

COMPUTED POINT SPREAD FUNCTIONS FOR LIGHT IN TISSUE
USING A MEASURED VOLUME SCATTERING FUNCTION

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INTRODUCTION

Optical techniques are increasingly being used in the field of medicine in areas as diverse as surgery (for cutting and coagulation), cancer treatment (through photoradiation therapy) and blood flow monitoring (by laser doppler measurements). At University College, we are using the technique of near infrared spectroscopy (nirs) to monitor changes in cerebral blood and tissue oxygenation in newborn infants (1), and are investigating methods of optical imaging across the head (2). In all these applications, a detailed knowledge of light transport in tissue is required. For spectroscopy studies, in order to quantitate data, one needs to know the effective photon pathlength through the tissue, and a knowledge of the path also allows one to calculate the volume of tissue from which results are being obtained. In the case of imaging through tissue, data is required on the point spread function (PSF) for the tissue, both for the prediction of the image quality that could be obtained using various imaging schemes, and for use in image enhancement and reconstruction computations.

In order to provide the above data, we have developed a Monte Carlo program to model light transport in brain tissue. This model requires as its input, data on the scattering and absorption properties of brain tissue. Some data on absorption properties have been published in the literature (3,4), but few results are available on its scattering properties. Previously therefore we have used a calculated volume scattering function (VSF) derived using Mie scattering theory and applied to a range of cell sizes (5). We have now measured the VSF for adult rat brain, and incorporated this into the model. The model has been further improved by the inclusion of specular reflection and refraction at the tissue boundaries, and by the addition of the reflected PSF to the calculated parameters. The model has been used to simulate the PSF for light transmission through, and reflection from, a homogeneous slice of brain tissue. A general formula has also been derived to describe the transmitted PSF as a function of tissue scattering and absorption coefficients and thickness.

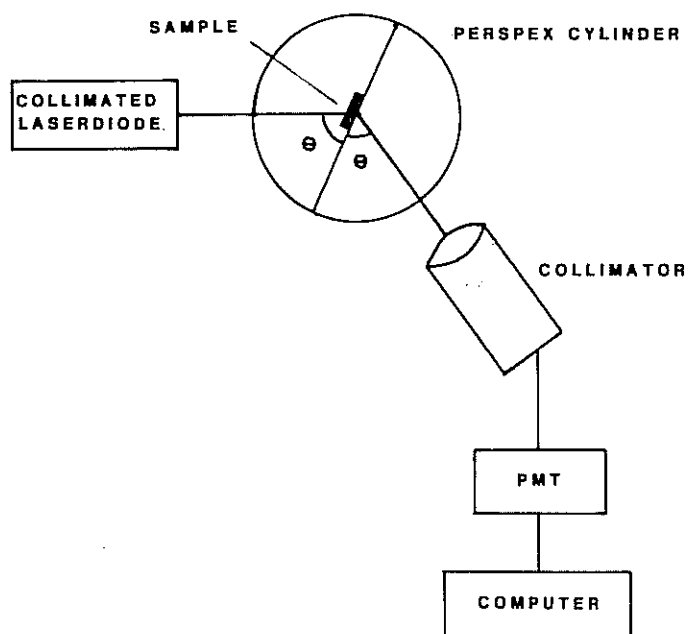


Figure 1. Schematic diagram of system used to measure the volume scattering function (VSF).

MEASUREMENT OF BRAIN TISSUE VOLUME SCATTERING FUNCTION

The VSF describes the scattered light intensity as a function of scattering angle for a single scattering event. In order to measure this function accurately one must therefore ensure that multiple scattering does not occur within the tissue sample. This requires the use of very thin tissue samples, a consequence of which is extremely low light levels in the scattered beam. The system used to measure the VSF is shown in Figure 1. This consists of a goniometer with an angular resolution of approximately one minute of arc. The sample is held in a 65 mm diameter

