Absorption Coefficient Measurements of Strongly Scattering Media Using Time-Resolved Transmittance of a Short Pulse in Near-Infrared (NIR) Wavelength Range*

Sergei G. Proskurin, Yukio Yamada and Yukari Takahashi

Mechanical Engineering Laboratory, Ministry of International Trade and Industry, 1-2 Namiki, Tsukuba, Ibaraki, 305 Japan
(Received November 11, 1994; Accepted June 8, 1995)

Absorption coefficient measurements of strongly scattering and weakly absorbing media have been performed using time resolved transmittance of a 100 fs pulse through a 30 mm slab containing latex spheres suspended in water and absorbing ink solutions. The scattering and absorption coefficients were selected so that the optical properties of the media were similar to those of biological tissues. Measured curves of time-resolved transmittance of the pulse through the media were used to estimate the optical properties of the media. The experiment was made at two different wavelengths, 784 nm and 810 nm. Estimated absorption coefficients were in good agreement with those measured in a nonscattering case by a spectrophotometer.

Key words: femtosecond pulse propagation, time-resolved transmittance, highly scattering media, optical properties of biological tissue

1. Introduction

Optical transillumination of biological tissues in the visible and near-infrared wavelength ranges has become a new medical diagnostic technology during the past few years.1–5 With this method the distribution of light absorption in the tissues is qualitatively shown as a contrast in the pictures although blurred by the strong scattering of light by the tissues themselves. The absorption measurements provide physiological information on the oxygenation state of tissues.6–8 Previous studies using continuous or pulsed light transillumination showed pictures giving information on the oxygenation state in brain, muscle, breast tissues, and biological solutions9–10. Since it is difficult to measure the optical properties quantitatively by steady state measurements, time-resolved transmission and reflection measurements are expected to provide quantitative estimates of absorption in living tissues.

Time-resolved transmittance and reflectance of ultrashort light pulses incident on random media like biological tissues carry more information than steady state measurements about scattering and absorption of the media which are either optically homogeneous or inhomogeneous. Optically inhomogeneous media requires development of a new technology of optical tomography.11–17 However, the photon migration in homogeneous media must be studied before this is realized because features of weak absorption must be extracted from the signals distorted by strong scattering in tissues. One possible method of measuring weak absorption is to detect the so-called ballistic or snake photons18–20 which arrive at the detector with the minimum time of flight corresponding to the directly transmitted or unscattered component. This technique reaches its limit, however, when tissues exceed about 20 mm in thickness because the ballistic or snake component becomes lower than the noise level of the detectors even with a highly advanced detecting system. Another method is to use the whole time course of transmittance or reflectance.9,10 By comparing the experimental curves with analytical or numerical calculations, the scattering and absorption coefficients of the media can be obtained.

In this report, we conduct the time-resolved transmission measurement of homogeneous media simulating biological tissues in terms of optical properties in the near-infrared wavelength range. The purpose of the experiment is to obtain the absorption coefficients of the media by comparing two curves of time-resolved transmittance. If the scattering coefficients of the two media are the same, the difference in optical densities between them at each time eliminates the effect of scattering and gives information on the difference in the absorption coefficients.

2. Method and Experimental Setup

2.1 Method

Reports on measurement of scattering and absorbing media like biological tissues have appeared,19–22 but most of them used sliced thin samples in vitro; this is because a continuous light source was employed for measurement. With continuous light the path of scattered light is not defined and it is very difficult to determine the optical properties of bulky biological tissues in vivo. This problem is solved if a pulsed light source and time-resolved measurement are used because information on the time course of the transmitted pulses provides the total path-length equivalent to the time of flight. We therefore used a combination of an ultrashort pulse light source and an ultrafast light detecting system to measure the optical properties of random media simulating biological tissues.

*Presented at the 7th International Workshop on Multiple Scattering Lidar/Light Experiments (MUSCLE7), July 21–23 1994, Chiba, Japan.
Let us consider a light pulse with the intensity of \( I_0 \) incident on a homogeneous slab of scattering and absorbing medium with the scattering and absorption coefficients of \( \mu_s \) and \( \mu_a \), respectively, as shown in Fig. 1. The time-resolved transmittance of the pulse at time \( t \) through a medium \( i \), \( T_i(t) \), is expressed by Eq. (1) as the scattered component, \( S(\mu_s', t) \), multiplied by the attenuation caused by the absorption following the extended Beer-Lambert law,

\[
T_i(t) = I_0 S(\mu_s', t) \exp(-\mu_a l) ,
\]

