor patients in magnetic resonance imaging (MRI) scanners in which conducting components cannot be used due to the high electromagnetic field strengths [6].

1.2. Brain tissue

A serious concern in the treatment of patients after major neurosurgical procedures and particularly in the days after traumatic head injury is to prevent secondary damage from raised intracranial pressure (ICP) due to swelling of the brain or bleeding. Increased intracranial pressure impedes cerebral blood perfusion leading to a damaging lack of oxygen and nutrients and an accumulation of metabolites in the brain [7]. For many years, management of patients at serious risk of raised intracranial pressure has included intracranial pressure monitoring via a burr hole drilled through the skull, in order to facilitate insertion of the pressure transducer itself or a fluid-filled catheter connected to an external transducer.

More recently, it has become increasingly common to facilitate such access using cranial bolts, which are screwed into the skull providing a sealed system with minimal risk of fluid leakage or infection [8]. The optical fiber probe we have developed is primarily intended to be inserted via a cranial bolt, allowing oxygen saturation measurements to be made directly from the brain tissue. A pair of optical fibres may be inserted into the 'pO_2' and 'temperature' lumens of a triple-channel IM-3 cranial bolt (Integra Neurosciences Inc. Plainsboro, NJ, USA) as shown in fig. 1.

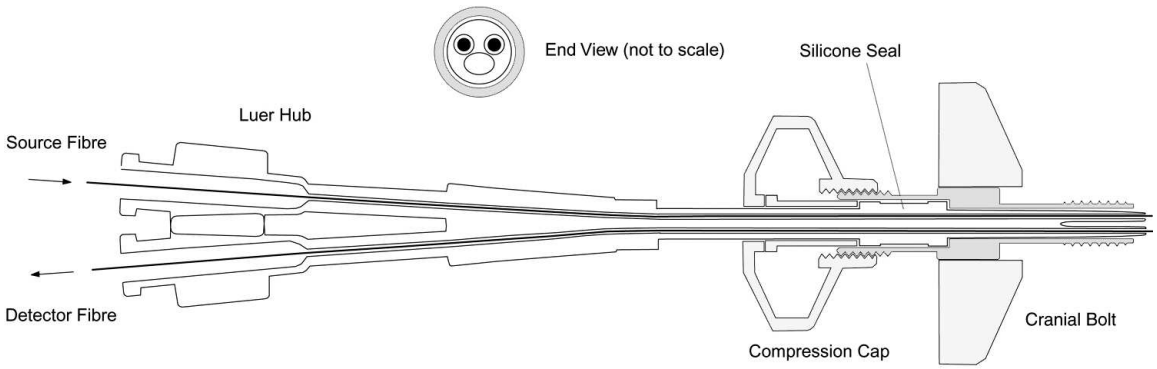


Fig. 1. IM-3 cranial bolt with optical fibres inserted.

1.3. Spinal cord

A further potential application is the measurement of PPG signals and oximetry measurements from the spinal cord. Patients recovering from spinal cord injury are at risk from secondary injury due to ischemia [9]. An optical fibre probe could provide a clinically useful monitoring modality, giving an indication of blood supply and arterial oxygen saturation within the spinal cord. It is envisaged that the fibres could be inserted into the epidural space via an epidural needle and left in place for the duration of the monitoring period.

To undertake the challenge of exploring new pulse oximetry technologies and monitoring sites, the present study was aimed at developing and evaluating the reliability of a new fibre optic brain tissue reflectance pulse oximeter used for critically ill patients. The technological

developments of such a pulse oximeter probe and PPG signals measured by the new probe from the rat spinal cord dura and the human brain will be presented.

