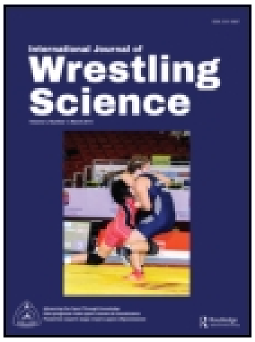

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Biophotonic Technique to Study Muscle Tissue Metabolism of Athletes

Martin Wolf[1], Adkham Paiziev[2], and Fikrat Kerimov[2]

ABSTRACT. Near-infrared spectroscopy is an affordable technology that can be used in monitoring muscle oxygenation in exercise and sport setting. In this study, we presented a portable, wireless, multichannel near-infrared spectroscopy device for real-time monitoring of muscle activity. Wireless communication was applied to data transmission in order to avoid cumbersome wires, and the whole system is highly integrated. We took special care to eliminate motion artifact when designing the near-infrared spectroscopy sensor for attachment to human skin. In addition, the system is designed with a high sampling rate so as to monitor rapid oxygenation changes during muscle activity. The wireless near-infrared spectroscopy sensor was designed using commercially available electronic components that were mounted onto a 4-layer rigid-flexible printed circuit board. We performed in vivo experiments including arterial occlusion and isometric voluntary forearm muscle contraction among wrestlers and demonstrated that the system can effectively monitor muscle oxygenation parameters, even in exercise.

Keywords: muscle, physiology, strength training, testing, training control

Near-infrared spectroscopy (NIRS) is one biophotonic technique that can be used to monitor oxygenation and hemodynamics in a variety of human tissues, including skeletal muscle. Because of the differing light absorption properties of oxygenated hemoglobin ($Hb0_2$) and deoxygenated hemoglobin (HHb), in the near-infrared range of the electromagnetic spectrum (see Figure 1), shining light into the tissue can yield information relating to the concentrations of each form of the chromophore (Wray, Cope, Delpy, Wyatt, & Reynolds, 1988). This technique is entirely noninvasive, and provides real-time, in-vivo information relating to changes in oxygenation of the tissue. It also provides a measure of blood volume changes in the tissue by reporting alterations in total concentration of $Hb0_2$ + HHb, to give a measure of total hemoglobin. NIRS has been used in a sports and exercise science setting for a number of decades, and it has provided insights into changes in muscle oxygenation (StO_2) during a wide range of exercise modalities (Wolf, Ferrari, & Quaresima, 2007). Different investigators have reported the feasibility of conventional NIRS in monitoring the pattern of skeletal muscle chromophore changes during rest, isometric exercise, and ischemia (e.g., Quaresima, Lepanto, & Ferrari, 2003). This paper provides an overview and analysis of the new portable, wireless tissue oximetry (OxyPrem) device based on NIRS, and its potential application in wrestling science.

To maximize training for wrestling competition, coaches and wrestlers are interested in improving the physiologic capacities that are most important for successful performance. One of most important performance parameters in wrestling are oxygen consumption (mVO_2) and the maximal aerobic power (VO_2max) upper- and lower-body muscles of athletes (Horswill, Scott, & Gated, 1989). To measure VO_2max, one needs to use an incremental treadmill running protocol and gas exchange of CO_2 and O_2 on a systemic level (Horswill, Scott, & Galea, 1989). However, accepted methods to measure systemic aerobic power cannot reveal separate skeletal muscles performances of upper and lower body on a local level. For freestyle wrestling, it is most important to train the lower extremities; performance of upper extremity muscles is very important in Greco-Roman wrestling. Traditional NIRS devices are noninvasive, which can be used to monitor changes in oxygen saturation and hemoglobin concentra-

