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Photoplethysmographic sensors for perfusion measurements in spinal cord tissue

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Abstract. Sensors for recording photoplethysmographic signals from the nervous tissue of the spinal cord are described. The purpose of these sensors is to establish whether perfusion is compromised in various states of injury which occur in certain animal models of spinal cord injury, for example compression injury. Various measures of perfusion are applicable such as the amplitude of the photoplethysmograph signal and the oxygen saturation, measured using a dual wavelength configuration. Signals are usually compared to baseline measurements made in uninjured subjects. This paper describes two types of probe, one based on optical fibres, and one in which optotes are placed in direct contact with the tissue surface. Results from a study based on a compression model utilising a fibreoptic sensor are presented.

1. Introduction

The mechanisms of tissue damage during and after spinal cord injury (SCI) are complex and poorly understood. Trauma causing SCI is classed as primary injury and can produce laceration, stretching or compression of the delicate nervous tissue of the spinal cord. Primary injury can give rise to hemorrhage, edema and ischemia which can cause further injury (known as secondary injury) after the initial impact (Castro-Moure *et al* 1997). This can cause serious permanent loss of function, however appropriate and rapid hospital treatment can potentially minimize secondary injury.

Several models have been developed to investigate various SCI mechanisms in adult rats. Such models mimic the effects of primary injury, mostly due to laceration and contusion (Crowe *et al* 1997). Other models, such as that used in the current study, provide quantitative information on the effect of compression on neuronal damage and subsequent recovery. Disruption of the blood supply, either by laceration, occlusion or other deformation of blood vessels can potentially lead to areas of tissue becoming seriously deprived of oxygen. The tissue of the spinal cord, like all central nervous system tissue, is extremely sensitive and irreversible injury can result from hypoxia within a very short time (Nemoto 1978). Laser Doppler flowmetry (LDF) measurements have been used to quantify perfusion in the spinal cord before and after injury so that the contribution of ischaemia to the total amount of secondary injury may be better understood (Westergren *et al* 2001).

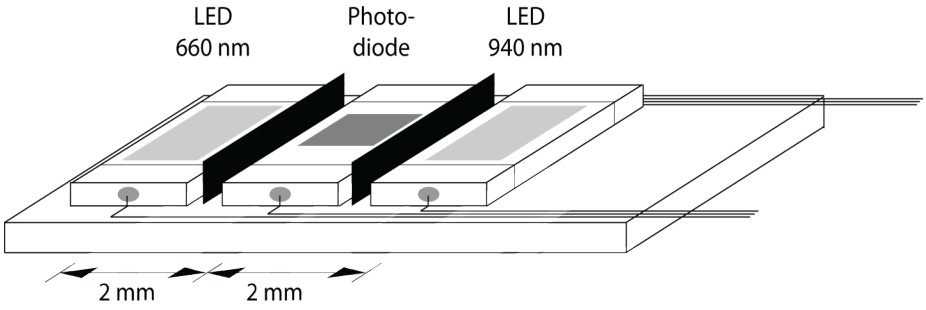
Similar efforts to quantify the tissue perfusion have focused on photoplethysmography (PPG), which produces a signal whose amplitude gives an indication of the degree of pulsation of the arteries within the tissue (Allen 2007). Many commercial pulse oximeters report this variable as the 'perfusion index' of the tissue (Hager *et al* 2003). This paper describes two types of sensor, which

were both designed specifically to make PPG measurements from the spinal cord tissue of rats studied using a compression injury model (Huang et al 2006, Nystrom 1988). Two types of sensor were designed for a series of PPG-based measurements made during compression model experiments. The first used optodes placed in direct contact with the tissue of the spinal cord, while the second utilised optical fibers to transmit light to and from the cord tissue. The performance of the two probes were compared and their suitability for their intended application is discussed.

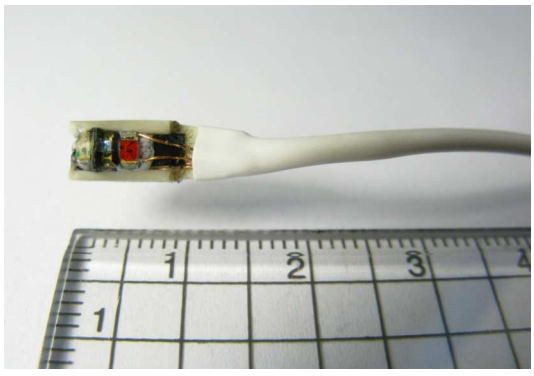
2. Materials and methods

2.1. Contact probe

The non-fibre optic ('direct contact') probe is fabricated from surface-mount red and infrared emitters and a surface mount photodiode mounted onto a rectangular polypropylene strip. The red emitter is a light emitting diode (LED) of peak emission wavelength 660 nm, while the infrared emitter is an LED of peak emission 940 nm. The emitters are mounted on either side of the photodiode as shown in Figure 1 so that the distance between each emitter and the photodiode was 2 mm. The overall dimensions of the probe (*h* x *d* x *w*) were 10 x 4 x 3 mm Strips of black absorbing material placed between each optode reduce the effect of optical shunt (detection of light directly from the emitter). The sensor works in 'reflectance mode', i.e. the photodiode detects light re-emitted from the tissue surface (Mendelson *et al* 1988).



