EVALUATION OF THE OPTICAL PROPERTIES AND TISSUE OXYGEN SATURATION OF THE TISSUES OVERLYING THE GREATER TROCHANTER

Ka-Him Lui, Eric Wing-Cheung Tam
Department of Health Technology and Informatics, The Hong Kong Polytechnic University, Hong Kong, China

INTRODUCTION

Pressure ulcers are localized areas of tissue damages in skin and/or underlying tissues resulted from prolonged unrelieved external loading. Localized ischemia and ischemia-reperfusion injuries are postulated to be two of the main etiological factors for pressure ulcers (1 - 4). Various attempts have been made by researchers to investigate the tissue oxygenation changes under compression. Bader (5) showed that under repetitive loading, transcutanous oxygen tension (T_cPO_2) level measured at compression site will vary according to tissue viability. Li (6, 7) used spectral analysis to examine the blood flowmotions measured from reflectance spectrometry and laser Doppler flowmetry (LDF). He demonstrated that there were increased endothelial-related metabolic and decreased myogenic activities in post compression reactive hyperemia period. However, due to the limited penetration power of the instrumentations, the measurements obtained were mainly from the skin layer. Recently, there are increased concerns in pressure ulcers originated from deep tissues. To elucidate the causation of deep tissue injuries, new techniques are required to examine tissue oxygenation at deep tissue under the loading site.

Near infrared (*NIR*) spectroscopy can provide *in vivo* measures on the absorption coefficient (μ_a) and scattering coefficient (μ'_s) in deep tissues (8). Oxyhaemoglobin (HbO_2) and deoxyhaemoglobin (Hb) are the main chromophores and have different absorption spectra in NIR region. Using the μ_a obtained from at least two wavelengths in the NIR region, concentration of HbO_2 and Hb, total hemoglobin concentration ([tHb]) as well as tissue hemoglobin oxygen saturation (S_tO_2) can be determined. The concentration of HbO_2, [tHb] and S_tO_2 provides information of oxygen store, blood supply and tissue oxygenation level within the tissues. With the use of μ_a and μ'_s, the maximum sampling depths (MSD) of the measurement can be estimated (9).

In vivo quantitative evaluation using NIR spectroscopy has been performed on brain (11, 12), forearm (13, 14) and thigh (14) in other studies. However, the optical properties and tissue oxygenation of the risk areas for pressure ulcer such as greater trochanter (GT) are still unclear. In this study, we examined the optical properties and tissue oxygenation at the forearm and GT of healthy subjects using the multi-distance frequency domain (MDFD) method (15).

METHODS

Instrumentations

The μ_a and μ'_s, were measured by spectrophotometer (Imagent, ISS, USA) using MDFD method. The concentration of HbO_2 and Hb, [tHb] and S_tO_2 were calculated using equation 1 to 4. The optical probe consists of a four optical fibers arranged with 1.5, 2, 2.5 and 3 cm source-detector separation. Eight laser diode sources emit NIR light at peak wavelengths of 690 nm and 830 nm with modulation frequency at 110 MHz. Calibration was done by placing the fiber optic probe on a solid phantom with absorption coefficient of 0.135 mm^{-1} (690 nm) and 0.131 mm^{-1} (830 nm) as well as transport scattering coefficients of 5 mm^{-1} (690 nm) and 4.3 mm^{-1} (830 nm).

The forearm measurement

Nine healthy subjects, aged 22.3 ± 1.6 years old, participated in this part of the study. They were asked to lie supine with their palms facing up (figure 1). The fiber optic probe was

affixed on the skin surface of flexor digitorum superficialis (finger flexor muscles) on the upper part of the forearm. Each measurement was taken for 3.5 minutes and repeated 3 times on both left and right forearm.

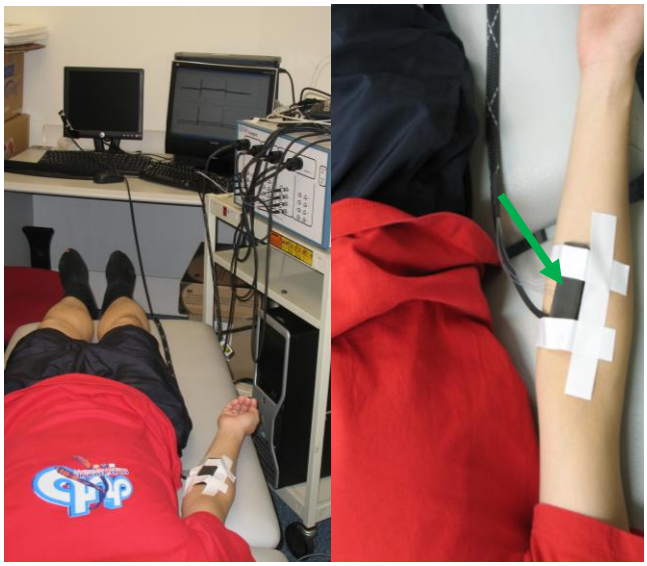

Figure 1: Experimental configuration and the probe alignment (arrow) on forearm.

