SIMULATIONS OF PHOTON MIGRATION AND IMAGE FORMATION IN HIGHLY SCATTERING MEDIA

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ABSTRACT

A computer model has been used to simulate transillumination imaging of a sharp edge in the center of a highly scattering object. It is shown that the width of the edge-spread-function of an infinitely absorbing edge increases with the migration time of the photon in a non-linear fashion. Furthermore, the spread - function is offset with respect to the edge: the offset is linearly related to the migration time. The effect is explained in terms of the non-linear nature of the imaging process.

INTRODUCTION

It has recently been shown by several investigators that images of an absorbing, highly scattering object can be made using the photons which take least time to migrate through the object. Wang et al (1) have demonstrated "ballistic imaging", which makes use of those few photons which travel directly from source to detector without scattering. However, the intensity of the ballistic photon beam is so low that other investigators have elected to utilize the intensity of the earliest arriving (forward scattered) photons (2,3,4). It is assumed that if the migration time of the photons is short, then the mean path of the photons lies not too far from the direct source - detector axis. The earliest arriving photons may then be used as a measure of the intensity of photons travelling along the ray between the source and detector.

Two dimensional, transillumination images may be made by moving a source and detector together in a raster across opposite surfaces of a thin object, and plotting the intensity of the transmitted beam. Transverse images may be made using filtered back-projection methods. By suitable choice of source and detector positions, it is possible to collect a data set which simulates the projection data collected by a CT scanner. The image of the original object can then be made using conventional CT algorithms. For either of these approaches to imaging, it is important to know what effect scattering will have on the resolution of the final image. Hebden and Kruger have investigated this effect experimentally and using Monte Carlo models (2,5). They find as expected, that the lateral resolution of the image decreases as the migration time of the photons increases. Recently, they investigated experimentally the edge spread function (ESF) of a sharp edge imaged by projection through a highly scattering medium (6). They confirmed that the ESF was broader as the time of migration increased, but found that the mid point (50% transmission) of the ESF was displaced from the true position of the edge.

We have modelled the migration of light in a highly scattering medium as a diffusion process in order to simulate the effects of imaging a sharp edge in the center of a highly scattering medium. We confirm that the ESF is displaced from the true position of the edge, and propose an explanation for the effect. We have investigated the relationship between the lateral migration of the photons from the imaging axis, and the shape of the ESF.

METHODS

The calculations were made using an IBM 6000 computer running the language IDL (Research Systems, Inc. Colorado). We represented the motion of light in the scattering medium as a diffusive process (7,8,9). The assumption of diffusive motion is reasonable if the distances of migration are much larger than the mean free path length between scatterers. For tissue the mean transport free path is approximately 1 mm, and we are studying the migration over distances of several centimeters. The spatial resolution of the matrix used for the calculations was 0.5 cm.

The migration chamber which was simulated is shown schematically in Fig 1. It is a slab, 4.5 cm thick 16 cm tall and 32 cm wide; the transport coefficient was set to be 8 cm^{-1}. It was assumed that there was no absorption from the scattering medium, but a totally absorbing wall covers half the mid plane. The source and detector were positioned on opposite sides of the chamber at mid height, and were placed at different distances (Xe) from the edge of the wall. The axis between the source and detector is described here as the imaging axis.

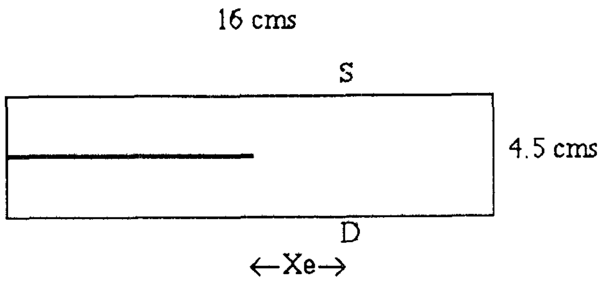

Fig 1. Schematic plan of the migration chamber. A totally absorbing wall covered one half of the mid plane. Migration was simulated for source and detector pairs positioned at the mid-height of the chamber, at distances, Xe, from the edge of the wall.