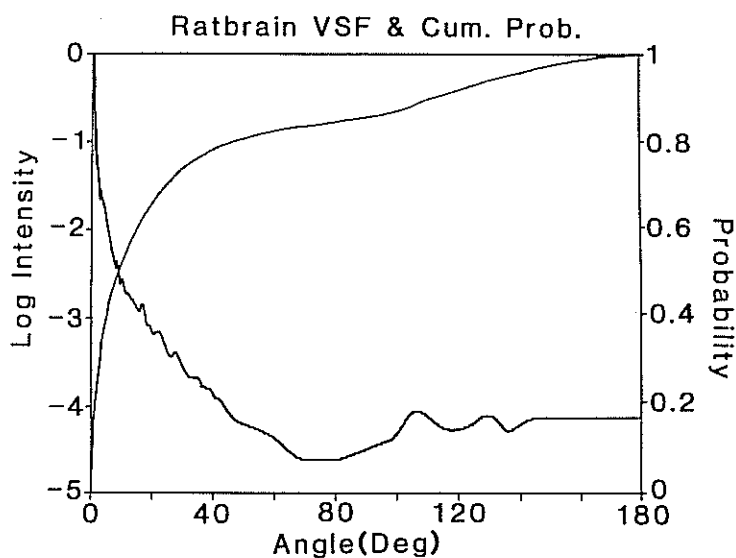


Figure 2. Averaged VSF and cumulative probability for adult rat brain tissue at 783 nm.

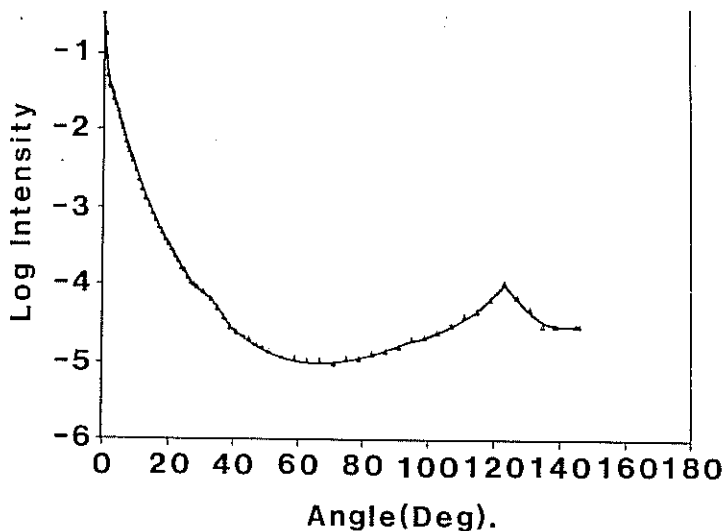


Figure 3. Averaged VSF for human red blood cells at 783nm. The sharp peak at 120° is an instrumental artifact.

clear acrylic cylinder, which is manufactured from two halves, which are separated by a 12.5 mm thick spacer. The spacer has a 10 mm hole in the middle to contain the brain slice. The light source used was a 783nm collimated laser diode, which produced a beam of 1mm diameter. A photomultiplier was used to detect the light, its output being fed to a computerised data collection system. With no sample in the cylinder, the half width of the system response was 0.5°. Scattering measurements were made on nine samples of brain tissue taken from freshly killed adult wistar rats. Thin samples were taken from various areas of the brain, and the results then combined to produce an average VSF for brain tissue. This result is shown in Figure 2. Data for scattering angles greater than 150° were not obtainable with this system, so the value at 150° has been used. As expected, the VSF is strongly forward peaked. Figure 2 also shows the cumulative probability for the scattering angle (θ). This is defined as:

$$P(\theta) = \frac{\int_0^\theta I(\theta) \sin\theta \, d\theta}{\int_0^\pi I(\theta) \sin\theta \, d\theta}$$

The cumulative probability is required by the Monte Carlo model to generate the scattering angle at each interaction (6).

The system illustrated in Figure 1 has also been used to measure the VSF for human blood. To do this, a spacer of 0.5 mm thickness was used, and diluted blood with a haematocrit of 0.8%, was circulated through the resulting sample cell using a peristaltic pump. The results of these measurements can be seen in Figure 3.