The GT measurement

In this part of the study, eleven healthy male subjects (aged 22.5 ± 1.8 years old) participated. They were asked to adopt a side-lying posture (figure 2). The thickness of the tissue overlying the GT was measured using an ultrasound system (SonoSite, Inc., USA). The fiber optic probe was affixed onto the skin surface over the GT using double-sided adhesive tape. Each measurement was taken for 3.5 minutes. Measurements were taken on tissues over both left and right GTs with 5 minutes rest in between. The experiment was repeated for 3 times.

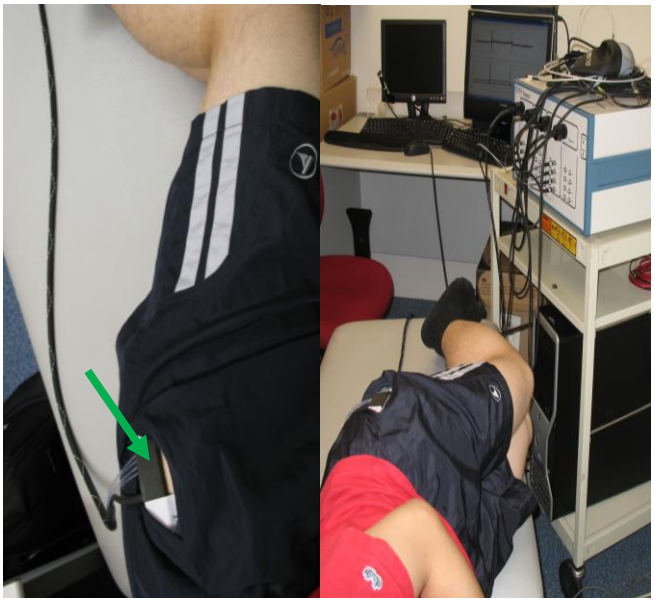

Figure 2: Experimental configuration and the probe alignment (arrow) on GT.

Analysis of maximum sampling depths (MSD)

The MSD of the NIR spectroscopic measurements on GT and forearm were determined using equation 5 with the average source-detector distance (d) and penetration depth (δ) calculated using μ_a and μ_s' (equation 6).

RESULT

The μ_a, μ_s', concentration of Hb and HbO_2, [tHb] and S_tO_2 of the left and right forearm and GT were shown in Table 1 and 2 respectively. The average MSDs of forearm were found to be 6.8 ± 1 mm at 690 nm and 8.2 ± 1.1 mm at 830 nm. The average MSDs of GT among subjects were 11.1 ± 4.1 mm and 10 ± 2.9 mm at 690 nm and 830 nm respectively.

Table 1: μ_a, μ_s', concentration of Hb, HbO2, [tHb] and S_tO_2 on left and right forearm

	Left forearm (n = 9)	**Right forearm (n = 9)**
μ_a (690 nm)	0.2 ± 0.03 cm^{-1}	0.2 ±0.04 cm^{-1}
μ_a (830 nm)	0.2 ± 0.02 cm^{-1}	0.2 ± 0.04 cm^{-1}
μ_s' (690 nm)	4.8 ± 0.4 cm^{-1}	4.5 ± 0.9 cm^{-1}
μ_s' (830 nm)	3.3 ± 0.3 cm^{-1}	3 ± 0.6 cm^{-1}
Concentration of Hb	32.7 ± 6.5 μM	32.7 ± 4.2 μM
Concentration of HbO_2	60.4 ± 7.8 μM	62.2 ± 9.7 μM
[tHb]	93.1 ± 10.5 μM	94.9 ± 12.6 μM
S_tO_2	64.8 ± 5.1 %	65.3 ± 2.9 %

Table 2: Tissue thickness, μ_a, μ_s', concentration of Hb, HbO2, [tHb] and S_tO_2 on the tissue over left and right GT

