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Technical note

A portable wireless near-infrared spatially resolved spectroscopy system for use on brain and muscle

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ABSTRACT

We have designed, built and successfully tested a prototype portable and wireless near-infrared spectroscopy system. It takes forward the well-established series of NIRO spectroscopy instruments made by Hamamatsu Photonics (Hamamatsu City, Japan). It uses an identical optical probe, and has a data acquisition rate of 10 Hz. It illuminates the tissue with laser diode sources at 3 wavelengths of 775, 810 and 850 nm, and detects the reflected light with 2 silicon photodiode detectors at 2 different separations, enabling spatially resolved spectroscopy to be performed. We have tested it with both *in vitro* and *in vivo* experiments to establish its basic functionality for use in studies of both brain and muscle.

1. Introduction

Over the last 30 years, there has been steady progress in the development of instrumentation for near-infrared spectroscopy (NIRS) and imaging of human tissue [1,2]. More recently there has been increased interest in exploiting the benefits of the technology for ambulatory monitoring of tissue oxygenation and haemodynamics. A range of applications have employed portable, wireless systems. A recent example of this is given by Hesford et al. [3] who describe the use of a wireless NIRS device to monitor tissue oxygenation of the left and right quadriceps muscle in elite speed skaters. Other systems have been developed to provide wireless measurements of cerebral oxygenation and haemodynamics in various subjects, including children and sheep [4–7].

We describe here the development and initial testing of a portable, wireless NIRS system with a flexible optical probe suited for measurements in both muscle and brain. Our system is based on the NIRO series of NIRS instruments developed by Hamamatsu Photonics (Hamamatsu City, Japan) which incorporate both spatially resolved [8] and modified Beer-Lambert law spectroscopy [9] to provide an absolute measure of tissue oxygenation (tissue oxygenation index (TOI)), and trend measures of the changes in concentration of oxyhaemoglobin(HbO_2) and deoxyhaemoglobin(HHb). The NIRO-100 has 3 laser diode sources at wavelengths of 775, 810 and 850 nm and 2 PIN photodiode detectors. It can take measurements at a rate of up to 18 Hz, weighs 8.7 kg, has dimensions of 240 × 240 × 350 mm and requires a mains power supply.

It was decided that a portable, lightweight and wireless version of this system should be designed and built. Such a system will greatly increase the scope of the possible applications of this technology in muscle and brain research. One obvious area is that of sports science – the ability to monitor muscle oxygenation levels during exercise, when the subject should ideally not be constrained by a wired system. Another area of application would be the study of the brain under circumstances where a large, heavy, mains-powered system is not practical – for example when the experiments require the subject to be moving around. This would include neurodevelopmental studies of young children and ambulatory monitoring of seizure patients, to name just two of many possible applications.

2. Instrumentation

2.1. Overview

Fig. 1 is a block diagram of the complete wireless instrument. Each subsystem is described below.

The system is physically divided into two main sections – the optical system on the one hand and the control, data acquisition and wireless electronics on the other hand. These two sections are shown in Fig. 2(i). The optical system case has dimensions 18.5 × 7.5 × 7.0 cm, and weighs 510 g. The control electronics housing is 20 × 15 × 5.5 cm, and weighs 710 g (including battery). They are joined together by a multicore cable employing a standard D connector.

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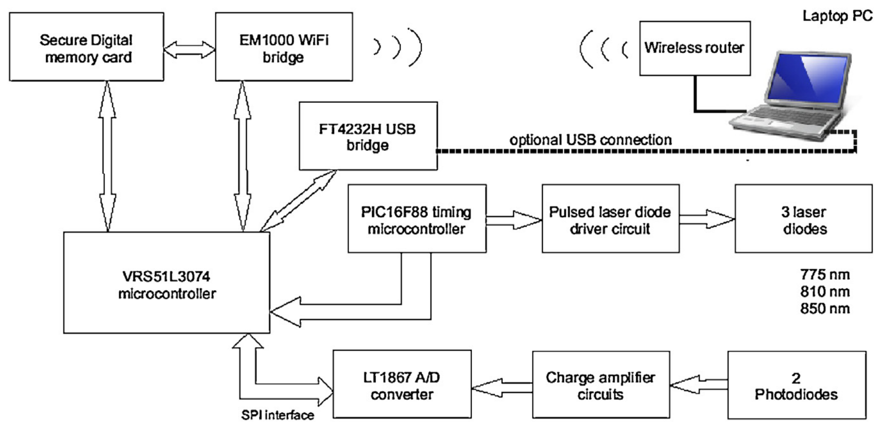

Fig. 1. Block diagram of entire system.

