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Cerebral and muscle oxygen saturation measurement by frequency-domain near infra-red spectrometer

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Abstract—*Tissue oxygen saturation quantification was obtained using a frequency-domain multi-source method based on two wavelength light-emitting diodes. Brain saturation was 60·3 ± 1·1% (n = 12). Brachioradial muscle saturation declined during forearm ischaemia and maximal voluntary contraction from 73·7 ± 1·8 and 74·7 ± 1·8% at rest to 44·2 ± 3·3 and 61·4 ± 2.9%, respectively.*

Keywords—*Brain, Muscle, Near-infra-red spectroscopy, Oxygenation*

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1 Introduction

NON-INVASIVE near-infra-red (IR) spectroscopy has been found to be a useful means of monitoring intracerebral oxygenation and haemodynamics in the fetus and newborn infants (BRAZY *et al.*, 1985; WICKRAMASINGHE *et al.*, 1985; WYATT *et al.*, 1986; PRYDS *et al.*, 1990; LIVERA *et al.*, 1991; PEEBLES *et al.*, 1992), and oxygen transport in muscle (DE BLASI *et al.*, 1993). Near-infra-red radiation (700–1100 nm) penetrates several centimetres into living tissue. Strong scattering in tissue results in diffuse transmission and a lack of *a priori* knowledge of the optical path length required for quantifying oxy- and deoxyhaemoglobin concentrations.

Expensive and complex picosecond laser source and fast detectors have made it possible to measure the path length (DELPY *et al.*, 1988). An alternative and cheaper approach for the measurement of optical path length and vascular haemoglobin saturation is suggested by the development of frequency-domain spectrophotometers (FISHKIN *et al.*, 1991).

In a previous frequency-domain study, we showed that, using a number of different source-detector distances, it is possible to derive an analytical expression for the absorption and scattering coefficients in a strongly scattering medium independently of *a priori* assumptions about the path length (FANTINI *et al.*, 1994a). On the basis of this multi-distance method, a two wavelength instrument for tissue oxygen saturation (St) monitoring has been developed (FANTINI *et al.*, 1995). This approach does not require any *a priori* assumptions about the value of the scattering coefficients as this coefficient is directly measured. This new instrument has been utilised in the present study to measure brain and muscle St at rest and during forearm ischaemia and exercise.

2 Method

Two near-IR bands, peaked at 715* and 850 nm†, were generated by two arrays of four intensity-modulated light-emitting diodes (LEDs). The average optical power emitted by LEDs is less than a few mW and is distributed over a wide solid angle. These LEDs are sinusoidally modulated at a frequency of 120 MHz by driving them with a low-voltage oscillating signal. The eight LEDs are driven by a multiplexing circuit which turned them on one at a time under computer control. The light, collected by a fibre-optic bundle (diameter 0·3 cm) positioned 1·7 and 3·5 cm from the first and the last LED, respectively, is connected to a photomultiplier tube§. The LEDs and the bundle were included in a holder positioned on the left of the forehead, 3 cm from the middle line, or on the brachioradial muscle of the left forearm.

The 120 MHz frequency provides the best compromise among the three requirements of high modulation of the source, high sensitivity of the detector, and high sensitivity of the measured quantities (slope, phase shift, average light intensity, and amplitude of intensity oscillations). The photomultiplier tube gain is modulated at a frequency of 120 · 0004 Mhz. The photomultiplier tube output is fed to a data acquisition card** inserted in the personal computer, featuring current/voltage converters, the signal amplification stage and a 12-bit A/D converter.

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* Hewlett-Packard HEMT-6000
† Motorola MFOE1203
§ Hamamatsu R928
** Mod. A2D, ISS, Inc., Champaign, Illinois

The 400 Hz low-frequency component of the photomultiplier output is isolated using a variable-bandwidth digital filter and is digitised through a fast Fourier transform routine. Each of the eigth light sources is turned on for a time multiple of the 400 Hz wave period. All the collected periods at 400 Hz are averaged together, giving an average wave consisting of 16 points. At the end of this acquisition process, the 16-point wave is transformed using a fast Fourier transform algorithm to give the values of the DC, AC and phase of the fundamentals harmonic frequency of 400 Hz for all 8 LEDs. The slopes associated with the DC, AC and phase are computed as described previously (FANTINI *et al.*, 1994b). Once the slopes are known, the absolute values of the scattering and absorption coefficients at the two source wavelengths can be obtained (FANTINI *et al.*, 1994b).

The entire process is then repeated to provide continuous monitoring of the scattering and absorption coefficients' values. Light source equilibration was accomplished by driving each LED with different currents. The light intensity and the phase were calibrated by placing the measurement head on a solid block of a substance with absorption and scattering coefficients similar to the tissue values. These values of the optical properties of the calibration block are measured by using a single intensity-modulated light source and the diffusion model for the semi-infinite geometry (FANTINI *et al.*, 1994b).

The overall accuracy of the measurement in the macroscopically homogeneous semi-infinite medium in the diffusion model was better than 4% for the absorption coefficient (in the range $0 \cdot 02$–$0 \cdot 04$ cm^{-1}) and better than 15% for the reduced scattering coefficient (in the range 4–16 cm^{-1}) (FANTINI *et al.*, 1995). Oxy- and deoxyhaemoglobin concentrations were derived from extinction coefficients and absorption coefficients as previously described (FISHKIN *et al.*, 1995). The ratio of oxyhaemoglobin/total haemoglobin was utilised to calculate St. Muscle St was attributed only to haemoglobin saturation changes. The low partial pressure of myoglobin and the fact that myoglobin concentration in skeletal muscle is about three times lower than haemoglobin suggests only a small contribution from this compound (O'BRIEN *et al.*, 1992).