2. Materials and Method

2.1. Measurement system

The optical fiber oximetry system comprises three main parts:

2.1.1. Probe. The probe consists of two parallel silica optical fibers (SpecTran Speciality Optics, Avon, CT, USA) with a core diameter of 400 μm, an outer cladding diameter of 730 μm and a numerical aperture (NA) of 0.39. Each fiber is terminated at one end with an SMA connector and the other end is cut and polished flat. The fibers are coated in a protective PVC jacket, which is stripped away over a length of several centimetres from the un-terminated end. The two optical fibers are held a fixed distance apart at the distal end by a plastic molding.

2.1.2. Instrumentation. This is housed in an aluminium box containing: light sources; SMA mounted red (660 nm) and infrared (850 nm) LEDs (The Optoelectronic Manufacturing Corporation Ltd, Redruth, UK); a photodetector; an SMA mounted PIN photodiode (The Optoelectronic Manufacturing Corporation Ltd); a power supply (2 x 12 V lead-acid batteries); and, a circuit comprising two switchable regulated current sources connected to the LEDs and a differential transimpedance amplifier, a demultiplexing circuit and filters (to attenuate noise and to separate the ac and dc components of the signal) connected to the photodiode. One optical fiber is connected to the two light sources via a bifurcated optical fiber assembly (Ocean Optics Inc., Dunedin, FL, USA). The other fiber is coupled directly to the photodetector.

2.1.3. Data acquisition system. The LEDs are controlled by the digital multiplexing signal from a 16-bit PCMCIA data acquisition card (DAQCard-AI-16XE-50, National Instruments Inc., Austin, TX, USA) installed in a Sony VAIO PCG-Z600HEK notebook computer running a LabVIEW (National Instruments) Virtual Instrument (VI). The VI allows the user to control the multiplexing frequency of the light sources and the sampling frequency. The VI reads each of the two PPG signals at a rate of 100 samples per second, displays the PPG waveform and records both signals in a spreadsheet file. The PPG signal is normalized by dividing by the dc signal for each wavelength. This is because the ratio PPG ac:dc is used in the algorithms to estimate SpO_2 in pulse oximeters.

A block diagram of the system is shown in Fig. 1.

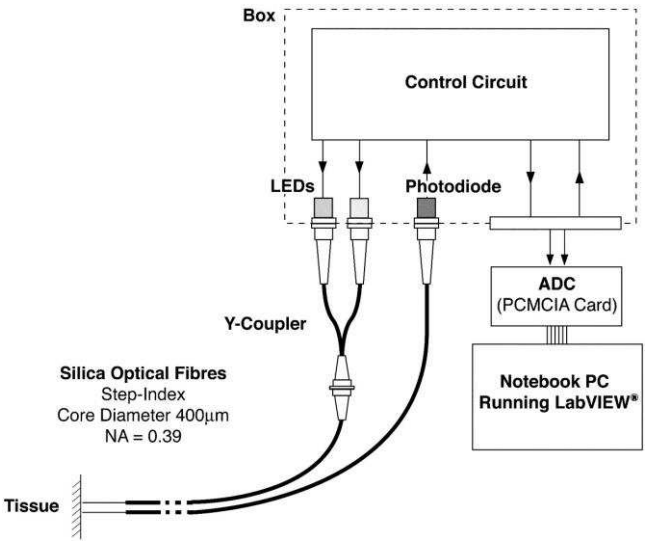


Fig. 1. Block diagram of PPG measurement system.

2.2. Measurement from rat spinal cord

A dedicated optical fibre probe was constructed, consisting of two optical fibers, their centres laterally separated by a distance of 1.0 mm. The fibers were passed along a metal tube attached to a metal bar measuring 4 mm long by 1.5 mm wide. The fiber ends were inserted into the bar so they were flush with the lower surface of the bar as shown in Fig. 2(a). The lower surface of the bar is curved to fit the contour of the rat spinal cord thus avoiding any localized compression of the tissue. The metal tube was supported within a stereotactic frame so that it can move in the vertical direction only.

