MODELS OF REMOTE OPTICAL SENSING IN LAYERED TISSUES
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Abstract
An analysis of time-resolved photon propagation through layered biological structures is discussed.

Introduction
Several non-invasive medical diagnostic procedures involve tissue penetration by optical photons. Among these are laser flowmetry for studying blood flow in the skin [1,2] and time-resolved absorption spectroscopy for measuring hemoglobin oxygenation in the brain [3,4]. Those applications both involve photon penetration through layered media. In the case of skin, light first must penetrate the translucent avascular epidermis, as well as an irregular junction region, before reaching the dermis, which is composed of several stratified layers of blood-containing vessels. When used to probe brain tissue, photons first must traverse layers of skin, skull, and dura mater.

The optical properties of the superficial layers will affect the degree to which one can examine the underlying vascularized tissue. If the delivering and detecting optical fibers of a device (the "optodes") are closely separated, the tendency will be to probe the surface layers of a composite medium. Computations using a lattice model of a two-layer semi-infinite medium indicate the possibility of a sharp transition, where the properties of the interior, underlying, layer are probed only if the optodes spacing exceeds a value which depends on the thickness of the superficial layer [5,6]. The studies which lead to such conclusions pertain to static, or stationary, quantities — for example, the diffuse surface reflectance, the absorption profile as a function of depth, and the average depth probed by the reemitted photons.

Analysis
The emphasis, here, is on time-resolved measurements, specifically of hemoglobin oxygenation in the head. For a homogeneous tissue, when one inserts a pulse of photons at time t=0, the tissue absorption coefficient can be determined from the decay of the emission pulse-time profile \( I(t) \) as \( t \) gets very large, viz.

\[
\frac{d \ln I(t)}{dt} = \mu C_t
\]

where \( \mu \) is the bulk absorption coefficient and \( C_t \) is the speed of light in the tissue [3,4]. When properly normalized, \( I(t) \) is the probability that a photon will reach the detector at time \( t \), given that the spacing between the optodes is \( r \). In principle, one thus would need only to look at the tail of the distribution to determine the absorption coefficient. In practice, though, the signal may become quite noisy before the region of asymptotic decay is achieved, and it might be necessary to fit data close to the maximum of the curve where the logarithm of \( I(t) \) does not have a constant slope. The consequent uncertainty in determining the slope could diminish the usefulness of Eq. (1).

However, one oftentimes is interested in measuring differences in absorption (for example, due to changes in blood oxygenation), rather than absolute values. It thus may be useful that the ratio of two distributions \( I(t) \) and \( I'(t) \) is given, in certain instances, as

\[
\frac{I'(t)}{I(t)} = \exp(-\delta \nu C_t t)
\]

where \( \delta \nu \) is defined as \( \delta \nu = \nu_s - \nu_c \). Equation (2) is strictly true for media which can be considered to be homogeneous with respect to absorption, whatever the photon pathways. The advantage of using a relationship like that given in Eq. (2) is that the linear logarithmic range is more clearly defined and quantitated (see Fig. 1).

The following simple argument can be used to show how Eq. (2) comes about. Let \( P(k) \) be the probability that a photon follows path \( k \) as it moves from the point of insertion towards the detector, and let \( P_k' \) be the probability of "surviving" while migrating along that path (i.e., the probability of reaching the detector without being absorbed). Then the probability, \( Q \), that a photon reaches the detector is given as

\[
Q = \sum_{(k)} P_k' P(k)
\]

If the absorption, only, were to vary (e.g., due to a change in blood oxygenation), only the \( P_k' \) would change.

For illustrative purposes, let us now consider a composite medium containing regions of varying absorbance, \( \delta \nu \). The absorbances in these regions are not necessarily identical, but we assume that any changes which occur are identical in all regions. When examining the photons which are reemitted at time \( t \), it thus is possible to write \( P_k' \) as

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where \( f \) represents the fraction of the path (of length \( n - t \)) that lies within the regions where absorption changes occur. Thus, before an absorption change,

\[
P_1 = \sum_{(k)} P_k^0 \exp(-f \delta \rho C t)
\]

and, after an absorption change,

\[
P_2 = \sum_{(k)} P_k^0 \exp(-f \delta \rho C (t + 1)) \exp(\delta \rho C t) \exp(\delta \rho C)
\]

In homogeneous media \( f = 1 \), so Eq. (2) rigorously follows.

\[
Q = \sum_{(k')} P_k^1 
\]

An expression like Eq. (2) in general would not be applicable. However, if the absorption coefficients along some paths (\( k' \)) are much greater than along others (\( k'' \)), the probabilities \( P_k^1 \) will divide into two groups, where the typical value of \( P_k^1 \) is much smaller than the typical value of \( P_k^0 \). In this case one finds

\[
Q = \sum_{(k')^+} P_k^1 \exp(f \delta \rho C - t)
\]

Thus, if the regions of high absorbance are superficial layers, the underlying regions are visible in time-resolved measurements according to Eq. (2). The same conclusion is reached if the absorption coefficients of all layers are similar, but the scattering lengths of the superficial layers are much shorter than that of the interior. Then, photons in the upper layers will scatter with much greater frequency than those in the lower layer, so the total time taken to reach the detector on average will be increased.

If the optodes are sufficiently far apart, photons reaching the detector close to the time corresponding to the maximum of \( I(t) \) mostly will have moved in the lower layer. Although the proportion of transits occurring within the upper layers increases for long reemission times, photon signals will be diminished by absorption and may be too noisy to analyze. Such effects can be demonstrated by analyzing time-resolved data obtained from appropriately designed 'phantoms' [R. Bonner, B. Chance, M. Maris, P. McCormick and R. Nossal, unpublished]. The data shown in Fig. 1 were acquired with optodes placed on opposite sides of an intact rat head [4].

References