where \( c_0 \) is the speed of light in the medium which is the speed of light in vacuum \( c \) divided by the refractive index of the medium \( n \). In our experiment, \( c_0=0.226 \text{ mm/ps} \) since the refractive index of water at the wavelength of about 800 nm is \( n=1.33.24 \). The subscript \( i=1, 2, 3 \) denotes three different media with different absorption coefficients. To determine the difference in the absorption coefficient among the three media, the scattering coefficients for the three are assumed to be the same and are described by the reduced scattering coefficient \( \mu_s \) which is defined as \( \mu_s(1-g) \), where \( \mu_s \) is the linear scattering coefficient and \( g \) is the anisotropy factor of the scattering. The function \( S(\mu_s', t) \) is the same for the three media because the reduced scattering coefficients are the same. The equation derived by Patterson et al. \(^9\) shows that the function \( S(\mu_s', t) \) looks like:

\[
S(\mu_s', t) = (4\pi Dc_0)^{-1/2} \exp\left(-\frac{k_0^2}{4Dc_0}t\right) ,
\]

where \( k_0 = \frac{2\pi}{\lambda_0} \). The constants \( k_i \) in Eq. (2) are given by:

\[
k_1 = L - \frac{1}{\mu_s} , \quad k_2 = L + \frac{1}{\mu_s} , \quad k_3 = 3L - \frac{1}{\mu_s} , \quad k_4 = 3L + \frac{1}{\mu_s} ,
\]

where \( L \) is the thickness of the slab. It is noted that in this equation the diffusion coefficient \( D \) is defined by including \( \mu_s \), but we give it as \( D=1/(3\mu_s) \).

\[
\Delta OD_i(t) = \ln(T_i(t)/T_j(t)) = \frac{(\mu_{ai} - \mu_{aj}) l}{c_0 \alpha} = \alpha l ,
\]

where \( \alpha \) is the gradient of the line to be experimentally determined. From this equation it is found that the absorption coefficient of the medium \( j \), \( \mu_{aj} \), can be obtained by the determined gradient \( \alpha \) and the known absorption coefficient of the medium \( i \), \( \mu_{ai} \), as shown by Eq. (4).

\[
\mu_{aj} = \mu_{ai} + \frac{\Delta OD_i(t)}{c_0 \alpha} .
\]

Since \( \Delta OD_i(t) \) is linear at any time \( t \) because \( \alpha \) is constant everywhere. From a physiological point of view, oxygenation of hemoglobin in blood is important information, and the oxygenation state changes not the scattering coefficient but the absorption coefficient of blood. Therefore, measuring the absorption coefficient is much more important than measuring the scattering coefficient for the purpose of oxygenation determination.

Another method of determining the absorption coefficient is to use the \( \Delta OD_i(t) \) value at the shortest time of flight. \(^{31}\) Because the thickness of the sample cell \( L \) is known, the shortest time of flight can be calculated easily by \( t_s = L/c_0 \). Then, if \( \Delta OD_i(t_s) \) is obtained by the measurement the absorption coefficient of the medium \( j \), \( \mu_{aj} \), can be calculated by Eq. (5).

\[
\mu_{aj} = \mu_{ai} + \frac{\Delta OD_i(t_s)}{c_0 \alpha} .
\]

Although it is theoretically possible to obtain \( \mu_{aj} \) from Eq. (5), the signals at the shortest time of flight are very weak and often not measurable for thicker samples. Also, it is often difficult to define the shortest time of flight with the accuracy necessary for Eq. (5) to be applied. Although we did attempt to use this technique to determine the absorption coefficient, the measured values varied greatly with a small shift of time and were much less accurate because of the difficulties mentioned. This means that this technique was not used to measure the absorption coefficient.

Measurement of the absorption coefficient requires two media having different absorption coefficients but the same scattering coefficient. This condition is realized when the absorption coefficient of one medium changes with time while its scattering coefficient remains unchanged; it is otherwise very difficult to prepare two media with the same scattering coefficient, particularly for biological tissues. The above desired condition can be obtained, however, if one medium is irradiated by light at two different wavelengths. Variation of the absorption coefficient of hemoglobin in the near-infrared wavelength range is usually much greater than the variation of the scattering coefficient of whole blood or biological tissues. The change of wavelength by 30 nm to 40 nm around 800 nm is enough to detect the change in the absorption coefficient of hemoglobin, while the change in the scattering coefficient with the same change in wavelength is small enough to be considered constant. \(^{26}\) We therefore used two media having different absorption coefficients with the same scattering coefficients irradiated by one wavelength, and also used two wavelengths in the near-infrared wavelength range as explained in the following section.

**2.2 Experimental Setup**

In the experimental setup shown in Fig. 2, the incident pulse with about 100 fs full width at half maximum was...