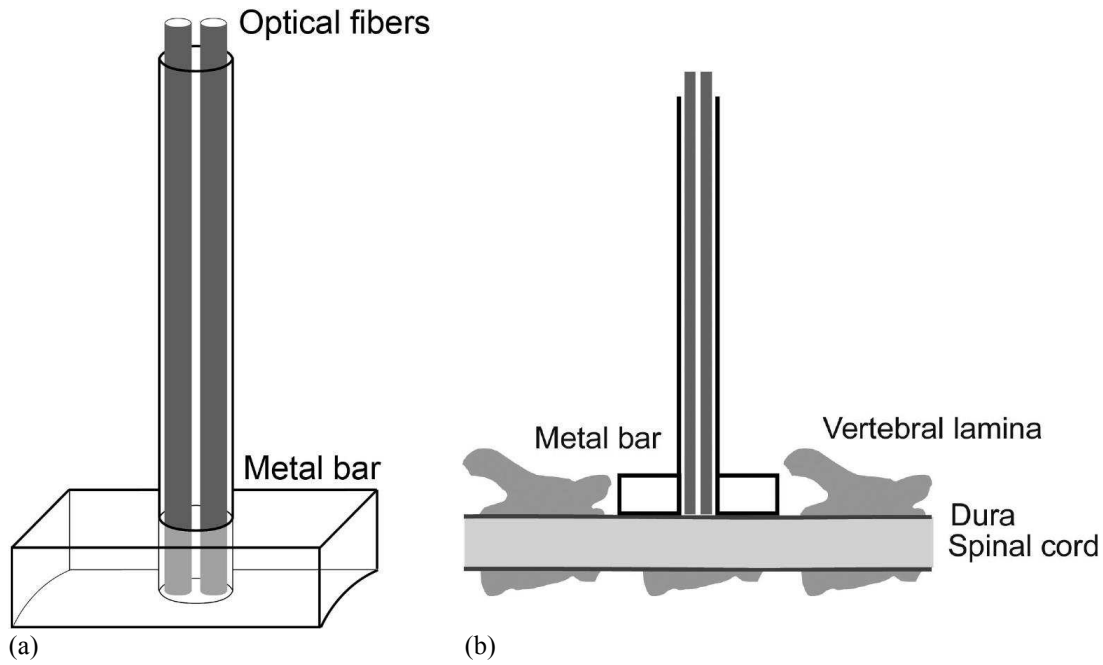


Fig. 2. (a) Apparatus for rat spinal cord PPG measurement. (b) Diagram showing apparatus *in situ.*

Six adult female Sprague-Dawley rats, each weighing approximately 250 g were anesthetized using Halothane. A 5 cm skin incision was made along the thoracic spine and dissection was done to expose the underlying spinal column. The laminae of T12 vertebra (approximately 5 mm in length) were removed to expose the dura over the underlying spinal cord. The probe was lowered to gently rest on the surface of the spinal cord dura as shown in Fig. 2(b).

A continuous PPG signal was recorded for one minute simultaneously at both the red (660 nm) and infrared (850 nm) wavelengths. The acquired signal was filtered using a 2nd order bandpass Butterworth filter with the passband ranging from 1.2 Hz to 16.0 Hz. A higher range of frequencies was chosen for this filter than for the human measurements due to the much higher heart rate of the rat compared to the human.

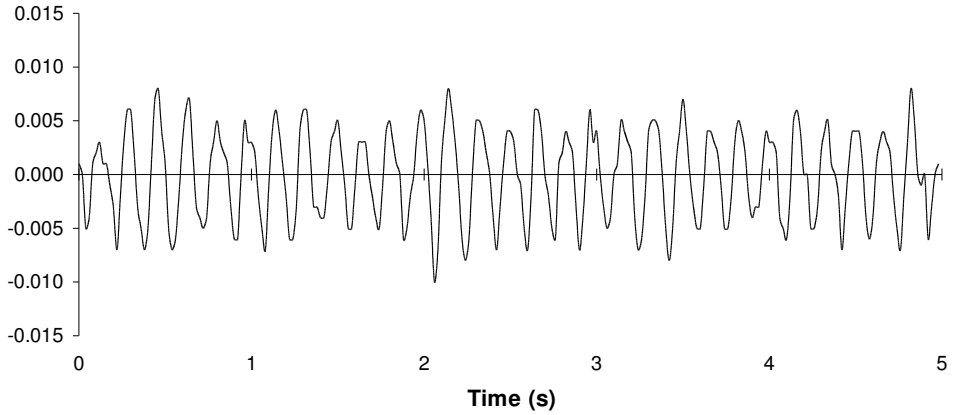
2.4. Measurement from human brain tissue

