Portable Microcontroller-Based Instrument for Near Infrared Spectroscopy

Mario E. Giardini[*a], Mario Corti[a,b], Paolo Lago[a,c], Andrea Gelmetti[a,c]

[a]INFM, via Bassi 6, I-27100 Pavia, Italy

[b]Univ. Milano, Dip. Chimica e Biochimica Medica, Milano, Italy

[c]Pol. S. Matteo, Ing. Clinica, Pavia, Italy

ABSTRACT

Near Infrared Spectroscopy (NIRS) can be employed to noninvasively and continuously measure in-vivo local changes in haemodynamics and oxygenation of human tissues. In particular, the technique can be particularly useful for muscular functional monitoring.

We present a portable NIRS research-grade acquisition system prototype, strictly dedicated to low-noise measurements during muscular exercise.

The prototype is able to control four LED sources and a detector. Such a number of sources allows for multipoint measurements or for multi-wavelength spectroscopy of tissue constituents other than oxygen, such as cytochrome aa_3 oxidation.

The LEDs and the detector are mounted on separate probes, which carry also the relevant drivers and preamplifiers. By employing surface-mount technologies, probe size and weight are kept to a minimum. A single-chip mixed-signal RISC microcontroller performs source-to-detector multiplexing with a digital correlation technique. The acquired data are stored on an on-board 64 K EEPROM bank, and can be subsequently uploaded to a personal computer via serial port for further analysis.

The resulting instrument is compact and lightweight. Preliminary tests of the prototype on oxygen consumption during tourniquet-induced forearm ischaemia show adequate detectivity and time response.

Keywords: portable NIRS, LED, digital

1. INTRODUCTION

The problem of the evaluation of the oxygen content in muscle during exercise can be approached by optical transmission measurements. The possibility of performing the measurement during an unattended activity, such as outdoor sports or everyday life can open interesting application possibilities. To this respect, a small, compact, robust battery powered instrument would be highly desirable.

From an optical point of view, biological tissue can be considered as an absorbing matrix in which a high number of inhomogeneities, which act as light scatterers, are present[1]. When collimated NIR light is injected into the tissue and the collimated transmission is observed, light losses are mostly due to scattering rather than to absorption. In such wavelength region, the optical absorption is dominated by haemoglobin, the blood constituent that carries oxygen by fixing it in an oxygenated form (oxyhaemoglobin) and releasing it into the tissue, thus reverting to a deoxygenated form (deoxyhaemoglobin). The absorption spectra of haemoglobin[2] are reported in Fig. 1. We note that below 800 nm (isosbestic point) the absorption is strongly dominated by deoxyhaemoglobin, while above the isosbestic point oxyhaemoglobin

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[*] Correspondence: Email: mgiardini@smatteo.pv.it; Telephone +39 0382 503965; Fax +39 0382 503922

absorption prevails. A small contribution to absorption is given by cytochrome aa_3, another molecule involved in oxygen metabolism. Again, such molecule has an oxidized and a reduced form; a quantitative determination of the differential absorption spectrum may give information on tissue oxygen consumption. The last NIR absorption source, which should be taken into account for quantitative non-invasive spectroscopy on the tissue, is skin pigmentation; however, such absorption term does not change during the measurement.
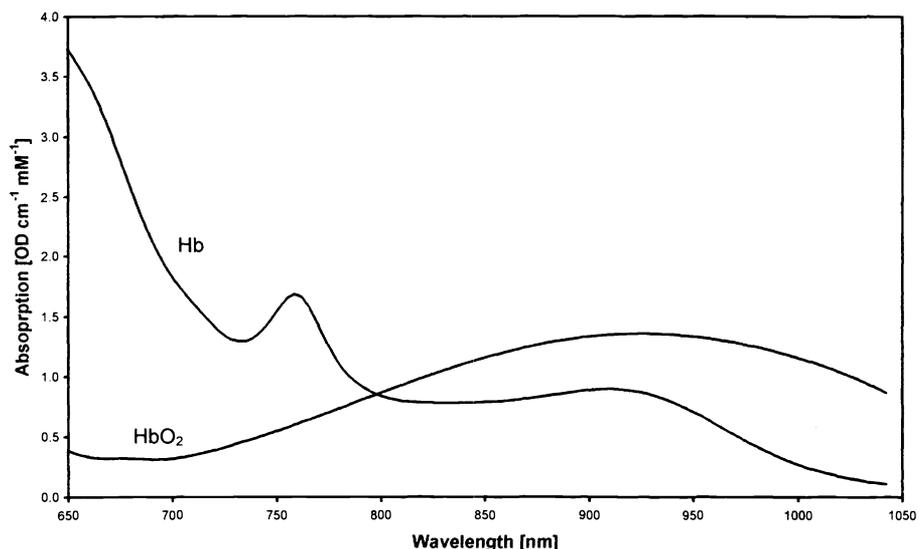

Fig. 1 – oxyhaemoglobin (HbO_2) and deoxyhaemoglobin (Hb) NIR absorption spectrum, from ref. 2.

