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The estimation of recovery time of calf muscle oxygen saturation during exercise by using functional near infrared spectroscopy

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ABSTRACT

Q2 Several methods of near infrared spectroscopy such as functional near infrared spectroscopy (fNIRS) and pulse oximetry have been applied for monitoring of tissue oxygenation or arterial oxygen saturation. Some vascular diseases can be diagnosed through measurements of tissue oxygenation. In this study, the temporal variation of oxygenation of calf muscle after exercise is studied by fNIRS. First, the accuracy of a low-cost fNIRS system is studied by measuring the oxygenation of a lipid phantom. Moreover, in-vivo study is performed to evaluate the precision of this system. Then, the variation of muscle oxygenation of four persons during exercise is measured and also the recovery time after walking/running is measured by this fNIRS system.

1. Introduction

Near infrared spectroscopy (NIRS) as a non-invasive biomedical optical imaging method has been applied for monitoring bio-chromophors such as water, hemoglobin, melanin and other bio-polymers inside biological tissues [1–7]. NIRS methods such as functional near infrared spectroscopy (fNIRS) and pulse oximetry can be used for monitoring hemodynamic signals [8–12]. Advantages of NIRS such as low-cost, portability, functionality and fast data acquisition compared to other monitoring modalities have caused many valuable studies by using NIRS in hematology, dermatology and neurology to be performed [13–18]. NIRS can be a functional monitoring method, so this optical method can quantize the temporal and spatial variation of concentration of chromophors inside biological tissues [13–15]. The hemodynamic signals based on different elements like variations of concentration of oxygenated-hemoglobin (HbO_2) and deoxygenated-hemoglobin (deoxy-Hb) can be studied by NIRS [14–16].

The fNIRS has more advantages compared with pulse oximetry. A pulse oximeter can only be used on fingertip or earlobe, this limits its applications. So, pulse oximetry cannot be applied for monitoring hemodynamic responses of cerebral cortex or hemodynamic signals of muscles, while many of cognitive controls and tasks can be studied by fNIRS. In fNIRS, two wavelengths are selected, with one wavelength above and one below the isobestic point of 810 nm at which Hb and HbO_2 have identical absorption coefficients. Using the diffusion equation, relative concentration can be calculated as a function of total photon path length [19,20]. The diffusion of photons inside biological tissue is considered in fNIRS, hence this system can monitor both diffused reflected and transmitted photons [21,22]. In pulse oximery, only the variation of hemoglobin is considered and other biomolecules like skin pigments and cytochrome-c-oxidase are not considered. In addition, pulse oximeter is only used for the arterial compartment by time gating the measurements, but fNIRS can be applied for assessment of all the vascular compartments (arterial, venous and capillary). Morever, fNIRS can measure hemodynamic, metabolic and fast neuronal responses to brain activation and also it can be used in patients with low perfusion states and peripheral vascular and fNIRS gives exact oxygen level in the blood [22–27].

In spite of these limitations, pulse oximetry is applied to evaluate arterial peripheral diseases. A number of studies have been performed to determine the parameters that should be measured to those tests that could help and provide the clinician with information about the tissue oxygenation, the severity of the disease, and the results of the applied therapies [22]. Pulse oximetry can be applied for diagnosis of blood vascular diseases. Peripheral vascular disease (PVD) is a progressive arterial narrowing or obstruction mainly caused by an atherosclerotic process which reduces blood flow to the lower limbs during exercise or also at rest. Iliac arteries (lower abdomen leading to the legs) and femoral arteries (legs) are among the peripheral vessels most commonly affected by the disease. The reduced oxygen supply (from the oxy-hemoglobin in the blood) to the muscle tissue results in a cramping pain in the thigh or calf muscles, and can limit walking capabilities [5,11].