Patients undergoing elective neurosurgery who required bolts as part of their routine care were recruited for the study. The cranial bolt was inserted by the neurosurgeon, according to the manufacturers instructions. The fibres were inserted into the bolt as described in section 1.2. The insert was then placed in the cranial bolt and signals recorded for a period of four minutes. The acquired signal was filtered using a 2nd order bandpass Butterworth filter with the passband ranging from 0.39 Hz to 8.0 Hz. The fibres were then removed and the surgery resumed.

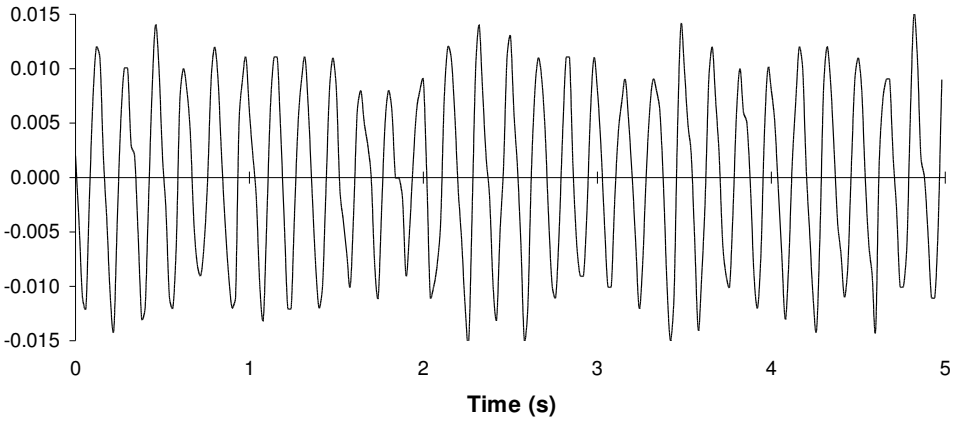
3. Results

3.1. Measurement from rat spinal cord.

Good quality PPG signals were achieved consistently in all six rat spinal cord recordings. Five-second samples of the normalized PPG traces for red (660 nm) and infrared (850 nm) light obtained from the rat spinal cord are shown in Fig. 5. The waveform is reasonably well defined at both wavelengths. The dichrotic notch and other details are not clearly defined due to the high heart rate of the rat relative to the signal acquisition sample rate.



(a)