(a)



(b)

Figure 1. (a) Diagram of the contact reflectance mode probe. (b) photograph of the contact probe with scale in cm.

Although this sensor was found to produce reliable PPG recordings from the finger, the design was abandoned as it was found that the overall dimensions yielded this probe too large for practical use in rats, leading to development of a fibre optic probe (Phillips *et al* 2009).

2.2. Fibre optic probe

The probe consists of two parallel silica optical fibres (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 fibre is terminated at one end with a subminiature version A (SMA) connector and the other end is cut and polished flat. The proximal end of one of the fibres is connected to the two light sources via a bifurcated optical fibre assembly (Ocean Optics Inc., Dunedin, FL, USA). The proximal end of the other fibre is coupled directly to the photodetector. For the compression experiments, the probe was adapted for use with the compression model apparatus. The distal ends were passed along a metal tube attached to a metal bar measuring 4 mm long by 1.5 mm wide. The fibre ends were inserted into the bar so they were flush with the lower surface of the bar as shown in Figure 2(a). The central axes of the two fibres were laterally separated by a distance of 1.0 mm The lower surface of the bar is curved to fit the contour of the rat spinal cord thus avoiding any localised compression of the tissue. The metal tube was supported within a stereotactic frame so that it could move in the vertical direction only.

2.3. Instrumentation.

This is housed in a metal box containing: a power supply (2 x 12 V lead-acid batteries); 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 PPG signal) connected to the photodiode. The ac signal was band-passed filtered with a passband ranging from 1 Hz to 19.4 Hz, while the dc signal was low-pass filtered with a cut-off frequency of 19.4 Hz. An additional amplifier for the ac signal was also used with a gain of 101. For use with the fibre-optic probe, 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) were added to the front panel of the instrumentation unit.

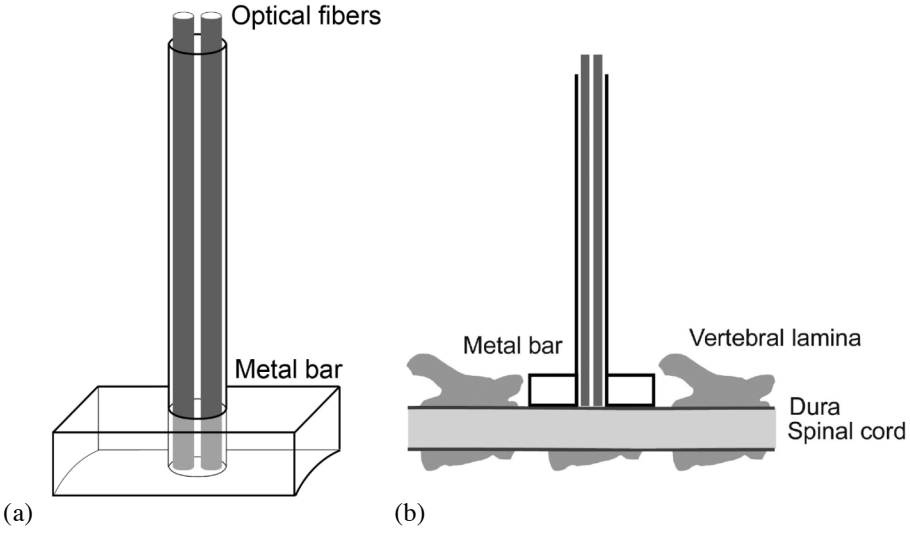


Figure 2. (a) Apparatus for rat spinal cord PPG measurement. (b) Diagram showing apparatus *in situ*.

2.4. *Measurement from rat spinal cord using fibreoptic probe*

All experimental protocols of this study were approved by the animal care committee of Queen Mary University of London, UK in accordance with the UK Animals (Scientific Procedures) Act 1986 and international guidelines on the ethical use of animals. The spinal cords of 6 female Sprague–Dawley rats weighing approximately 250 g were used for this study. The rats were deeply anesthetized in a fume box with a mixture of 5% Halothane (Meril, Essex, UK) in addition to a mixture of oxygen and nitrous oxide (1 : 1 ratio) at a flow rate of 750–1000 mL⁄min. Subsequent anesthesia throughout the procedure was maintained using 1.5–2% halothane with oxygen and nitrous oxide at unchanged ratio delivered through a nose-piece. The skin and muscle overlying the spinal column were incised and a laminectomy was then performed at T12, leaving the dura undisturbed. The compression bar was placed in light contact with the spinal cord by suspending the base of the compression platform onto the exposed T12 cord dura under microscopic control (see Figure 2(b)). Measurements were recorded from the PPG system for 5 minutes. A weight of 50 g was then applied statically to the platform for exactly 5 minutes, during which time PPG signal recording continued. The weight was then removed and PPG signals recorded for a further 5 minutes. The platform was then removed, the muscle layers were sutured and the skin layers closed with wound clips. Oxygen saturation values were not calculated for this study.