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uijw.
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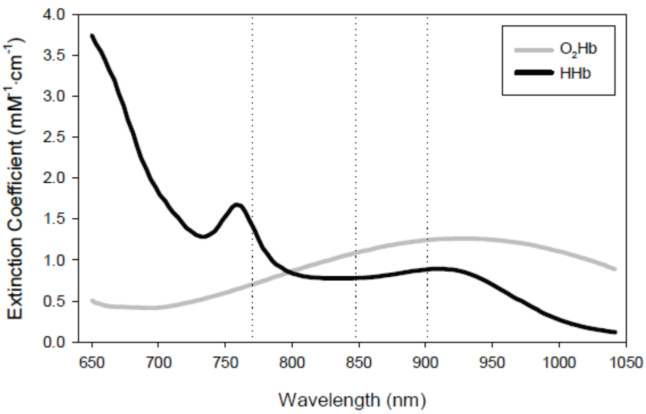

FIGURE 1 Absorption spectra of O_2Hb and HHb in near-infrared wave range.

tion in the muscle microvasculature during exercise. However, the majority are too large to be worn on the body and therefore research has been primarily limited to laboratory-based experiments. Furthermore, in situations where the NIRS monitoring of freely moving athletes is required, the application of cable connections is not possible. The recent development of reliable portable NIRS devices presents the opportunity to measure muscle oxygenation and blood flow in vivo during simulated competition in a realistic sporting setting. In the present work, we offer tissue oximetry (OxyPrem) to measure hemodynamic parameters of skeletal muscles (tissue oxygen consumption (mVO_2), total hemoglobin, tissue oxygen saturation (StO_2), tissue reoxygenation after stimuli) in rest and exercise.

METHODS

Instruments

The Laboratory of Biomedical Optic (Neonatology Hospital of Zurich University, Switzerland) elaborated the new NIRS device (OxyPrem) for noninvasive measurement of localized tissue oxyhemoglobin ([O_2Hb] and deoxyhemoglobin (HHb) concentration and StO_2 by means of NIRS (Arri, Muehlemann, Biallas, Bucher, & Wolf [2005]; see Figure 2). It applies four light sources with three light-emitting diodes with nominal wavelengths of 760 nm, 805 nm, and 870 nm, and two detectors. The pair-wise source-detector separation is 1.5 and 2.5 cm. OxyPrem is a continuous-wave (CW) NIRS device with a function principle similar to the well-known and widely applied pulse oxymeters. Light in the near-infrared spectrum (NIR light), i.e. with a wavelength between 650 and 1000 nm, is emitted into living tissue and detected after its transmission. From the absorption in tissue (i.e., the difference of emitted and detected light intensity), the concentration of oxyhemoglobin and deoxyhemoglobin can be calculated, since the absorption properties of these substances are known and the absorption effects of other substances can be neglected. OxyPrem is attached on the bare skin over the tissue of interest (brain or muscle). After powering up OxyPrem, it can be connected to an OxyPrem-CAU (a notebook computer with a Bluetooth antenna), and the data acquisition software Tubis can be installed. Tubis records the raw light intensity signal as detected by the light detectors of OxyPrem. The data are stored, which can be exported and analyzed offline to compute [HHb], [O_2Hb], and StO_2. This raw-data file also contains records of the movements of the OxyPrem sensor-head as measured by a three-axis accelerometer on the OxyPrem sensor head. Tubis controls the OxyPrem sensor remotely via a Bluetooth link. Tubis enables the user to initiate and terminate the measurement, to set the light source intensities to appropriate levels, and to monitor the quality of the acquired signal. The wireless NIRS sensor was designed using commercially available electronic components, which were mounted onto a four-layer rigid-flexible printed circuit board. The flexible parts of the printed circuit board in combination with a highly flexible casing made of medical grade silicone enable the sensor to be aligned to curved body surfaces. Although LEDs have a broader emission spectrum than lasers, they have several advantages: they can be applied directly on the body surface without need for lenses or fibers and they are inexpensive. Four PIN silicon photodiodes in combination with trans impedance amplifier stages are used as detectors.

FIGURE 2 View of portable wireless Oxyprem device.

