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Development of Forehead Probe for Brain Oximeter

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ABSTRACT

Measurements of brain hemoglobin oxygen saturation have undergone continuous evolution. Traditional methods for its determination which includes jugular bulb oximetry require the invasive procurement of blood samples. Besides inherent patient discomfort, inconvenience and processing time requirements of such procedures constitute the primary drawbacks of existing technology. This in turn inhibits continuous real-time monitoring. With the new non-invasive method, such limitations can not only be amended, but also opens new possibilities for patient care. Brain oximetry based on Near Infrared Spectroscopy (NIRS) provides a continuous, non-invasive and real time monitoring of brain tissue oxygen saturation. The present work briefly describes the physics behind the brain oximetry and focuses on the designing of a reusable flexible Printed Circuit Board (PCB) which acts as a forehead probe for brain oximeter.

Introduction

Every year several people suffer from traumatic brain injury (TBI) which is a major cause of severe disability and death. When brain cells are damaged, they are incapable of regeneration, thus leading to necrosis. The lack of regeneration causes primary damage as well as secondary damage. Primary damage (e.g. bleeding, skull fracture) cannot be prevented and causes irreversible cell damage[1]. Secondary damage is caused by hypoxia after the head trauma[2]. In contrast with primary damage, secondary damage can be avoided. Therefore, measurement of oxygenation in the brain using brain oximeter is crucial in complex conditions such as TBI, cerebrovascular diseases, cerebral palsy etc[3]. The advantages of brain oximetry are: (i) it provides cerebral tissue blood oxygen saturation ($SctO_2$) values continuously and noninvasively at the bedside and (ii) $SctO_2$ is a sensitive index of cerebral hypoxia[4],which is one of the main causes of brain injury in clinical settings[5].

Brain oximetry with Near Infrared Spectroscopy (NIRS) offers a non-invasive and continuous measurement of brain oxygen delivery and consumption. It measures $SctO_2$ at the microvascular level(arterioles, venules and capillaries only)[6-8]. Near infrared(NIR) light can penetrate through the brain tissue to a depth of about 2cm without harmful ionization[9]. In the NIR region, there are many absorbing light chromophores, but only three are important in respect to oxygenation. They are the oxygenated hemoglobin (HbO_2), deoxygenated hemoglobin (Hb) and cytochrome oxidase(CtOx).Hb and HbO_2 are found inside the red blood cells and CtOx is the enzyme which is located in the mithochondrial membrane. The concentration of CtOx in living tissue is usually atleast an order of magnitude below that of Hb[10]. Therefore, its contribution is often neglected.

The fundamental physical property that allows the brain oximeter to measure the oxygen saturation of hemoglobin is that blood changes color as hemoglobin absorbs varying amounts of light depending on its saturation with oxygen[11]. HbO_2 does not absorb much red light, but as the hemoglobin oxygen saturation drops, more and more red light is absorbed and the blood becomes darker. At the NIR range of light however, HbO_2 absorbs more light than Hb.

NIRS technology based brain oximeter provides a safe method of assessing $SctO_2$.It is the assessment of physiological changes associated with brain activity by utilizing the optical properties of the brain tissue. This technique is based on the translucency of brain tissue in NIR spectrum and absorption spectra of Hb and HbO_2[12]. When the light from an emitting light source passes through the brain, some of it will be absorbed by the tissue and by Hb and HbO_2 in variable amounts depending on their concentration levels in the circulating blood in the cortex [13,14]. The rest of the transmitted light that returns to the surface is detected by a set of detectors which measure how much of the light was absorbed[15]. Basically due to the significant difference in the NIR light absorption spectra of Hb and HbO_2, it is possible to compute the changes in their concentration levels using the intensity of detected light. Being fast and non-invasive in nature, brain oximeter based on NIRS seems to be an asset to the bedside monitoring of TBI patients[16].

The paper aims at designing a flexible PCB which acts as a forehead probe for non-invasive monitoring of brain hemoglobin oxygen saturation. Attempts have been made to incorporate only the necessary optical components (IR LEDs of different wavelengths) and photodetectors on flexible forehead probe and all other electronic circuitry (digital logic etc.) mounted on another PCB.

Methodology

Basically there are two methods of light transmission through the measuring site to measure oxygen saturation - Transmission method and Reflectance method.

In the transmission method, the light emitter & the photodetectors are opposite of each other with the measuring site in-between. This method has various limitations such as it can be used only on limited areas of the body such as fingers and ear lobes, its measurements are not accurate in the poor peripheral conditions of tissue and it cannot detect carboxyhemoglobin (COHb) and methemoglobin (metHb) concentrations leading to

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erroneous measurement of oxygen saturation in case of carbon-monoxide poisoning and methemoglobinemia.

In the reflectance method, the light emitter and the photodetectors are next to each other on top the measuring site. The light bounces from the emitter to the detector across the site. It overcomes the limitations of transmission method and therefore the principle of NIRS based on reflectance method was used in the present work.

