Functional Near Infrared Spectroscopy for Measuring Bone Hemoglobin Content after Exercise in Individuals with Spinal Cord Injury

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***Abstract*— Bone blood perfusion has an essential role in maintaining a healthy bone structure. However, current methods for measuring bone blood perfusion are expensive and highly invasive. The spinal cord injury (SCI) population is at high risk of cardiovascular diseases and profoundly accelerated osteoporosis. Thus, we aim to investigate changes in bone blood perfusion with rowing in able-bodied and in individuals with SCI. This study presents a custom functional near-infrared spectroscopy (fNIRS) instrument to monitor oxygenated and de-oxygenated hemoglobin changes in the human tibia. Six individuals with SCI and nine able-bodied rowers performed a 10-minute rowing exercise. With exercise, able-bodied rowers showed an increased blood content, while the same increase was not observed in SCI rowers. Our preliminary results show that fNIRS can non-invasively detect changes in oxygenated and de-oxygenated hemoglobin concentration in the human tibia.**

I. Introduction

Bone vascularization plays an essential role in bone growth, modeling and remodeling [1]–[4]. Bone blood vessels are responsible for nutrient delivery and oxygen control, highly influencing bone metabolic activity [5]. Changes in blood perfusion may be indicative of pathology. For example, an increase in blood perfusion results from cancers, hyper-remodeling, osteoarthritis, and bone marrow lesions; while a decrease in blood perfusion results in osteoporosis, osteonecrosis, and fracture non-union.

In the spinal cord injury (SCI) population, there is profoundly accelerated osteoporosis. Those with SCI lose approximately 40% of their bone mass in the first 1 to 3 years after injury [6], increasing the risk of fracture in the rich trabecular sites of the proximal tibia and distal femur [7]. Moreover, cardiovascular diseases are the leading cause of death in the SCI population [8]. Current studies suggest that there might be peripheral vascular factors that increase cardiovascular risks [9]. Functional electrical stimulation (FES) rowing has been successfully used to improve overall cardiovascular health [10] and shows promise in improving bone health [11]. Good blood perfusion is essential in maintaining a healthy bone structure. However, the current methods for measuring bone blood perfusion are expensive, highly invasive, and require the use of contrast dyes and ionizing radiation [12].

In the present study, we developed an inexpensive device capable of measuring blood oxygenation in the human tibia using Functional Near-Infrared Spectroscopy (fNIRS) [13]. Functional NIRS relies on spectral differences in the light absorbing properties of oxygenated and de-oxygenated hemoglobin in human tissue. The objective of this study was to measure blood perfusion using fNIRS in the tibia and to investigate changes in bone blood perfusion with rowing in able-bodied and in those with SCI.

II. Methods

A. Participants

Six individuals with spinal cord injury were recruited from current patients in the Spaulding Rehabilitation Hospital SCI exercise program for FES-rowing. All those with SCI were adults with spinal cord injury of American Spinal Injury Association A and C at the neurological level of C5-L2. Nine able-bodied individuals were recruited via flyers on university campuses. All procedures were approved by the Institutional Review Board at Spaulding Rehabilitation Hospital, and all participants provided written informed consent.

B. Exercise Protocol

All participant were asked to perform a 10-minute protocol, which involved 2-minutes of rest, 5-minutes of rowing, followed by an additional 3-minutes rest. An adapted Concept2 (Model D) ergometer was used for all the tests. For those with SCI, an Odstock 4-channel electrical stimulator was used to activate the quadriceps and hamstrings through surface skin electrodes placed over the muscle motor points. For the rest intervals, the participants were sitting on the rower, with a knee angle of 120º. The intensity of the rowing exercise given by wattage was kept constant and was subject specific, intended to represent 70% of the peak achievable for each individual. This was estimated from the corresponding percentage of age-predicted heart rate for the able-bodied (220 beats/min-age), and from prior peak aerobic capacity tests that had been performed for the exercise program for those with SCI.