	Left GT (n = 11)	**Right GT (n = 11)**
Tissue thickness from skin to bony prominence	1.51 ± 0.35 cm	1.51 ± 0.43 cm
μ_a (690 nm)	0.059 ± 0.027 cm^{-1}	0.068 ±0.035 cm^{-1}
μ_a (830 nm)	0.072 ± 0.029 cm^{-1}	0.086 ± 0.04 cm^{-1}
μ_s' (690 nm)	7.1 ± 1.7 cm^{-1}	7.0 ± 1.6 cm^{-1}
μ_s' (830 nm)	6.6 ± 1.5 cm^{-1}	6.5 ± 1.4 cm^{-1}
Concentration of Hb	8.6 ± 4.6 μM	9.6 ± 5.5 μM
Concentration of HbO_2	23.4 ± 9.4 μM	28.4 ± 13.2 μM
[tHb]	31.9 ± 12.8 μM	38.1 ± 17.9 μM
S_tO_2	73.7 ± 7.5%	75.6 ± 6.5 %

DISCUSSION

This study measured the optical properties of tissues over the GT and the forearm. It is observed that the μ_a in GT were less than half of those in forearm. The lower absorption effect of light in the tissue over GT allows a deeper penetration of light. The MSD in tissue over the GT were about 3 to 4 mm deeper than those in forearm. The MSD in the GT measurement was on average 11.1 mm at 690 nm and 10 mm at 830 nm and the tissue thickness was about 15.1 mm. This means that our measurements can reach the deep tissues overlying the GT. It was noted that the variation of the MSD among individual subjects are quite high. The standard deviation was about 3 to 4 mm. This was contributed mainly from the high standard deviations of u_s'. The standard deviations of u_s' in GT were higher than those in forearm. This may be properly due to the fact of different adipose fat layers among subjects and in different anatomical sites (16). Further investigation is needed to find out the underlying reason. The result suggests that the source detector distance has to be tuned for individual subject so that measurement can be done on the depth of target muscle layer (see equation 5).

The [tHb], [HbO_2] and S_tO_2 of forearm in this study were on average 94 μM, 61.3 μM and 65.1% respectively. These values are comparable to results of another study (13), 113 μM, 69 μM and 61.1% determined on the same position of forearm using time resolved NIR spectroscopy. It was observed that the results of [tHb] and [HbO_2] in GT, about 35 μM and 25.9 μM, were much less than those in forearm. The value of [tHb] and [HbO_2] reflect the localized tissue blood volume and oxygen store respectively. In fact, the forearm has a denser blood vessel network and higher oxygen store to maintain the oxygen supply compared to tissues over GT (17). These results demonstrated that NIR spectroscopy can quantify the availability of oxygen supply and oxygen store and differentiate their differences in different anatomical sites. Further studies should be conducted to evaluate other high risk area of pressure ulcer such as ischial tuberosity and the sacrum.

In the GT measurement, no significant difference of HbO_2 concentration ($p = 0.683$ for left GT, $p = 0.4$ for right GT), [tHb] ($p = 0.474$ for left GT, $p = 0.307$ for right GT) and S_tO_2 ($p = 0.784$ for left GT, $p = 0.219$ for right GT) among three trials were found. The consistency was checked in order to ensure there is sufficient time for the recovery of the compressed tissues in this left and right alternative measurement protocol. Impaired and delayed tissue recovery of oxygen supply has been shown in superficial skin of debilitated subjects (5). Any similar effect in the deep tissue is still unclear. Further work is required to examine such effect on the deep tissues of debilitated subjects so that it can have a better understanding in the etiology of pressure.

EQUATIONS

$$[\mathrm{Hb}] = \frac{\varepsilon_{HbO_2,\lambda_2}\mu_{a,\lambda_1} - \varepsilon_{HbO_2,\lambda_1}\mu_{a,\lambda_2}}{\varepsilon_{Hb,\lambda_1}\varepsilon_{HbO_2,\lambda_1} + \varepsilon_{Hb,\lambda_1}\varepsilon_{HbO_2,\lambda_2}} \quad (1)$$

$$[HbO_2] = \frac{\varepsilon_{Hb,\lambda_2}\mu_{a,\lambda_1} - \varepsilon_{HbO_2,\lambda_1}\mu_{a,\lambda_2}}{\varepsilon_{Hb,\lambda_1}\varepsilon_{HbO_2,\lambda_2} + \varepsilon_{Hb,\lambda_2}\varepsilon_{HbO_2,\lambda_1}} \quad (2)$$

$$[tHb] = [Hb] + [HbO_2] \quad (3)$$

$$S_tO_2 = \frac{[HbO_2]}{[Hb] + [HbO_2]} \times 100\% \quad (4)$$

$$MSD = \sqrt{\frac{d\delta}{2}} \quad (5)$$

$$\delta = \frac{1}{\sqrt{3\mu_a(\mu_a + \mu_s')}} = \frac{1}{\sqrt{3\mu_a\mu_s'}} \quad (6)$$

where [Hb] and [HbO_2] were the concentration of Hb and HbO_2, $\varepsilon_{Hb,\lambda_1}$ $\varepsilon_{HbO_2,\lambda_1}$ $\varepsilon_{Hb,\lambda_2}$ and $\varepsilon_{HbO_2,\lambda_2}$ were the specific absorption coefficient of Hb and HbO_2 at wavelength λ_1 and λ_2

ACKNOWLEDGEMENTS

The author would like to thank the Department of Rehabilitation Sciences, Hong Kong Polytechnic University for the equipment support.