3. Results

Prior to applying any compressive loads, good quality PPG signals were achieved consistently from all six animals. Good quality PPG signals were achieved consistently from all six animals. Figure 3 shows a five-second sample of a PPG signal from the spinal cord dura of one subject.

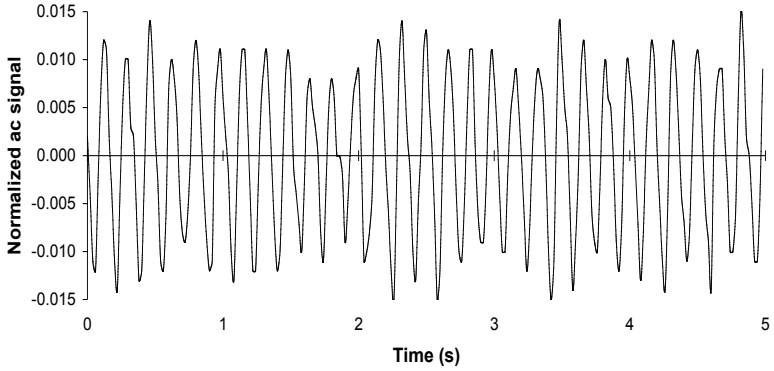


Figure 3. Five-second recording of infrared PPG from the spinal cord before compression.

An example of the waveform obtained for the entire 15-minute measurement period is shown in Figure 4. It can be seen that in this example, the amplitude of the PPG signal decreased dramatically on compression. The PPG signal was attenuated for the duration of the compression. When the compression was relieved, the PPG amplitude increased to roughly two-thirds of its baseline value and then gradually increased. After five minutes the PPG amplitude was approximately equal to the baseline value.

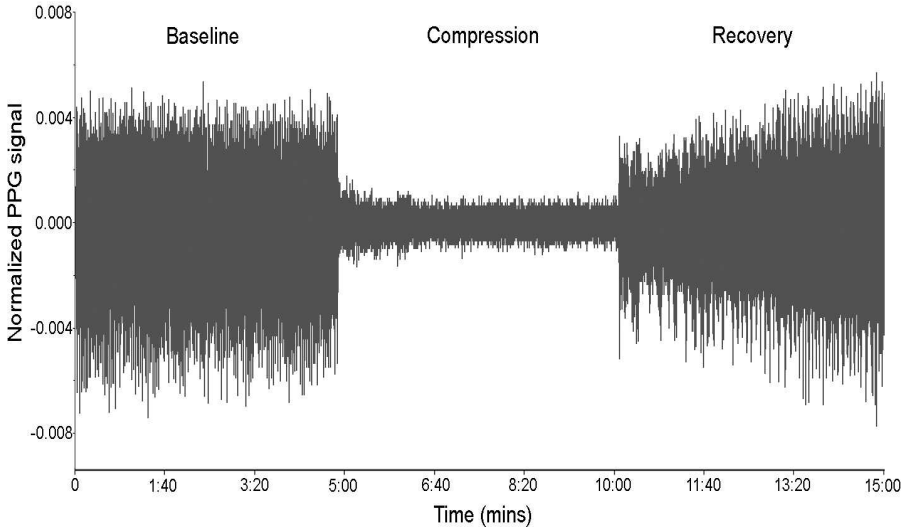


Figure 4. 15-minute recording of infrared PPG from the spinal cord before, during and after compression.

It was found that all six animals showed a reduction in average PPG amplitude from baseline following compression of the cord.

4. Discussion

Although both types of sensor potentially could be used for these measurements, the fibre-optic probe was more suitable as the are of contact with the tissue is smaller and it could be adapted more readily to the compression model apparatus. It was found that good quality infrared PPG signals could be obtained from the spinal cord dura using a fiber-optic probe during static compression model measurements in rats. Compression of the spinal cord resulted in reduced pulsation indicated by attenuation of the PPG signal amplitude. This suggests that ischemia may occur during compressive injury. The reduction in PPG amplitude persisted even after removal of the compressive load, suggesting a further potential mechanism for secondary injury.

The next stage in the development of this project will be a trial using a larger number of subjects exposed to different compression loads. A comparison of PPG amplitude attenuation and recovery of motor function may hopefully shed light on the likely extent of ischemia in compressive spinal cord injury.

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