2.2. Optical system

The optical system and its associated electronics are shown on the right hand side of Fig. 2(i). The light source electronics are on the top circuit board, and the detector electronics on the bottom board.

The light source is a device that has three separate laser diode chips contained in one package. These emit at 775, 810 and 850 nm. The single package enables easier coupling into an optical fibre bundle. The bundle employed is 2 mm in diameter and 2.5 m long. Because the laser diodes operate with very short pulses of high current, they need a fairly sophisticated power supply and drive circuitry, capable of providing very large currents (up to 15 Amps) for very short periods of time (100 ns).

The light detectors are a pair of silicon PIN photodiodes with dimensions of 6 mm × 1.5 mm positioned 6 mm apart. These photodiodes are positioned in the array itself, not in the main opto-electronics unit. This eliminates the need for optical fibre coupling between the subject and the photodiode, thus improving signal-to-noise ratio (see Fig. 2(ii) for the geometry of the array). The photodiodes and their associated charge amplifiers are connected to the main unit via a cable 2.5 m in length. The subject end of the source optical fibre and the photodiode unit are held in a flexible array, which maintains the source-detector separation at 40 mm. This is the same optical probe that is used in the NIRO-100 instrument. The optical measurement proceeds as follows: the laser diodes are pulsed in sequence, each laser diode being switched on for just 100 ns every 576 μs. This short duty cycle with a bright pulse of light results in a better signal to noise ratio overall, as the detected light level can be much greater relative to the thermal noise floor of the detector, while maintaining the same average incident light intensity [10]. There is also a 'dark pulse', a time interval with no laser diode pulse present, to allow an ambient light reading to be taken. Each photodiode is connected to a charge amplifier, so the total amount of light emanating from the tissue as a result of an individual laser pulse is integrated at the earliest possible stage in the system. The charge amplifier circuitry outputs an analogue voltage that is proportional to the total amount of light received by the photodiode over the measurement period. It outputs a measurement every 144 μs, resulting in a data acquisition rate of 6.944 kilosamples per second per photodiode.

2.3. System control, data acquisition and integration

The system is controlled from a standard laptop PC, via a simple graphical user interface. The PC software is written in Delphi. This is an integrated development environment, based originally on the Pascal programming language. It allows rapid development of graphical user interfaces. A wireless link to the system is provided by a standard WLAN router (Linksys WRT54GR).

The portable part of the system is further controlled and integrated by a VRS51L3074 microcontroller (Ramtron, Colorado, USA). This is an 8051 based controller, running at 40 MIPS. The timing signals for the pulsing of the laser diodes are provided by a subsidiary microcontroller, a PIC16F88 (Microchip, Arizona, USA) which is a much simpler 8 bit microcontroller. This chip also sends timing pulses to the main microcontroller which ensure that the sampling of the analogue signals coming from the charge amplifiers is performed at the correct time. Analogue to digital conversion is provided by an LT1867 integrated circuit (Linear Technology, California, USA). This is an 8 channel, 16 bit device. Obviously in this application, only two analogue inputs are needed. The acquired data is down-sampled to enable more efficient storage, and the final acquired data rate is 10 samples per second for each wavelength and photodiode. The digitized data is transmitted wirelessly to the laptop PC. It is also stored locally on a 2 GB Secure Digital memory card. This way no data is lost if the wireless connection drops out for any reason. As experimental data is only generated at 417 bytes/second, the 2 GB card allows 1300 h of data to be stored. This obviously greatly exceeds the system running time available from the existing lithium polymer battery (see Section 2.4).

An FT4232H USB bridge integrated circuit (Future Technology Devices International Ltd, Glasgow, UK) provides connectivity between the VRS51L3074 microcontroller and the laptop PC via a USB cable. This can be useful if the wireless connection is unavailable for any reason.

2.4. Power supply

The system is powered from a 7.4 V (2 cell) lithium polymer battery, with total capacity of 2800 mAh. This feeds two switch mode voltage regulators that provide the 5 V and 3.3 V supplies necessary to run the various parts of the system. Current consumption is high at 670 mA, but with this size of battery we are still able to run the system for four hours continuously.

2.5. Wireless connection

The wireless connection to the system is provided by an EM1000 Wi-Fi™ bridge (Tibbo technology Inc., Taiwan). This communicates directly using the 802.11 protocol with a Linksys WRT54GR wireless router that is attached to the laptop via an Ethernet cable. The router and laptop together form the base station for the system.