While certainly simple from a theoretical and instrumental point of view, optical transmission requires a sampled volume, which should be transmissive enough to detect the transmitted light. Mainly because of scattering losses, this limits the application of direct transmissive measurements to small tissue thicknesses. In the last years, a number of instruments have therefore been constructed, which work on the optical spectrum analysis of the light backscattered by a depth of a few millimetres under the surface of thick tissue[3,4]. Mainly because of the difficulties in the interpretation of the resulting signals[5], the field is still very open to basic, clinical and instrumental research. In this paper, the description of a portable instrument dedicated to optical backscattering measurements from human tissue will be presented. The system is intended to be fitted on non-expert patients during unattended exercise.

The instrument, which has been developed within the activities of INFM and of the Clinical Engineering Division of IRCCS Policlinico S.Matteo, Pavia, Italy, has been called IRIS-2, for "InfraRed In-vivo Spectrometer".

2. THE MAIN UNIT

IRIS-2 is composed by a main unit, to which an emitter and a receiver probe are connected. In the literature, most quantitative algorithms rely on the backscattering data at 4 different wavelengths. The instrument is therefore capable of controlling up to 4 LED sources, located on the emitter probe; the backscattered signal is detected and preamplified on the

receiver probe. The sources can either be time-multiplexed, for measurements which require a high time resolution, or they can be multiplexed and filtered by a digital correlation technique, such as lock-in.

The main unit consists essentially in a battery powered acquisition system, with EEPROM data storage. To this acquisition system is interfaced an analog preamplifier. The acquisition system takes care of the source synchronization and of the setting of the preamplifier gain.

The structure of such main unit is represented in Fig. 2. The core of the unit is composed by a single-chip mixed-signal RISC microcontroller (PIC17C766, Microchip Technologies), with embedded 1k RAM, 32k ROM, USART, 10-bit analog-to-digital (AD) converter and SPI interface. The microcontroller generates directly the on-off signals for the source modulation, which are fed to the probe through a connector. The probe drives the sources; the transmitted light intensity is detected by the probe detector and amplifier and brought through a connector to the analog section of the module. On the analog section, the intensity signal is amplified by a 2-stage AC-coupled variable gain amplifier, whose gain is statically set by the microcontroller before the measurement. The signal is then converted by the AD converter embedded on the controller, which performs all the digital filtering and/or multiply-accumulate operations required by the multiplexing scheme chosen by the user. The acquired signal is then stored on a 64k EEPROM bank, interfaced to the controller via the SPI interface. The acquired data can be serially uploaded to a personal computer through the microcontroller USART and a TTL-to-RS232 level converter.
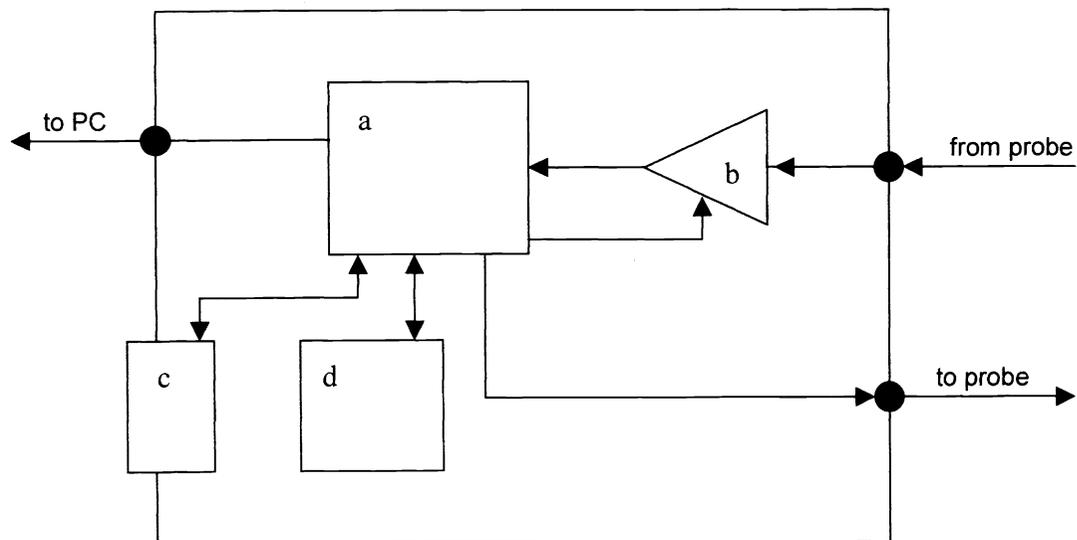