THE MODEL

Some details of the Monte Carlo model have been discussed previously (5). In the simulation, the path of individual photons is

Table 1. The range of absorption and scattering coefficient used in the Monte Carlo model.

Absorption Coefficient (mm^{-1})	Scattering Coefficient (mm^{-1})
1.0	4
0.4	2
0.167	1
0.105	0.5
0.077	0.333
0.0606	0.25
0.05	0.20
0.02	0.167

followed as they enter a homogeneous slice of tissue, perpendicular to the surface. Scattering is assumed to occur at discrete centres, and at each interaction, a new scattering length and scattering angle are determined by random numbers and the cumulative probabilities for scattering length and scattering angle. (The latter determined from the measured VSF for rat brain). Absorption is assumed to take place uniformly along the photon path. The photons are followed until they exit from the front or rear surface where specular reflection and refraction are taken into account. Data is stored on the photons exit coordinates, angle and total pathlength. The resulting data can be analysed and displayed as a function of any of the stored parameters.

RESULTS

Simulations have been performed for a homogeneous tissue slab having a thickness of 10 mm, and a refractive index of 1.4. A wide range of tissue absorption (μ_a) and scattering (μ_s) coefficients (Table 1) have

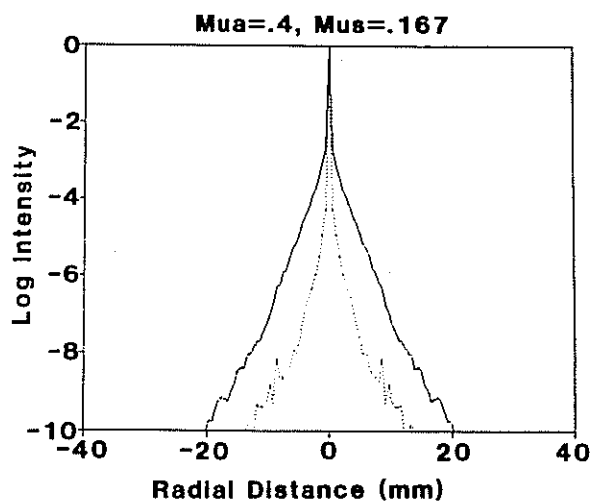


Figure 4. Transmitted and reflected PSF for tissue of relatively high absorption and low scattering coefficient. Intensities have been normalised and are plotted on a logarithmic scale.

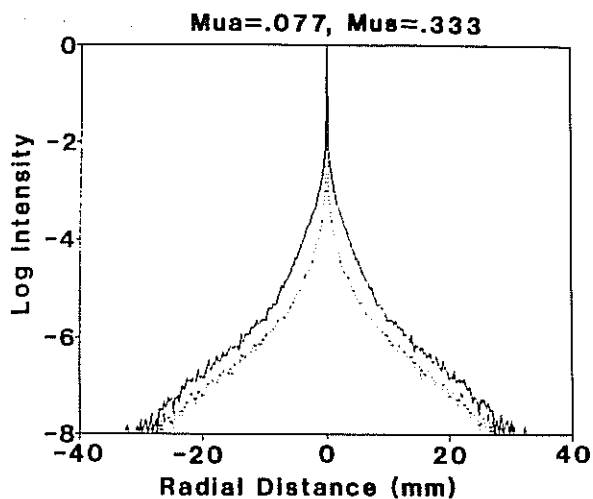


Figure 5. Transmitted and reflected PSF for tissue of medium absorption and scattering coefficient. Intensities have been normalised and are plotted on a logarithmic scale.

been modelled, encompassing the extremes of values quoted in the literature (3,4). For each combination of scattering and absorption coefficients, the model was run for a total of 100,000 photons. The data obtained has been analysed to give the transmitted and reflected PSF, and the total transmission and reflection. Figures 4, 5 and 6 show the reflected and transmitted PSF for different combinations of scattering and absorption coefficients. The transmitted PSF has been fitted to a

