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Design of a new reflectance pulse oximeter by obtaining the optimal source-detector space

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ABSTRACT

Pulse oximetry is an important medical monitoring technique. Interest in the use of reflectance mode of pulse oximeters has been grown for monitoring the arterial oxygen saturation (SaO_2). The design sensor has an effective role in improvement of reflective pulse oximeters performance. In this study, the light propagation in tissue has been analyzed for development of reflection pulse oximetry. After analyzing theory, the optimal source-detector space was determined and a revision on SaO_2 formulation calculated with Lambert–Beer law performed to reduce the errors. The new type of reflectance pulse oximeter was designed based on the theory calculation and then calibrated by in vivo experiments. The detecting signal have least dependence on changes in scattering properties of the tissue for obtained optimal space. One of the advantages of this design is reduction of influence of unconscious movement. In this novel design, calibration and validation experimental results show the repeatability potential and accuracy of the system.

1. Introduction

The arterial oxygen saturation (SaO_2) was measured by electric device namely pulse oximeters that can be used in transmission or reflection modes. Clinicians depend on these instruments to provide accurate analyses of the oxygenation of the patient's arterial blood [1,2]. Due to importance of oxygen saturation in healthcare, the new developed sensors and systems has attracted great attention for monitoring of SaO_2 recently. The demand for reflective mode pulse oximetry to monitor oxygen saturation has been continuously increasing because it can be used at diverse measurement sites such as the feet, forehead, chest, and wrists. In the other words, more broad applications can be achieved with the reflectance mode. There are some reports on the reflection mode pulse oximetry sensors. Mendelson et al. [3] and Dassel et al. [4] investigated these sensors using one photo detector and one light source. In 1998, a design was presented using multiple photo detectors with a single light source by Mendelson et al. [5]. They also studied power optimization in 2003 [6]. To study the quality of

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the signal, a design using 20 LEDs placed concentrically around a single photo detector was investigated by Takatani et al. [7,8].

The principle of pulse oximetry is based on Lambert–Beer law by neglecting the influence of the scatter and considering the Red (RD) and Infrared (IR) light path lengths equally [9]. In fact, with transport of the photons through the weak absorption media, the scattering has great effect on reflectance, and the path length of RD and IR has great difference. Therefore, reduction of this effect is essential, although all of these can cause the obvious measure error. To detect RD and IR, one photoelectric cell was used in most of the oximetry sensors. It leads to decreasing the Signal-to-Noise (SNR) and much losing of biological information. The goal of this paper is to study of source-detector space influence on reflectance. The optimal source-detector space, where the reflectance has least dependence on changes in scattering properties, was obtained for RD (660 nm) and IR (940 nm).

The light path length distribution of RD and IR was discussed accordance to the sensor designed in this paper. Then SaO_2 formulation was revised according to this approach. Also, in this study, the newly designed reflectance pulse oximeter sensor calibrated with the help of an in vivo experiment. Then the system was used to measure SaO_2 and its results were analyzed.

2. Materials and methods

2.1. Theory analysis for source-detector space

Light propagation through scattering media has attracted great attention in many areas of physics, biology, medicine, and engineering. The radiative transfer equation [10] as a complex integrodifferential equation, is used to describe this process. Also, this equation is reduced to the diffusion equation under the strong scattering conditions. Since in near-infrared (NIR), the absorption and scattering are low and high in the biology tissue, respectively, so diffusion theory may be applied to solve the problem the photons transmit through the tissue. Several researchers have investigated a solution for a diffusion equation for layered turbid media. Takatani et al. [11] derived analytical expressions for steady-state reflectance by using Green's functions to solve the diffusion equation, and Dayan et al. [12] used Fourier and Laplace transforms to obtain solutions for steady-state and time-resolved reflectances. In addition, Kienle and Patterson [13] improved a solution for the steady-state diffusion reflectance problem with considering source-detector space ρ (larger than a few millimeters) and an extrapolated boundary condition.

In this study, with refractive indices $n_{tissue} = 1.4$ and $n_{detector} = 1$, the improved solution is expressed as Eq. (1). The geometry of the problem has been shown in Fig.1.

$$R_{imp}(\rho.z_0) = 0.118\Phi(\rho.z_0) + 0.306R(\rho.z_0) \quad (1)$$

In this equation, R_{imp} indicates the collected diffuse reflectance. Fluence rate and the z component of the photon flux across the tissue-air boundary are symbolized with $\Phi(\rho,z_0)$, $R(\rho,z_0)$, respectively. These are given as:

$$\Phi(\rho.z_0) = \frac{1}{4\pi D}\left[\frac{1}{r_1}e^{-(\mu_{eff})r_1} - \frac{1}{r_2}e^{-(\mu_{eff})r_2}\right] \quad (2)$$

$$R(\rho.z_0) = \frac{1}{4\pi}\left[z_0\left(\mu_{eff} + \frac{1}{r_1}\right)\frac{1}{{r_1}^2}e^{-(\mu_{eff})r_1} + (z_0 + 2z_e)\left(\mu_{eff} + \frac{1}{r_2}\right)\frac{1}{{r_2}^2}e^{-(\mu_{eff})r_2}\right] \quad (3)$$

where ρ is the distance between source and detector. $\mu_{eff} = \sqrt{\frac{\mu_a}{D}}$ is the effective attenuation coefficient where $D = \frac{1}{3\mu_t'}$ is the diffusion coefficient. $\mu_t' = \mu_a + \mu_s'$ is the transport coefficient where μ_a and μ_s' are absorption and effective scattering coefficients. r_1 and r_2 are given as follows:

$$r_1 = ({z_0}^2 + \rho^2)^{0.5} \quad (4)$$

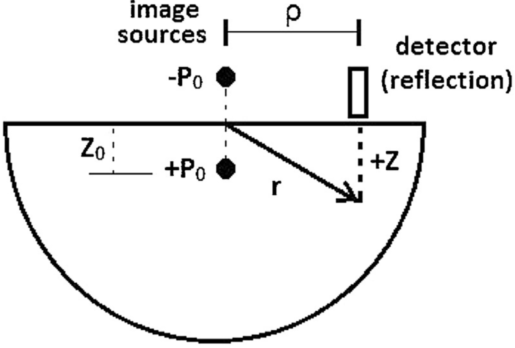

Fig. 1. The cross section of hemispherical geometry.