Fig. 2 – The main unit: (a) microcontroller, (b) variable gain amplifier, (c) I/O devices, (d) EEPROM

The operator interface to the main unit has been kept to a minimum, keeping in mind the intended use of the instrument. No keys or display are therefore present, but only a 5-position lockable selector knob, a press switch, a LED and the serial interface to the computer. A trained operator connects the instrument to a computer, turns the knob to an "expert user" position, sets the operating parameters and disconnects the instrument. The system is then applied on the patient, the selector knob is turned and locked on an "acquisition" position and the acquisition is started by pressing the switch. A flashing LED and an acoustic "beep" signal warns of the correct operation or of errors. At the end of the desired acquisition time, the selector is turned to a "stop" position and the acquisition is stopped. By turning the switch to a "transmit" position, the acquired data can be dumped to the serial port. A lockable "neutral" position has been provided on the knob, to allow for extra protection against unwanted operation during unattended exercise.

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3. THE PROBE

The probe employed in the performance test is actually composed by separate source and detector sections, which are applied on the patient with adhesive bands and an obscuring cuff. They are contained in separate aluminum cases, and are connected to the main unit via separate 1 m cables, as in Fig. 3.

The emitter probe carries four plastic-case LED pairs with peak wavelengths of 660 nm, 700 nm, 850 nm and 880 nm (Kingbright L-53-SRCE, Kingbright L53HD, Stanley DN304 and Siemens SFH485 respectively). The probes are driven directly on the probe head by suitable current drivers, which are switched on and off by the signals sourced from the main unit. It is connected to the main unit by a multiconductor cable with individual conductor shielding. A filter on the probe head avoids retroinjection of the switching currents.

On the detector probe is mounted a 5 mm^2 silicon photodiode. Such detector is amplified by a 2-stage transimpedence amplifier, with cancellation of the background light by a subtraction-mode highpass filter[6]. The signal is fed via a single-shield multicore cable directly to the variable gain amplifier of the main unit.

All the proximity electronics has been assembled in surface mount technology, with two-side component mounting. The circuits have been inserted directly into the aluminum probe heads.
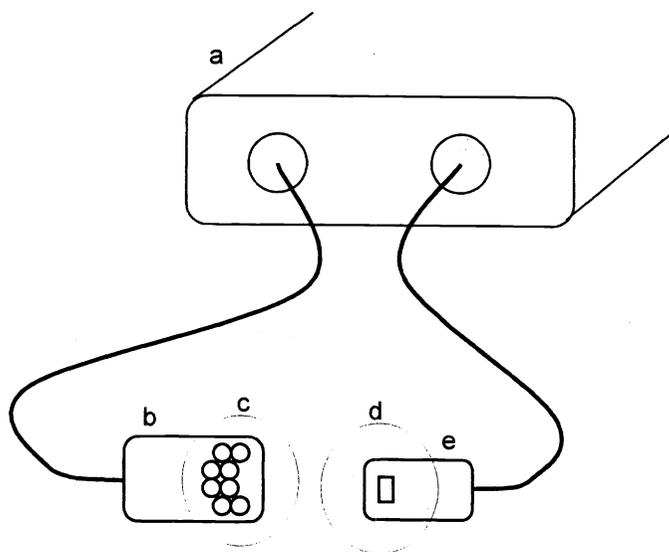

Fig. 3 – The probe: (a) main unit, (b) source probe, (c) LED pairs, (d) detector, (e) detector probe

4. PRELIMINARY PERFORMANCE TEST

The performance of the instrument has been tested on the well-known situation of a tourniquet-induced forearm ischaemia[7]. Such test is represented in Fig. 4. A patient is at rest, in a stationary state with respect to blood pressure, heart rate and muscle fatigue. A tourniquet is applied on the patient arm and inflated in order to shut off the blood supply to the forearm. During the ischaemia, oxygen consumption goes on and blood in the forearm is progressively deoxygenated. The forearm vessels respond to the deoxygenation by trying to increase the overall perfusion, hindered into this by the mechanical constraint that total blood volume must is kept constant by the occlusion. The tourniquet is then released, blood starts flowing again through the arm and oxygenation recovers its initial value, Since all volume constraints are removed, the vessels can increase their size, and so blood volume and oxygenation overshoot the stationary value, which is normally recovered a few minutes after ischaemia removal.