The computational techniques have been described in detail elsewhere (10). Briefly, we used an iterative computer program to generate the photon number density, $n_s(r,t)$, describing the photon density at point r, and time t following the injection of an impulse of photons at a source point s at time t=0. Then the time-resolved signal at any desired position, r, is simulated by the values of $n_s(r,t)$ at successive times. We also calculated the probable paths of the photons which take time Tm to migrate between a defined source, s, and detector, d. The path was described by the hitting density distribution, $h_{sd}(r,Tm)$ which is the relative number of times that photons pass through the volume element at r. We calculated this from $n_s(r,t)$ and $n_d(r,t)$ as described previously (10).

RESULTS

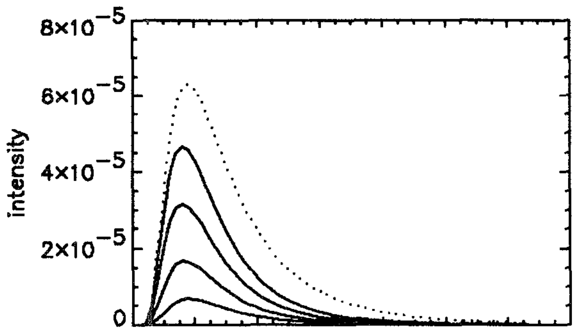

Fig 2 Time resolved signals recorded with the imaging axis different distances from the edge. Dotted curve : Xe = 8 cm). Solid lines from top to bottom : Xe = 0.75,0.25,-0.25, -0.75 cm.

Fig 2 shows the time course of signals obtained with the imaging axis different distances from the edge. The dotted curve shows the signal when the imaging axis is far from the edges, (Xe = 8 cm) and the solid lines show the results as the axis crosses the edge : Xe = 0.75,0.25,-0.25, and -0.75. The signals all have the usual response of a monotonically increasing intensity followed by a monotonically decreasing signal again.

The effect of scattering in the medium is that the intensity does not change abruptly across the edge. The change of intensity as a function of distance for different times of migration Tm are plotted in Fig 3. Each curve is scaled to its own maximum intensity.

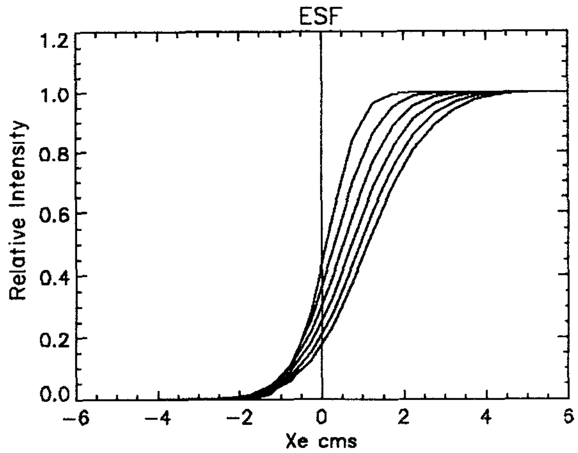

Fig 3. Edge spread functions for different migration times Tm. Successively from left to right Tm increases from 1 to 8 ns in 1ns steps.

These simulations show clearly that as the migration time Tm increases, the ESF becomes wider. The center position of this function, defined as the point at which the transmission is 50%, moves away from the position of the edge as Tm increases. The increased width of the ESF is expected as a consequence of the the lateral migration of the photons. The offset of the ESF was not an anticipated result , although it too arises as a direct result of the scattering of photons. It can be explained by reference to Figs 4 and 5.

