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Near infrared image processing to quantitate and visualize oxygen saturation during vascular occlusion

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ABSTRACT

The assessment of microcirculation spatial heterogeneity on the hand skin is the main objective of this work. Near-infrared spectroscopy based 2D imaging is a non-invasive technique for the assessment of tissue oxygenation. The haemoglobin oxygen saturation images were acquired by a dedicated camera (Kent Imaging) during baseline, ischaemia (brachial artery cuff occlusion) and reperfusion. Acquired images underwent a preliminary restoration process aimed at removing degradations occurring during signal capturing. Then, wavelet transform based multiscale analysis was applied to identify edges by detecting local maxima and minima across successive scales. Segmentation of test areas during different conditions was obtained by thresholding-based region growing approach. The method identifies the differences in microcirculatory control of blood flow in different regions of the hand skin. The obtained results demonstrate the potential use of NIRS images for the clinical evaluation of skin disease and microcirculatory dysfunction.

1. Introduction

Assessment of tissue oxygen saturation (StO_2) is important in monitoring several pathological changes, especially in critically ill patients. Microcirculation, tissue oxygen supply and consumption are often disturbed in such patients. Several techniques have been proposed in the past to investigate microcirculatory function in the skin. Daly et al. provides an extensive review of the state of the art on the advancement of blood flow imaging methods and the advances in noninvasive imaging modalities [1]. Also, Leahy et al. reviewed the main bio photonic methods to assess microcirculation as well as the advancement during years [2].

Among these different techniques, laser Doppler imaging (LDI) and laser speckle contrast imaging (LSCI) are the most advanced and used ones. LDI was developed for point wise monitoring and imaging of skin. Johansson and Charkoudian in [3,4] had presented their findings on microcirculatory blood flow in human hand based on LDI. Their work was done in

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relation to the applied pressure and during thermo-regulation. Although LDI has been applied in many applications, the complex nature of acquisition and calculations limits the integration of this technology in clinical applications [1]. Similarly first introduced in 1980, Laser Speckle Contrast Imaging (LSCI) is a powerful tool for full field imaging of blood flow. Boas et al. provided the review on the application of LSCI in multiple field e.g. neuroscience, dermatology, etc. [5]. The method has the advantage of being able to acquire images in real time, making it possible, for instance, to measure blood flow response to occlusion [1]. LDI and LSCI can measures the perfusion (i.e. the blood flow) of tissue but not the StO_2 level.

First described by Jöbsis in 1977 [6], near infrared spectroscopy (NIRS) is a non-invasive method for assessing blood flow and StO_2. Its reproducibility during brachial artery occlusion has already been demonstrated in healthy subjects [7], Light in the infrared region has the capacity to penetrate in skin and bone and further reach into deeper structures e.g. in muscle tissue. Near infrared light penetrates into tissue and experiences absorption, due to tissue chromophores such as haemoglobin (Hb) + myoglobin (Mb) in their oxy- and deoxy-forms, and scattering. Consequently, when light of different wavelengths is emitted through muscle tissue, it is absorbed to a different degree depending on the concentration of oxy and deoxy Hb. The difference in absorptions is used by NIRS-sensitive sensors to calculate the amount of Hb + Mb StO_2.

NIR spectroscopy has been largely used for measurement of changes in intravascular haemoglobin and intramuscular myoglobin for many applications [8–11]. In [11], Ferrari et al. have reviewed the development and applications of functional NIRS. Recently, Lipcsey et al. reviewed the application of NIRS in anaesthesia and intensive care [12]. In another study, they had estimated the forearm blood flow using NIRS [13]. Gruartmoner et al. have used near-infrared spectroscopy to study whether thenar tissue StO_2 and its changes derived from an ischaemic challenge are associated to weaning outcome [14]. Also, Gerovasili et al. used near infrared spectroscopy to study vascular occlusions in order to estimate different parameters [15]. They had provided the review of NIRS in clinical application specifically during vascular occlusion. A similar study is provided by Mayeur et al. They have presented their results performing vascular occlusion tests using NIRS in [16]. More recently, Hirasawa et al., has studied the skin blood flow of cerebral region using NIR spectroscopy [17]. The more comprehensive state of the art of such techniques based on NIRS is provided by Daly et al. [1].

Early studies have used an NIR spectroscopy probe placed on the thenar eminence and held in place by a form-fitting plastic adhesive. The probe has both illumination and detection optical fibres and uses the reflectance mode to measure scattering light reflected at some distance from where the light is transmitted into the tissue. Tissue oxygenation in the microvasculature of muscle tissue, comprising the arteriolar, capillary and venular compartments, is measured continuously, and then the values are transferred to a computer and analyzed using dedicated software [18].

Recent developments in NIR spectroscopic 2D imaging techniques have offered the possibility of visualizing StO_2 distribution in large tissue areas [19]. Moreover, the short acquisition time required to obtain NIR spectroscopic images facilitates the evaluation of micro vascular ‘dynamic’ conditions, such as the vascular response to physical or pharmacological stimuli.

1.1. *Motivation and objectives*

Currently, several methods are available for assessing peripheral vascular abnormalities. These methods provide functional or structural information but none of them explores microcirculation simultaneously in multiple areas. This is particularly important in some microcirculation diseases like as systemic scleroderma that is characterized by a very heterogeneous spatial distribution of the micro vascular abnormalities. As suggested by the pivotal study of Skarda et al., NIRS of the thenar eminence has a potential role in the clinical management of critical conditions as septic shock [20]. None of existing tools has been accepted as standard method for the investigation of microcirculation and, at present, they are used in different ways depending on the specific clinical question.

The aim of the present study is to use, for the first time, near infrared sensitive camera to not only quantitate but to visualize the distribution of StO_2 in large tissue areas. Moreover, the short acquisition time of NIRS camera allows the evaluation of dynamic condition such as the vasodilating response to short periods of ischaemia. The mapping of haemoglobin (Hb) StO_2 changes in the hand skin during baseline, ischaemia and reperfusion is the main objective here. The NIRS images acquired from NIRS camera are further processed with multiscale edge detection algorithms to extract thenar eminence region. At the final stage, by segmenting these NRS images, we were able to demonstrate the behaviour of StO_2 level during vascular occlusion.

2. Acquiring data during and after vascular occlusion

We worked on a semi-automatic segmentation technique to highlight areas of oxygenated blood in the hand skin using NIRS images. The acquired data set includes two sets of NIRS images from palmar and dorsal side of the hand, given in Fig. 1. Marked gradients in StO_2 (from blue = low to red = high) can be observed on palmar and dorsal faces. As by 2D NIRS imaging technique we imaged the entire hand, any number and site of ROIs (regions of interest) within the image could be selected and analyzed. In this report we just used thenar eminence and one phalange as two exemplifying ROIs without any pathophysiologic intent. We have selected thenar eminence (base of the thumb) of the palm and the 2nd phalange (finger bone) of the middle finger on the dorsal view as regions of interest (ROI) as shown in Fig. 1. The advantage of thenar eminence compared with other sites, in terms of minimizing variability, is the relatively thin fat tissue over the muscle and seems to be less influenced by oedema [13,19].

The Kent imaging camera used to take the NIRS images, is a non-invasive tissue oxygenation measurement system based on near infrared light. The camera reports and approximates value of Hb + Mb StO_2 in superficial tissue. The StO_2 is automatically calculated by the NIRS camera software. The oxygen saturation calculation methods used by the camera system are