C. Experimental Apparatus

We developed a custom near-infrared spectroscopy instrument to monitor oxygenated and de-oxygenated hemoglobin changes in the bone. Our instrument used a white-light tungsten halogen lamp (Fostec DCRII) to deliver light through a large optical fiber bundle to the skin that covers the tibia. Additionally, two fiber-coupled spectrometers (Ocean Optics, USB 2000) were used to measure the diffuse reflected light at two source-detector distances. The light source and the two detectors were attached to a holder placed on the anterior side of the tibia. The two detectors, placed at 1-cm and 2-cm distances from the source, allowed measuring light that propagates over two different optical path lengths which corresponds to different penetration depths. The light measured by the detector closest to the source (detector A) propagates primarily through the relatively thin (~2mm) skin layer. The light measured by the detector furthest to the source (detector B) on average penetrates deeper into tissue and is therefore more sensitive to the underlying bone (Fig 1).

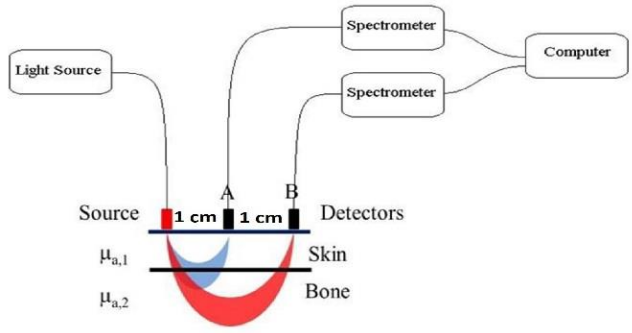

Figure 1. Functional NIRS setup.

D. Data Analysis

The extended modified Beer-Lambert law for a two-layer model was used to determine the changes in hemoglobin content from the changes in light absorption [14], [15]. Thus, the optical density (OD) obtained for detectors A and B (at a single wavelength) is given by:

$$OD_A = -ln\frac{I_A}{I_0} = \mu_{a,1}L_{1,A} + G_{1.A} + \mu_{a,2}L_{2,A} + G_{2.A}, \quad (1)$$

$$OD_B = -ln\frac{I_B}{I_0} = \mu_{a,1}L_{1,B} + G_{1.B} + \mu_{a,2}L_{2,B} + G_{2.B}, \quad (2)$$

where I_i is the signal strength, $\mu_{a,i}$ is the absorption coefficient for Layer i; $L_{i,j}$ represents the average path length in Layer i as a function of the physical source-detector distance and a differential path length factor (DPF), and G_i represents the loss in signal due to scattering. Since the scattering loss factors are difficult to estimate and we are only interested in quantifying changes between one state and another (e.g. before and after exercise) where the dominant effect would be due to absorption, the dependence on G_i can be eliminated by considering the difference between two measurements at different times.

Thus, the change in absorption coefficient in bone ($\Delta\mu_{a,2}$) is given by:

$$\Delta OD_B - r\Delta OD_A = \Delta\mu_{a,2}L_{2,B}, \quad (3)$$

where $r = L_{1,B}/L_{1,A}$.

Here, the dependence on wavelength (λ) is omitted, but this was measured between 650 and 800 nm in 1 nm increments in the near-infrared range. The effective path lengths $L_{1,A}$, $L_{2,A}$, $L_{1,B}$, $L_{2,B}$ in (1), (2) were estimated using open source Monte Carlo photon modeling software [16] and literature estimates of optical properties of skin and bone at different wavelengths [17]. The desired chromophore concentration changes could then be obtained as a least-squares estimate:

$$\Delta C = (E^T E)^{-1} E^T \Delta\mu_{a,2}, \quad (4)$$

where E represents the matrix of the known extinction coefficients of each chromophore.

The concentration change in oxygenated and de-oxygenated hemoglobin between rest and rowing was assessed in able-bodied and SCI FES-rowers. Changes in concentration of oxygenated and de-oxygenated hemoglobin within each group were assessed using a one-sample t-test. Differences in hemoglobin concentrations between able-bodied rowers and SCI FES-rowers were assessed using a two-sample t-test.