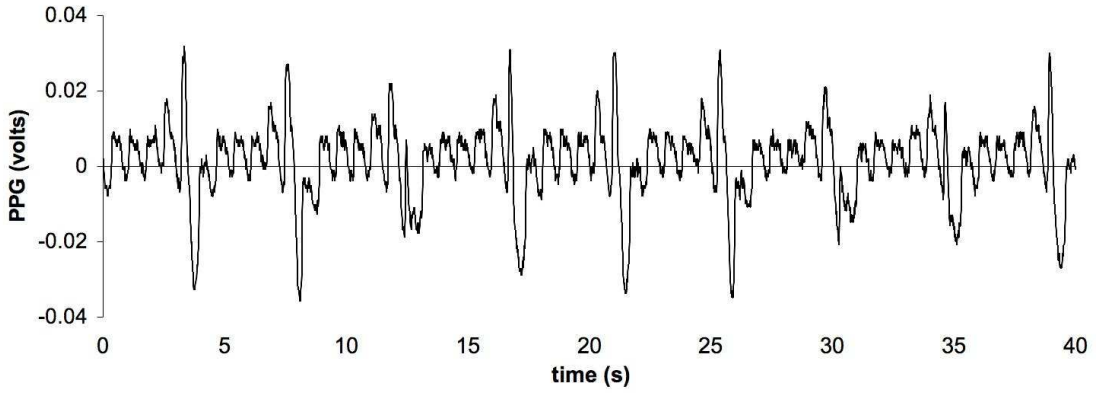


(b)

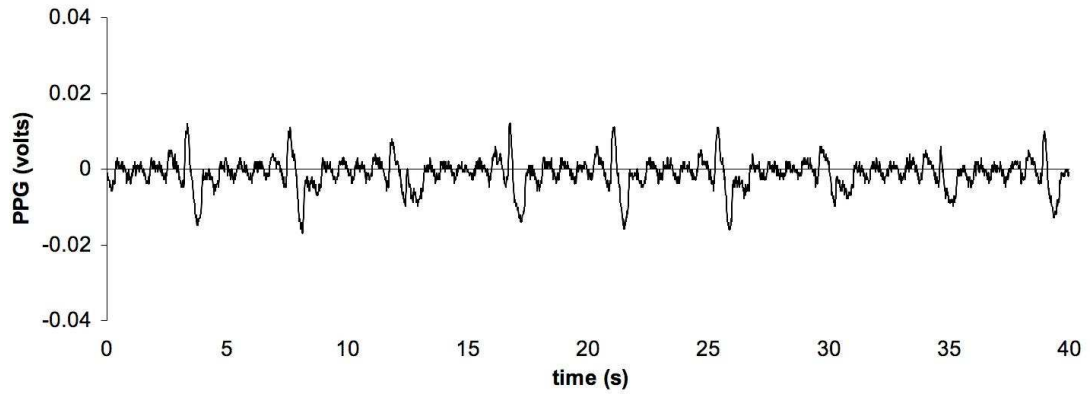
Fig. 5. (a) Red and (b) infrared PPG traces from the rat spinal cord.

3.2. Measurement from human brain tissue

At the time of writing, four patients have been recruited to the study. Signals were successfully obtained at both wavelengths for all four patients. The ac-filtered signals were detected for almost the entire measuring period for all four patients. Figure 6 shows the PPG traces obtained at infrared and red visible wavelengths.



(a)



(b)

Figure 6: (a) infrared [850 nm] and (b) red [660 nm] ac filtered and amplified PPG signals recorded from the brain tissue via a cranial bolt.

There were short periods where a pulsatile (ac) signal was not recorded. During all such periods, the reason for the loss of signal was one of the following:

- the fibres were not correctly positioned
- the signal amplifiers were saturated due to the gain being set too high
- the amplifiers were saturated due to the operating lights being on.
- the photodetector was picking up interference from an infrared surgical pointer locator (Stealth Surgical Navigation System, Medtronic Inc., Minneapolis, MN, USA).

4. Discussion

It was found that good quality red and near-infrared PPG signals could be obtained from the spinal cord dura of the rat and from human brain tissue using a fiber optic probe. The lateral separation of the optical fibers may be limited by the maximum diameter of a probe, whose size may be dictated by the intended application. For measurements in the brain, the cranial bolts currently available do not permit a fiber-fiber separation greater than 2 mm. This is sufficient, however, to obtain good quality PPG signals. These results provide justification for the development of an optical fiber oximetry system for the brain and other nervous tissue.

Although, pulsatile (ac) and non-pulsatile (dc) signals could be recorded in all patients, the amplitude of the ac signals was small compared with the dc signal (ac:dc ratio $\approx$ 0.2%). The red signal was particularly small in amplitude, due to the much lower absorption of red light, compared with infrared, of oxyhaemoglobin. The small amplitude is not necessarily a problem; the gain of the ac amplifiers should be increased for future studies, which will hopefully yield ac signals of much larger amplitude. Using a bandpass filter with a narrower passband may reduce low frequency ventilator induced artefact.