In 2001, Kragelj et al. applied a pulse oximetry to investiage parameters of postocclusive reactive hyperemia patients with PVD and in healthy volunteers. They showed that recovery times obtained from HbO_2 and Hb are significantly ($p < 0.01$) longer in PVD patients. Longer recovery times in PVD patients compared to healthy volunteers

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can be explained by slower resynthesis of phosphocreatine in this type of patient [11]. In 2003, pulse oximetry was applied to investigate the distribution of flow, concentration, and oxygenation of hemoglobin in calf muscle in patients with documented peripheral arterial occlusive disease (PVD), patients with risk factors for PVD, and healthy younger subjects at rest [28]. After that, a study to assess both tissue oxygen saturation and relative blood flow in the extremities of Peripheral artery disease (PAD) patients is done. Pulse oximeter is employed to measure hemodynamic response to treadmill and pedal exercises in 31 healthy controls and 26 patients. For tissue oxygen saturation, mild and moderate/severe PAD groups show pronounced differences compared to controls. Pre-exercise mean tissue oxygen saturation is lower in PAD groups by 9.3% to 10.6% compared to means of 63.5% to 66.2% in controls [12]. These studies illustrate that pulse oximetry and fNIRS can be applied as a good diagnosis tool for peripheral vascular disease or peripheral artery disease.

As mentioned in Ref. [11], the recovery time of muscle oxygenation is a good indicator of peripheral vascular disease. So, due to importance of temporal variation of muscle oxygenation, the estimation of calf muscle oxygenation is the key aim of this study. In the present paper, we have used the fNIRS method to monitor the temporal variation of oxygenation of calf muscle after exercise.

This current study is organized as follows. In Section 2, the method of estimation of hemodynamic signal by fNIRS is briefly reviewed. In addition, we have used the correlation coefficient to evaluate the accuracy of fNIRS, so this correlation coefficient is presented in this section. Then we explain some details of a low-cost fNIRS applied to measure hemodynamic signals. In Section 3, the accuracy of this low-cost system is evaluated by phantom and in-vivo studies. After that, the ability of this system to monitor recovery time during exercise is studied. In Section 4, we present a brief summary of results reported in the paper.

2. Materials and methods

2.1. Review of theory

In this section, we have briefly reviewed the method of estimation of variation of hemodynamic signal by fNIRS. In this method, diffusion equation and Robin boundary condition are applies to estimate the variation of hemodynamic signals as following:

$$-D\nabla^2\varphi(\vec{r},t)+a\varphi(\vec{r},t)+\frac{\partial\varphi(\vec{r},t)}{\partial t}=S(\vec{r},t) \tag{1}$$

$$\varphi(\vec{r})-2C_RD\frac{\partial\varphi(\vec{r})}{\partial z}=0 \quad \vec{r}\in\Gamma_s \tag{2}$$

here, $\vec{r}$ denotes position, $\varphi(\vec{r})$ is the fluence rate defined as the energy flow per unit area per unit time. The constant $D=1/[3(a+\sigma')]$ is diffusion coefficient, where a and $\sigma'=\sigma(1-g)$ are the absorption and reduced scattering coefficient, respectively. The anisotropic factor g which is defined as $\langle\cos\theta\rangle$ has a value between -1 and 1. $S(\vec{r},t)$ is the isotropic source term at position $\vec{r}$. Generally, the diffused signal is measured on the surface of tissue, so fNIRS uses boundary signals $\varphi_m(\vec{r}_i)$ where $\vec{r}_i$ indicates the position of ith detector on the surface of sample. Formula (2) denotes the Robin boundary condition, and C_R is the parameter which characterizes mismatch between refractive indices of the two media [4]. One can use numerical method such as finite element method (FEM) or boundary integral method (BIM) to solve the diffusion equation that are discussed in Refs. [2,3,29].