NIRS provides a continuous and non-invasive monitoring of $SctO_2$ by measuring the differential absorption of NIR light[17]. In this technique, NIR light is emitted at one point and sensed by a detector at a second point after passage through a medium such as skull bone which is transparent in the NIR range as shown in Fig.1. NIR light is absorbed by certain chromophores in the brain.

Thus, the attenuation of NIR light by these chromophores is related to brain oxygenation[18-20]. A "biological spectroscopic window" exists at the wavelength range 660-940 nm because only a few chromophores like Hb and HbO_2 strongly absorb light in this spectra range, allowing light to penetrate tissue to a great distance. In this wavelength range, absorption of light due to other biological compounds and tissues such as water, lipids, skin and bone is lower in magnitude and these biological compounds generally have a flat absorption spectra when compared to Hb and HbO_2 [21]as shown in Fig.2.

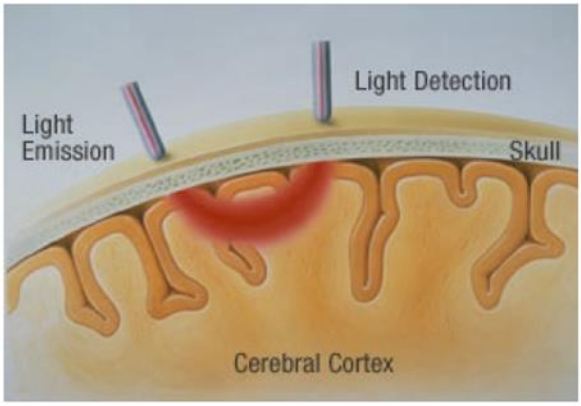

Fig.1 Principle of NIRS [22]

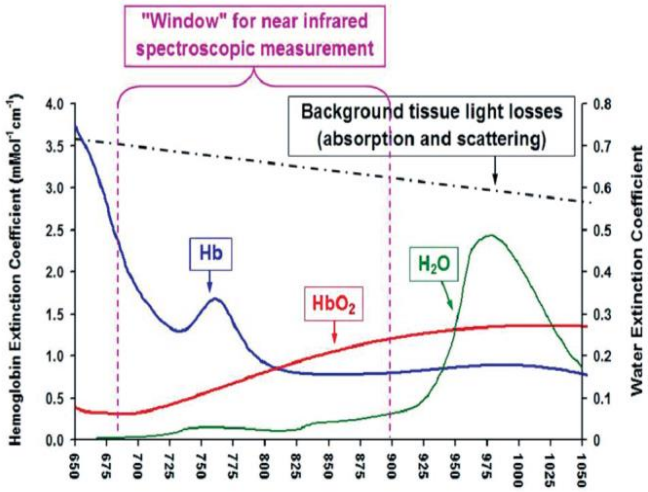

Fig. 2 Light absorption spectra of Hb and $HbO_2$and biological spectroscopic window in the NIR range [22]

In order to guarantee that only $SctO_2$ is being measured ,it minimize extracerebral contamination by equipping the photodetectors located at fixed distances from the light emitting source. The penetration depth of the light beam is proportional to the distance between the light emitting source and receiving photodetector[23]. The more distant detector (brain sensor) measures the saturation of all of the tissues penetrated by the light beam including skin, muscle tissue, skull and brain. The closer detector (scalp sensor) is spaced to capture the light only from skin and skull to measure the saturation[24]as shown in Fig.3.By subtracting the output obtained from the brain sensor and the scalp sensor, extracerebral contamination can be minimized [25].

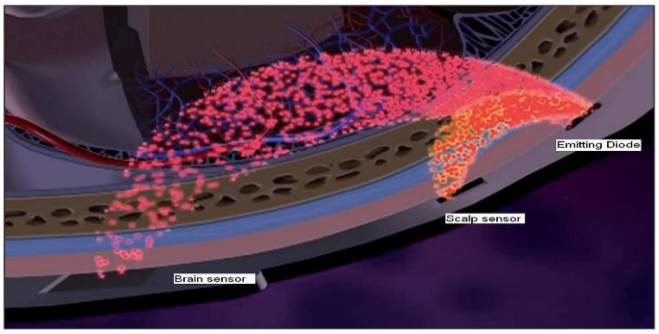

Fig.3 Technology of brain oximetry allows sampling of brain tissue from two photodetectors, each with light sources penetrating to different depths [26]

Lambert-Beer's Law and Oxygen Saturation in Hemoglobin

Brain Oximeter measures brain oxygenation using NIRS technique based on a light absorbent law called Lambert-Beer's law which describes the absorption of light intensity in a non-scattering medium. This law states that for an absorbing compound dissolved in a non-absorbing medium, the attenuation (A) of an incident light is proportional to the concentration of the absorbing compound in the solution (c) and the optical pathlength(d) [27].