In experiments to control maximal voluntary contraction of forearm muscle (brachioradialis muscle), we used handgrip dynamometer.

Procedures

Oxygen Consumption

Measurement of muscle O_2 consumption is of great importance in the investigation of in vivo skeletal muscle metabolism. Using venous occlusion, mVO_2 is calculated from the rate of increase in HHb (see Figure 3A; Beekvelt, Colier, Wopvers, & Engelen, 2001). Calculation of VO_2, from arterial occlusion assumes that total hemoglobin remains constant and can then be derived from the rate of decrease in O_2Hb (see Figure 3B).

Blood Flow

Venous occlusion is used to provoke a blood volume increase in the part of the limb distal from the pneumatic cuff. Within the initial period of the occlusion, the increase in blood volume per time is a measure for the blood flow. NIRS measures blood volume changes directly in the muscle of interest by monitoring changes in the hemoglobin/myoglobin content. Blood flow in arm or leg can be measured during venous occlusion by evaluating the linear increase in total hemoglobin within the first seconds of the venous occlusion (Figure 3A).

Reoxygenation Rate

Another variable that can be calculated in relation to recovery from arterial occlusion or exercise is the rate of O_2Hb reoxygenation. The reoxygenation rate reflects the velocity at which the recovery starts off after release of exercise or ischemia. This variable reflects the initial inflow of O_2Hb over a fixed time period and is, therefore, not influenced by the presence or absence of a hyperaemic response (Beekvelt, Colier, Wopvers, & Engelen, 2001).

Participants

We performed venous occlusion, arterial occlusion, and isometric brachioradialis muscle contraction experiments on one group of volunteers consisting of 5 men and 6 women and on a target group of 5 young wrestlers from Tashkent College of Olympic Reserve. All participants were given adequate instructions on the study, and the study was con-