The test has been performed on a male 32-year old voluntary. The probe has been fixed to a large forearm muscle keeping a 15 mm source-to-detector spacing. The apparatus has been set for lock-in detection and a point has been accumulated and stored every 1.5 s. The signals, normalized to the initial values, are reported in Fig. 5.

A quantitative interpretation of the time behaviour of the ischaemic intensity curves in not within the scope of this paper, and still poses problems which are under active discussion in the literature. As far as it regards a direct observation of the signals, however, we note that the two signals at 660 and 700 nm (resp. 850 and 880 nm), whose dominating component is inversely related to deoxygenated (resp. oxygenated) haemoglobin blood content, follow a behaviour that agrees with the ischaemia description proposed in the preceding paragraph.
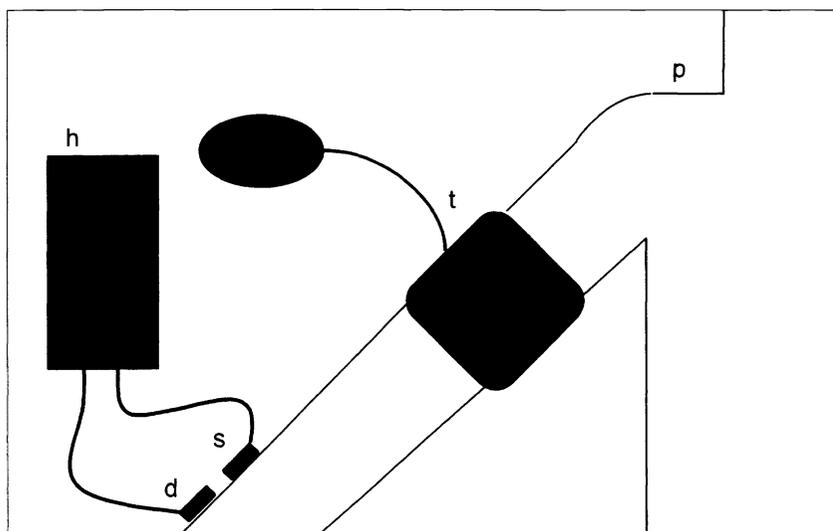

Fig. 4 – Tourniquet test: (m) main unit, (s) source probe, (d) detector probe, (t) tourniquet, (p) patient.
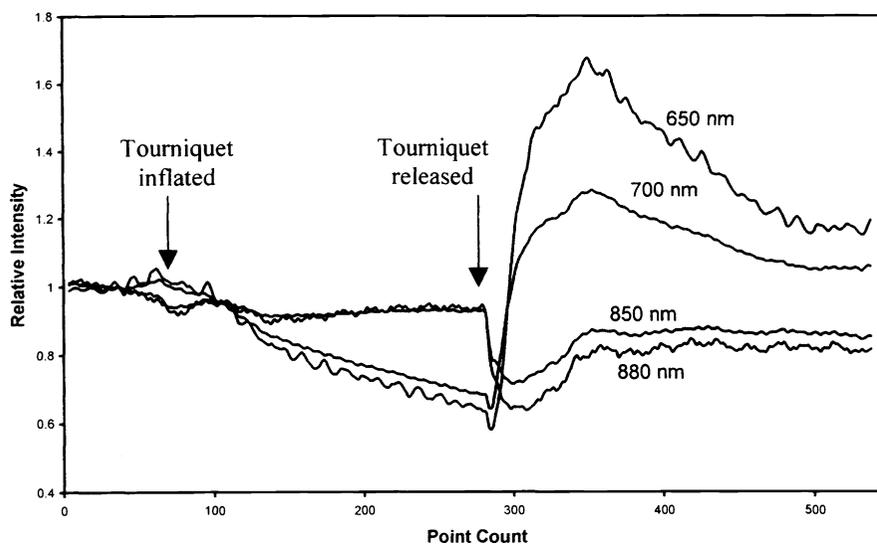

Fig. 5 – Signals measured during forearm ischaemia.

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5. CONCLUSIONS

A portable 4-channel NIRS acquisition system prototype has been briefly described in its overall structure, electronic and optical properties. The instrument has been tested on human forearm ischaemia and has shown adequate responsivity. The channel number provided is consistent with the possibility of quantitative measurements.

ACKNOWLEDGMENTS

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