$A = \log(I_0/I) = \varepsilon.c.d$

where I_0 is light intensity incident on the medium, I is light intensity transmitted through the medium, ε is the specific extinction coefficient of the absorbing compound.

In a medium containing more than one absorbing compounds, overall attenuation is the sum of individual contributions :-

$A = \log(I_0/I) = [\varepsilon_1.c_1 + \varepsilon_2.c_2 + \varepsilon_3.c_3 + \ldots.\varepsilon_n.c_n]d$

Experimental

The circuit schematic of the flexible forehead probe PCB was made using a software tool called OrCAD Capture which provides fast and intuitive schematic design entry for PCB development. To minimize the power requirements of the device, minimum hardware components were used. The flexible forehead probe for our present design consists of (i) optical components such as SMT photodetectors and dual wavelength SMT LEDs(660/940 nm, 735/890nm) and (ii) a control board i.e PCB consisting of microcontroller, analog-to-digital (A/D) converter, multiplexer (MUX), operational amplifier (op-amp), USB Connector and FFC Connector. The block diagram of PCB is shown in Fig.4.Fig.5 demonstrates the placement of the probe on the forehead.

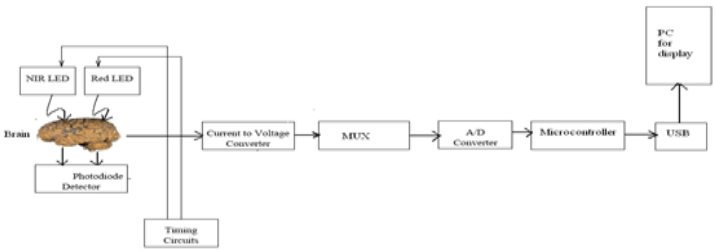

Fig.4 Block of hardware used in measuring optical signal from the brain

Fig. 5 Demonstration of probe placement over the forehead

Sequence of Data Flow

LED was turned on for a short duration and emitted light then penetrated the underlying tissues. Most photons were scattered by cerebrospinal fluid or absorbed by Hb and HbO_2, but a small fraction was reflected to the skin surface. The proportion of light returned to the surface was captured by the photodetectors. Each of the detectors received emitted light from LED and based on the coding in microcontroller, they were selected after a short duration. These detectors were placed at varying distances to sample different light path lengths through the tissue. The raw signal obtained by photodetectors was processed by opamp which was used in a current to voltage converter mode. The opamp output was sensed by MUX which selected one of the four input signals from photodetectors and send to the output called MUX OUT. This selection was done by the microcontroller. MUX OUT was then sensed by A/D converter. Finally the signal from the microcontroller was transferred to computer via USB connector for further processing and display. FFC cable was used to establish communication between flexible forehead probe and the PCB.

Results and Discussion

The forehead probe for brain oximeter was developed (Fig. 6)with the features such as comfortability, durability, compactness, secured fitness, cost effectiveness etc. that allows its use for patients of any age including infants, thus making NIRS based brain oximetry versatile.

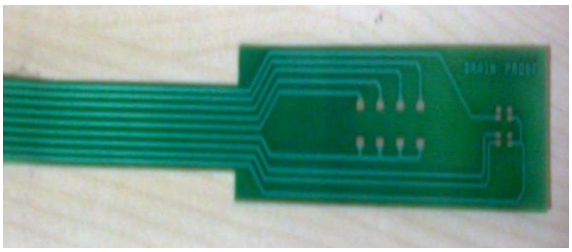

Fig. 6 Circuit schematic of flexible forehead probe

The forehead probe was also successfully tested with the PCB developed for sensing and displaying the current as given its input. A known current was given to the photodetectors using a programmable current source which was converted into voltage by op-amp and this voltage waveform was observed on CRO as shown in Fig.7.

Fig.7 Input waveform as observed on CRO

In order to ensure the reliability and accuracy of forehead probe sensor, calibration of photodetectors under the normal light and after covering by a black cloth was performed. The voltages across photodetectors were measured which are shown in Table 1.

Table 1 Voltages across Photodetectors

Photodetectors	Voltage under normal light	Voltage after covering by black cloth
D0	228 mV	20 mV
D1	230 mV	25 mV
D2	234 mV	30 mV
D3	233 mV	27 mV

Conclusion

The NIRS is an evolving technology that holds significant potential for technical advancement. The adopted technique and results obtained in the present work concluded that NIRS based brain oximetry provides a powerful and non-invasive method for assessing the cerebral tissue oxygen saturation during numerous pathological conditions with the desired level of accuracy at a remarkably low cost due to the involvement of simple, low power and cost effective electronic circuitry. The existing features of this technique ensures and promises NIRS based brain oximeter as a valuable clinical and research tool for real time monitoring of the cerebral tissue for the future generations. The data obtained by brain oximeter can be an asset in the diagnosis of neurological disorders and to the bedside monitoring of TBI patients.

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