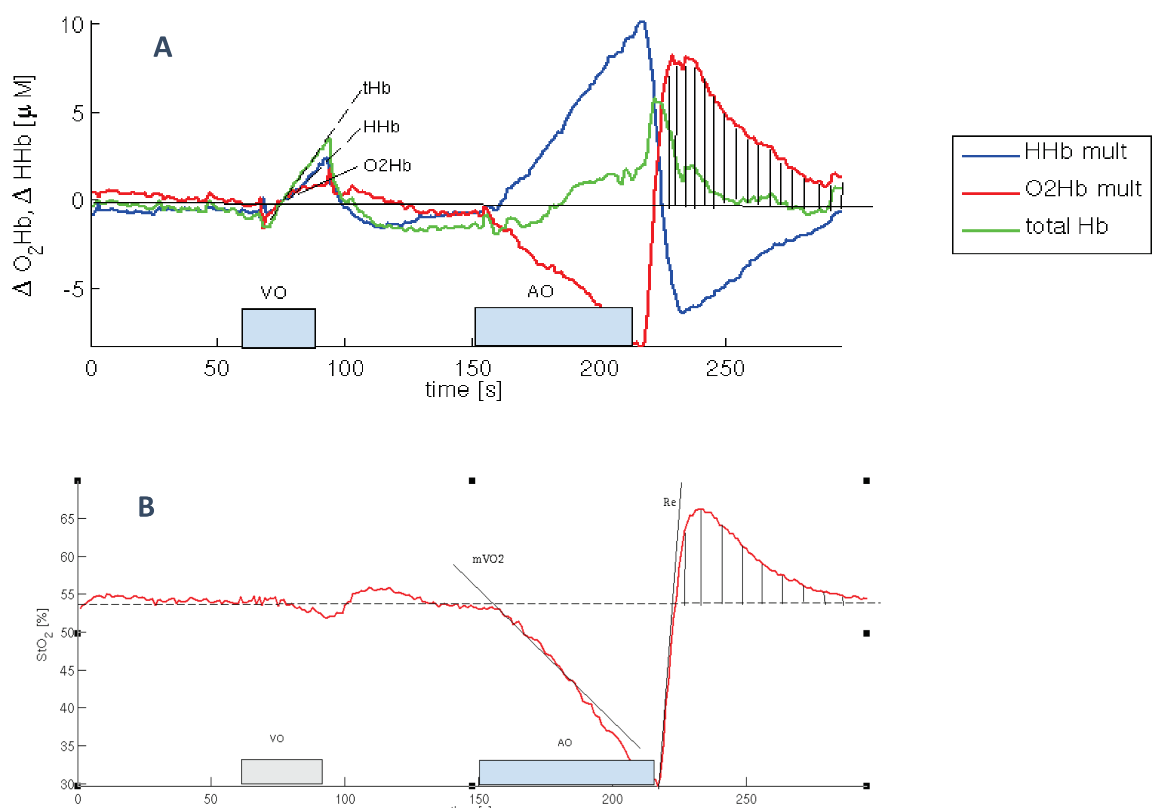

FIGURE 3 Quantitative near-infrared spectroscopy measurements during venous occlusion (A) and arterial occlusion (B). During venous occlusion, blood flow, muscle oxygen consumption (mVO_2) can be calculated. Using arterial occlusion, it is possible to calculate mVO_2 and the reoxygenation rate (Re).

ducted with the approval of the institutional review board at the Uzbek State Institute of Physical Culture in Tashkent, Uzbekistan.

RESULTS

We performed venous occlusion, arterial occlusion, and isometric voluntary forearm muscle contraction on 5 healthy men (23,2 ± 0.84 in age, 0.43 ± 0.05cm of SFT) and four women (22.0 ± 1.0 in age and 0.24 ± 0.04 cm SFT) of control group, as described in (Gerovasili, Dimopoulos, Tzanis, Anastasiou-Nana & Nanas, 2010). Concentration changes of HbO_2 and HHb were calculated by modified Lambert-Beer's Law (Quaresima, Lepanto, & Ferrari, 2003). The brachioradialis muscle of each individual was identified and marked and NIRS sensor head has been placed over marked point. A standard blood pressure cuff was attached to the upper arm. After 1 min baseline data collected, the cuff was inflated to a pressure 50 mmHg. Venous occlusion was maintained for 0.5 min, and then the cuff was released quickly and data was collected for a further 1-min rest period. Next cuff was inflated to pressure 250 mmHg (arterial occlusion) and pressure was maintained for 1 min and then the cuff was released (see Figure 3A). This figure shows the HbO_2 and HHb concentration changes in venous and arterial occlusion. During venous occlusion, we observed linear increasing of HHb, HbO_2, and total hemoglobin concentrations but during arterial occlusion HbO_2 fell nearly time-linearly when the occlusion was applied, and rose when the occlusion was removed. The HHb concentration change was increased and total hemoglobin tended to remain stable. After cuff release all hemodynamic parameters returned to basal values. In Figure 3B, the tissue oxygenation index (StO_2) depictured depend on time. The mVO_2 of subjects under investigation has been calculated as the slope of tangent to arterial occlusion curve StO_2 (see Figure 3B) during the first seconds of arterial occlusion for the control group (–0.65% per second ± 0.07 for men and –0.69% per second ± 0.19 for women). Accordingly, for the reoxygenation rate after cuff release, we obtained 12.2% per second (*SD* = 5.1) for men and 9.43% per second (*SD* = 4.14) for women. For target group members (wrestlers from Tashkent College of Olympic Reserve), the mVO_2 in average is –0.87% per second (*SD* = 0.3). The average tissue oxygenation index for wrestlers is approximately 75%, whereas in the control group, StO2 = 63%.