REFERENCES

[1] A. Stekelenburg *et al*, "Role of ischemia and deformation in the onset of compression-induced deep tissue injury," *J. Appl Physiol*, vol. 102, pp. 2002-2011, 2007.

[2] M. Belkin, R. Brown, J. Wright, W. LaMorte and R. Hobson, "A new quantitative spectrophotometric assay of ischemia-reperfusion injury in skeletal muscle," *Am. J. Surg*, vol. 156, pp. 83-86, 1988.

[3] D. Bader, C. Bouten, D. Colin and C. Oomens, *Pressure Ulcer Research-Current and Future Perspectives*, 1st Edition, Springer, Berlin, 2005.

[4] R. Goossens, R. Zegers,G. Hoek van Dijke, C. Snijders, "Influence of shear on skin oxygen tension," *Clin. Physiol*, vol. 27, pp. 111-118, 1994.

[5] D. Bader, "The recovery characteristics of soft tissues following repeated loading," *J. Rehabil. Res. Dev*, vol. 14, pp. 141-150, 1990.

[6] Z. Li, E. Tam, A. Mak and R. Lau, "Effects of prolonged compression on the variations of haemoglobin oxygenation—assessment by spectral analysis of reflectance spectrophotometry signals," *Phys. Med. Biol*, vol. 51, pp. 5707-5718, 2006.

[7] Z. Li, E. Tam, R. Lau, K. So, W. Wu and A. Mak, "Post pressure response of skin blood flowmotions in anesthetized rats with spinal cord injury," *Microvasc. Res*, vol. 78, pp. 20-24, 2009.

[8] P. Rolfe, "*In vivo* near infrared spectroscopy," *Annu. Rev. Biomed. Eng*, vol. 2, pp. 715-754, 2000.

[9] S. Feng, F. Zeng and B. Chance, "Monte Carlo simulations of photon migration path distributions in multiple scattering media," *Proc. SPIE*, vol. 1888, pp. 78-89, 1993

[10] K. Kurihara, A. Kikukawa, A. Kobayashi, "Cerebral oxygenation monitor during head-up and-down tilt using near-infrared spatially resolved spectroscopy," *Clin Physiol Funct Imaging*, vol. 23, pp. 177-181, 2003.

[11] D. Mehagnoul-Schipper *et al*, "Simultaneous measurements of cerebral oxygenation changes during brain activation by near-infrared spectroscopy and functional magnetic resonance imaging in healthy young and elderly subjects," *Hum. Brain. Mapp*, vol. 16, pp. 14-23, 2002.

[12] R. De Blasi *et al*, "Microvascular dysfunction and skeletal muscle oxygenation assessed by phase-modulation near infrared spectroscopy in patients with septic shock," *Intensive. Care. Med*, vol. 31, pp. 1661-1668, 2005.

[13] T. Hamaoka *et al*, "Quantification of ischemic muscle deoxygenation by near infrared time-resolved spectroscopy," *J. Biomed. Opt*, vol. 5, pp. 102-105, 2000.

[14] J. Hoffman *et al*, "Effect of Muscle Oxygenation during Resistance Exercise on Anabolic Hormone Response," *Med. Sci. Sports. Exerc*, vol. 35, pp. 1929-1934, 2003.

[15] J. Fishkin and E. Gratton, "Propagation of photon-density waves in strongly scattering media containing an absorbing semi-infinite plane bounded by a straight edge," *J. Opt. soc. Am. A*, vol. 10, pp. 127-140, 1993.

[16] M. van Beekvelt, M. Borghuis, B. van Engelen, R. Wevers and W. Colier, "Adipose tissue thickness affects in vivo quantitative near-IR spectroscopy in human skeletal muscle," *Clin. Sci*, vol. 101, pp. 21-28, 2001.

[17] F. Martini, W. Ober, C. Garrison, K. Welch and R. Hutchings, *Fundamentals of Anatomy & Physiology*, 7th Edition, Pearson Education, San Francisco, CA, 2006.