III. Results and Discussion

The measured intensity for both detectors for a representative able-bodied individual during a rowing test is presented in Fig 2. As seen in the intensity spectrum, the intensity of the scattered light drops during rowing exercise, as well as post-exercise for both layers, indicating an increase in blood perfusion.

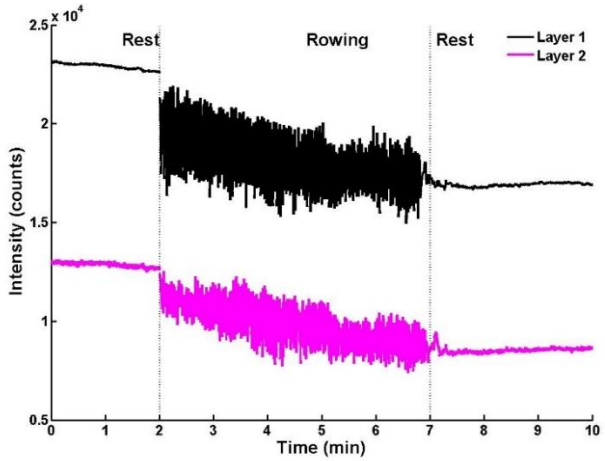

Figure 2. Intensity of the two layers system for a representative able-bodied individual during rest and rowing.

The changes in total hemoglobin concentration in the tibia between rest and rowing, and between rest and post exercise for the SCI and able-bodied groups are shown in Fig. 3. The changes in total hemoglobin concentration in the tibia are negative for all SCI FES-rowers. With exercise, 6 out of the 9 able-bodied rowers have an increase in total hemoglobin concentration. The changes in hemoglobin concentration in those with SCI did not reach significance with FES-rowing. For the able-bodied group, there is a significant change in total hemoglobin concentration ($p=0.01$) and de-oxygenated hemoglobin concentration ($p<0.01$) post rowing.

As a group, SCI FES-rowers had a significant lower total hemoglobin concentration compared to able-bodied during rowing ($p=0.04$). The lower total hemoglobin concentration of the SCI FES-rowers compared to the able-bodied were mainly due to a significantly lower de-oxygenated hemoglobin concentration both during rowing and post exercise ($p=0.01$, and $p=0.03$ respectively).

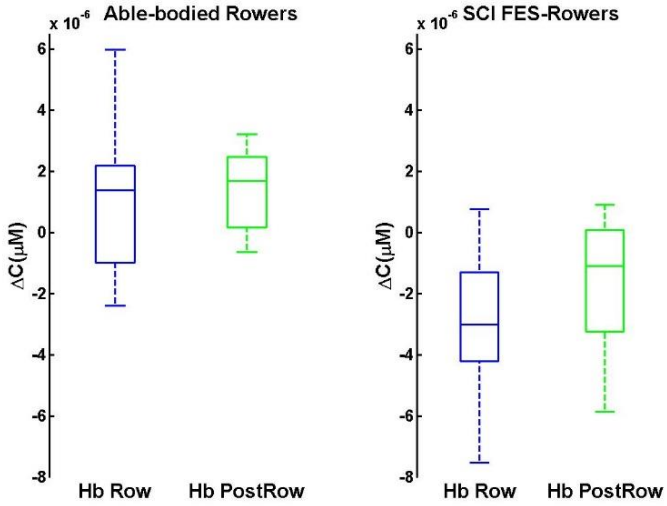

Figure 3. Total hemoglobin concentration change in able-bodied (left) vs. spinal cord injured (right) with rowing.

IV. Conclusion

The current study illustrates that the functional NIRS can non-invasively detect changes in hemoglobin concentrations in the tibia using diffusely reflected light. Moreover, our preliminary data indicates that exercise significantly increased blood content post-exercise for the able-bodied rowers, but did not cause the same increase in SCI FES-rowers, rather, a slight decrease was observed.

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