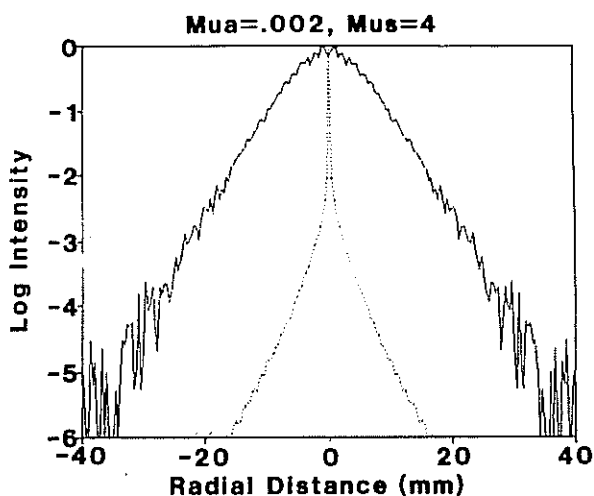


Figure 6. Transmitted and reflected PSF for tissue of relatively low absorption and high scattering coefficient. Intensities have been normalised and are plotted on a logarithmic scale.

Table 2. General equation describing the PSF in terms of tissue absorption and scattering coefficient and thickness.

1)	$I(r) = P1 \exp(-r^2 * P2)$	Gaussian term.
	$+ P3 \exp(-\sqrt{1 + (r/d)^2} * P4) / (1 + (r/d)^2)$	Diffusion term.
	$+ P5 \exp(-r * P6)$	Exponential Term.
	$+ K0$	Unscattered component.
where r = radial distance from the centre, d = tissue thickness.		
2)	$K0 = \exp(-(mua + mus) * d)$	
3)	$P1 = 10^{-(6.7 mua + 1.3 mus - 1.7)}$	
4)	$P2 = 8.4 mua + 2.3$	
5)	$P3 = 10^{((0.165 - 0.217 mus)((1/mua) - 23) - 0.6)}$	
6)	$P4 = 1.12 + 0.72 mus + 10 mua$	
7)	$P5 = 10^{(-0.71 mus + (0.068 * 1/mua) - 0.34)}$	
8)	$P6 = 0.48 mua - 0.1 mus + 0.81$	

generalised equation (Table 2) using a non-linear least squares curve fitting routine (7). The parameters P1 to P6 in the equation were subsequently fitted to functions of the absorption and scattering coefficients and tissue thickness. These equations are also given in Table 2.

DISCUSSION

The equations in Table 2 are the results of empirical fits to the data generated by the Monte Carlo model. They apply to a tissue thickness of 10mm, and to the range of absorption and scattering coefficients given in Table 1. They can however be applied to tissue of different thicknesses by suitable scaling of mua and mus. Although the equation is empirical, the choice of terms in the function was made on the basis of a simplified analysis of the light transport problem. The equation therefore consists essentially of four terms, the general characteristics of which are discussed below.

- a) The Gaussian term. This is thought to result from light which has undergone only a few small angle scatterings events (8). Its amplitude (P1) decreases with increasing scattering and absorption coefficient. The decrease with scattering is probably due to the increasing chance of multiple and large angle scattering. The width of the gaussian term (P2) depends only upon the absorption coefficient in the range covered in this simulation.
- b) The Diffusion term. This applies to the high scattering region of light transport (9). The behaviour of the amplitude of this term (P3) is more complex, but broadly speaking, it increases with increased scattering. The width of the diffusion term (P4) is largely dependent upon the absorption coefficient.
- c) The Exponential term. The physical basis for the inclusion of this term is not fully understood, but it is required to fully describe the PSF over the whole range of absorption and scattering coefficients. This term probably tries to fill the gap between the

small angle scattering and the diffusion regimes. Its parameters (P5 and P6) vary only slowly with absorption and scattering coefficients.

- d) The Unscattered component. These are the photons that travel through the tissues without undergoing any scattering event.

CONCLUSION

We have simulated the transport of light through brain tissue using scattering data derived experimentally. From these simulations we have been able to derive a generalised formula describing the shape of the transmitted point spread function. Using this formula, it is possible to calculate the PSF for brain tissue of differing thicknesses, absorption and scattering coefficients without having to perform a computationally extended Monte Carlo calculation.

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