It can be seen from Fig. 1 that the geometry of source–detector in fNIRS system is simple and the diffusion equation can be analytically solved [15,29]. Also, the absorbance of medium can be simply estimated:

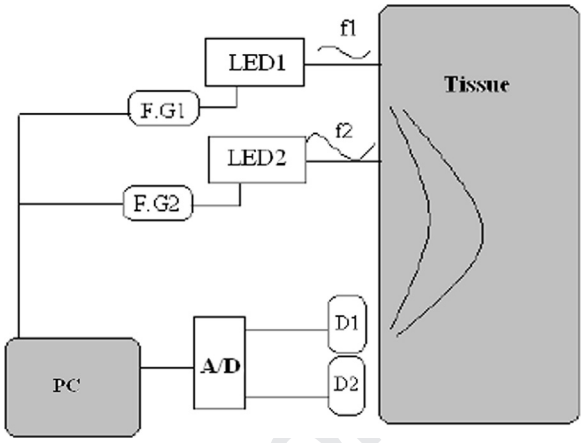

Fig. 1. Schematic presentation of reflectance geometry of fNIRS system, LED 1 and LED 2 are the two different LED at wavelength of 655 nm and 926 nm; F.G1 and F.G2 are the modulation module at frequencies of f1 = 1.39 kHz and f2 = 10.57 kHz. D1 and D2 are the commercial detectors and A/D is an analog to digital convertor.

$$A=-\ln(\varphi_d^o)=aL \tag{3}$$

where φ_d^o is the normalized diffused fluence measured by detector and $L=\vec{r}_i$ is the inter-optode distance between source and detector. The absorption coefficient is directly proportional to chromophore concentration, so the changes in absorbance $\Delta A=B\varepsilon\Delta CL$ can be applied to monitor variation of concentration of chromophores [30]. Where B is a path length factor, which accounts for increases in the photon path length caused by tissue scattering, and ε and C are the extinction coefficient and concentration of chromophore. The variation of hemodynamic signals can be related to concentration of two chromophores, namely Hb and HbO_2, we can show the changes in absorbance as following [31]:

$$\begin{cases}\Delta A_1=BL(\Delta C_1\varepsilon_1(\lambda_1)+\Delta C_2\varepsilon_2(\lambda_1))\\ \Delta A_2=BL(\Delta C_1\varepsilon_1(\lambda_2)+\Delta C_2\varepsilon_2(\lambda_2))\end{cases} \tag{4}$$

ε_1 and ε_2 are the extinction coefficients for Hb and HbO_2. By taking measurements at a second wavelength and using the known fluence at these wavelengths for each chromophores, Eq. (4) can be solved for concentration changes as follows:

$$\Delta\mathrm{Hb}=\frac{\ln(I_0(\lambda_2)/I(\lambda_2))\varepsilon_2(\lambda_1)-\ln(I_0(\lambda_1)/I(\lambda_1))\varepsilon_2(\lambda_2)}{(\varepsilon_2(\lambda_1)\varepsilon_1(\lambda_2)-\varepsilon_2(\lambda_2)\varepsilon_2(\lambda_1))BL} \tag{5.a}$$

$$\Delta\mathrm{HbO_2}=\frac{\ln(I_0(\lambda_1)/I(\lambda_1))\varepsilon_1(\lambda_2)-\ln(I_0(\lambda_2)/I(\lambda_2))\varepsilon_1(\lambda_1)}{(\varepsilon_2(\lambda_1)\varepsilon_1(\lambda_2)-\varepsilon_2(\lambda_2)\varepsilon_2(\lambda_1))BL} \tag{5.b}$$

and venous oxygen hemoglobin saturation (SvO_2) can be defined as

$$\mathrm{SvO_2}=\frac{\Delta[\mathrm{HbO_2}]}{\Delta[\mathrm{HbO_2}]+\Delta[\mathrm{Hb}]} \tag{6}$$

In this study, to compare the measured value obtained by fNIRS with expected values, we use the correlation coefficient, R, that can be calculated as following [32]:

$$R=\left(\frac{n\sum xy-(\sum x)(\sum y)}{\sqrt{n(\sum x^2)-(\sum x)^2}\sqrt{n(\sum y^2)-(\sum x)^2}}\right)^2 \tag{7}$$

where x and y are the expected and measured values, respectively and n is the number of data. R is a measure that determines the degree of coherency and correlation between expected value and measured values obtained by fNIRS system. A correlation coefficient close to unit indicates a good association between variables.