The second experiment was connected with quality monitoring muscle activity during isometric voluntary forearm muscle contractions at 10%, 30%, and 50% of maximum voluntary contraction. A dynamometer was used to measure maximal voluntary contraction of the subject and values for 10%, 30%, and 50% maximal voluntary contraction. For the control group, the mean measured maximal voluntary contractions were 35.4 kg (*SD* = 3.97 kg) for men and 19.8 kg (*SD* = 4.02 kg) for women. A NIRS sensor was placed on the forearm of the subject, over the brachioradialis muscle. 05 min baseline data was collected and then the subject performed 10%, 30%, and 50% maximal voluntary contractions

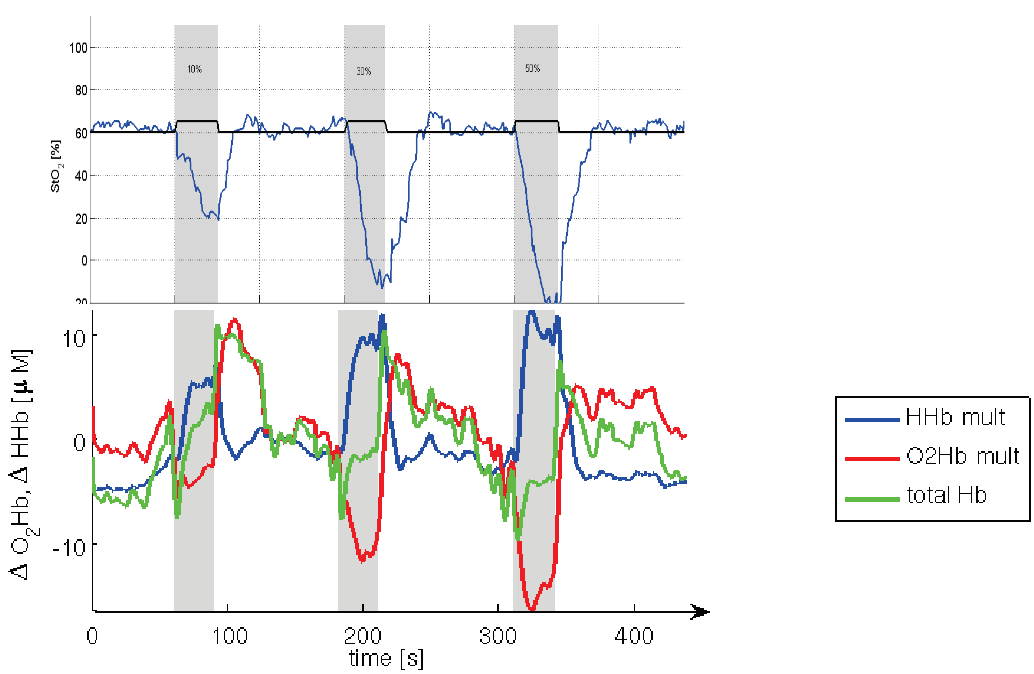

FIGURE 4 Behavior of hemodynamic parameters during successive three sets of isometric voluntary contractions of muscles at 10%, 30%, and 50% of maximum voluntary contraction.

in turn. Duration of every contraction 0.5 min and rest time between contractions 1 min. Figure 4 shows the concentration changes of HbO_2, HHb, and total hemoglobin observed in experiment. As we can see, concentration changes of HbO_2 decreased and HHb increased during each contraction phase (see lower graph of Figure 4). The maximum concentration changes of HbO_2 and HHb were positively correlated to the contraction intensity.

CONCLUSION

We have presented a portable multichannel wireless NIRS device for real-time monitoring of muscle activity. The miniaturized NIRS sensor and the usage of wireless communication make the whole device have a compact size, thus can be used in muscle monitoring. A lightweight and inexpensive miniaturized wireless NIRI device with good practical applicability has been realized. First experiments show that the measurement accuracy is comparable to well established NIRS instruments. The device is easy to handle and the battery lifetime is sufficient for many desirable applications. Test experiments of venous and arterial occlusion and isometric voluntary forearm muscle contraction demonstrate the system has the ability in monitoring muscle oxygenation parameters effectively even in exercise.

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