The ac signals exhibited large amplitude, low-frequency (~20 Hz) interference. The Stealth imaging system uses a high intensity infrared pulsed light source which is being detected by the photodetector. The surgeons have assured us that next time they could switch off the emitter during the measurements.

At present, we have not established a suitable algorithm to convert the measured signals into a clinically useful measurement (i.e. oxygen saturation). The purpose of this pilot study is to simply establish whether or not it is possible to obtain signals from the vascularised tissue of the cerebral cortex.

These results confirm that the optical fibre system can be used to effectively obtain pulsatile and non-pulsatile reflected signals from the brain tissue. Furthermore the type of optical fibres chosen and the depth of penetration are appropriate for successful signal acquisition.

Following this study a more extensive trial will be performed in patients recovering from head injuries. It is hoped that it will be possible to collect data for 24-48 hours, and that oxygen saturation will be calculated and compared with other modalities such as ICP and arterial oxygen saturation measured peripherally using a finger or ear probe.

References

[1] Y. Mendelson, "Pulse oximetry: theory and applications for noninvasive monitoring," Clin. Chem., vol. 38, no. 9, pp. 1601-1607, Sep. 1992.

[2] P. A. Kyriacou, S. Powell, R. M. Langford and D. P. Jones, "Esophageal pulse oximetry utilizing reflectance pulse oximetry," IEEE Trans. Biomed. Eng., vol. 49, no. 11, pp. 1360-1368, Nov. 2002.

[3] Y. Mendelson and B. D. Ochs, "Noninvasive pulse oximetry utilizing skin reflectance photoplethysmography," IEEE Trans. Biomed. Eng., vol. 35, no. 10, pp. 798-805, Oct. 1988.

[4] P. A. Kyriacou, S. Powell, D. P. Jones and R. M. Langford, "Evaluation of oesophageal pulse oximetry in patients undergoing cardiothoracic surgery," Anaesthesia, vol. 58, pp. 422-427, Jan. 2003.

[5] A. Armaganidis, J.F. Dhainaut, J.L. Billard, K. Klouche, J.P. Mira, F. Brunet, A.T. Dinh-Xuan and J. Dall'Ava-Santucci, "Accuracy assessment for three fiberoptic pulmonary artery catheters for SvO_2 monitoring," Intensive Care Med., vol. 20, no. 7, pp. 484-488, Aug. 1994.

[6] I. P. West, R. Holmes and G. R. Jones, "Optical fibre based pulse oximeter for monitoring in magnetic resonance scanners," Proc. of Spie - the Int. Soc. for Opt. Eng., vol. 2360, pp. 94-97, Sep. 1994.

[7] J. Ghajar, "Traumatic Brain Injury", The Lancet, vol. 356, pp. 923-929, Sep. 2000.

[8] R. W. Mortara, "Intracranial monitoring in the emergency setting," Med. Instrumentation, vol. 16, no. 4, pp. 197-198, Jul. 1982.

[9] F. Castro-Moure, W. Kupsky and H.G. Goshgarian, "Pathophysiological classification of human spinal cord ischemia [Review]," J. of Spinal Cord Med. vol. 20, no. 1, pp. 74-87, Jan. 1997.

[10] J. P. Cassella, J. Hay and S.J. Lawson, The Rat Nervous System: An Introduction to Preparatory Techniques, New York: Wiley, 1997, pp. 9-14.

[11] J. Roland , C. Bernard, S. Bracard, A. Czorny, J. Floquet, J. M. Race, P. Forlodou and L. Picard, "Microvascularization of the intracranial dura mater," Surgical and Radiologic Anatomy, vol. 9, no. 1, pp. 43-49, Mar. 1987.