Seven healthy untrained males and five female subjects were recruited from the laboratory (age range between 24 and 44 years). No subject was overweight. The study was performed in a warm, quiet room with the subject lying supine in a comfortable bed. The study was carried out according to the principles of the Helsinki Declaration, and informed consent was obtained. Measurements were obtained on the forehead and on the forearm. Forearm measurements were made during three consecutive protocols.

In the first protocol, an abrupt vascular occlusion was achieved by inflating a pneumatic cuff to a pressure of 240-260 mm Hg. The cuff occlusion was maintained for 8 min with the muscle resting. After cuff release, a 3 min recovery followed. In the second protocol, two isometric maximal voluntary contractions (MVC) of 30 s length were executed 30 and 90 s, respectively, after the beginning of ischaemia. The cuff was released 175 s after the start of the occlusion. In the third protocol, two isometric MVC of 30 s length were executed without vascular occlusion at 60 and 120 s, respectively, after the start of protocol. Data are represented as means ± SE. A paired t-test was used for statistical analysis.

3 Results

Brain St, calculated averaging 2 min recording, was $60 \cdot 3 \pm 1 \cdot 1\%$ (range $58 \cdot 4$–$68 \cdot 4\%$). The variation coefficient of repetitive measurements ranged from $1 \cdot 9\%$ to $7 \cdot 7\%$ (mean $3 \cdot 6 \pm 1 \cdot 7\%$). In order to obtain consistent and reproducible St changes, the instrument was utilised to monitor St in skeletal muscle.

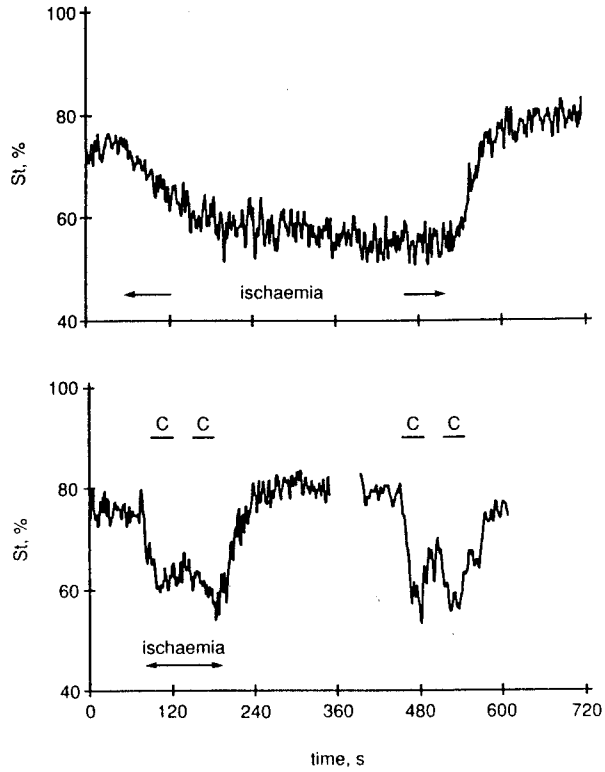

Fig. 1 *(a) Typical tracing of muscle oxygen saturation during ischaemia and release in resting forearm; (b) two 30 s isometric maximal voluntary contractions (C) performed with and without ischaemia; sampling time 1 s*

Table 1 Brachioradial muscle oxygen saturation (%)

	Ischaemia	Ischaemia +MVC	MVC
rest	$73 \cdot 7 \pm 1 \cdot 8$	$74 \cdot 1 \pm 1 \cdot 6$	$74 \cdot 7 \pm 1 \cdot 8$
maximal desaturation	$44 \cdot 2 \pm 3 \cdot 3$*	$49 \cdot 8 \pm 2 \cdot 4$*	$61 \cdot 4 \pm 2 \cdot 9$*

Values are means ± SE; $n = 12$; MVC = maximal voluntary contraction; *$p < 0 \cdot 01$ compared to resting condition

Typical St changes during ischaemia and maximal voluntary contraction with and without ischaemia are shown in Fig. 1. As expected, muscle St at rest was higher than brain St and promptly decreased in the three protocols. Muscle St during the protocols (Table 1) clearly indicates that no more oxygen extraction occurs even when St is higher than 40%.

4 Discussion

Non-invasive near-IR spectroscopy has been found to be a useful means of monitoring intracerebral oxygenation and haemodynamics in different circumstances (BRAZY *et al.*, 1985; PEEBLES *et al.*, 1992). The available technology does not permit the direct quantification of tissue oxy- and deoxyhaemoglobin concentrations without combining attenuation measurements with optical path length.

The results of this study indicate that a frequency-domain spectrometer can monitor brain and muscle oxygen saturation non-invasively. Quantification is obtained on the basis of a multi-distance method that permits the quantification of tissue scattering and absorption coefficients. This new instrument has been utilised to measure brain Stand forearm St during

ischaemia and exercise (Table 1). Brain St values fit with jugular bulb saturation data, as well as with brain regional oxygen extraction values measured by positron emission tomography (MARCHAL *et al.*, 1992). Similar changes of the relative concentration of oxy- and deoxyhaemoglobin during ischaemia and exercise have been elsewhere reported and discussed (DE BLASI *et al.*, 1993).

Taking into account that St reflects the balance between oxygen supply and energetic requests, the possibility of quantifying and monitoring St by a low-cost frequency-domain near-IR spectrophotometer might be extremely attractive for the management of tissue oxygenation in different critical conditions.

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