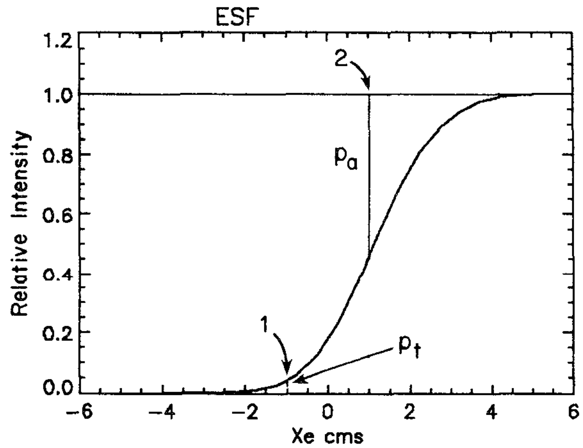

Fig 4: Edge spread function. Two positions for the imaging axis are marked equidistant on either side of the edge.

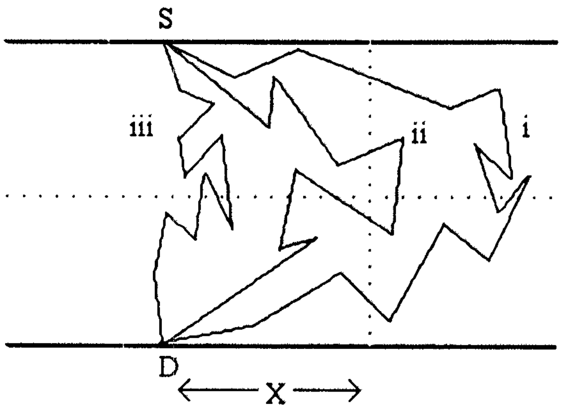

Fig 5 : Schematic diagram showing the three classes of photons:
i) Those that only cross the center line at x > X
ii) Those that cross the center line at x>X and also x<X
iii) Those that cross the center line at x<X.

Consider the light transmitted between source and detector for two positions of the imaging axis, equidistant from, but on opposite sides of the edge. At position 1, (Xe = -X), the imaging axis strikes the wall, yet a fraction p_t of the maximum intensity is still transmitted from source to detector. With the axis at position 2 (Xe = +X), the axis does not strike the wall, yet a fraction p_a of the light is absorbed. We consider paths of individual photons in the absence of the wall, and then identify which of these photons will or will not strike the wall when it is present. Because the medium is highly scattering ,the photon paths do not progress monotonically from source to detector, but travel forwards, backwards and sideways. They will (on average) cross each plane more than once. We can then distinguish three classes of photons (represented schematically in Fig 6) based on where they cross the center plane relative to a distance X from the SD axis.

i) a fraction p(x>X) cross only at positions x>X

ii) a fraction p(x><X) cross at positions on both sides of X

iii) a fraction p(x<X) cross only at positions x<X

In an isotropic medium the probabilities are independent of whether X lies to the left or the right of the SD axis.

It follows that when the axis is at position 1 (Xe = -X) the photons which reach the detector are those which *never cross* the center plane at positions closer than X. Therefore

$$p_t = p(x>X) \qquad \text{(Eq.1)}$$

In contrast, when the imaging axis is at position 2 (Xe = +X), the photons which are absorbed are all photons which *ever cross* the center plane beyond X. Therefore

$$p_a = p(x>X) + p(x><X) \qquad \text{(Eq 2)}$$

Thus $p_a > p_t$ for all values of X by an amount p(x><X), with the result that the edge spread function is not symmetric. The difference is due to the fact that the photons of class (ii) are absorbed in both situations.

The hitting density function $h_{sd}(r,t)$ was used to measure the transverse migration of photons along the central axis (in the plane of the wall) during the movement from source to detector. The distribution is shown in Fig.6. The solid line represents the hitting density in the absence of an absorbing object near to the imaging axis. The stars show the density when the imaging axis strikes the edge. The photon density is decreased even on the side clear of the wall because some photons which hit the volumes to the right of the wall also hit on the left too - class (ii) photons of Fig 5. The result is that fewer than 50% of the photons will be transmitted when Xe=0, as seen in Fig 3.

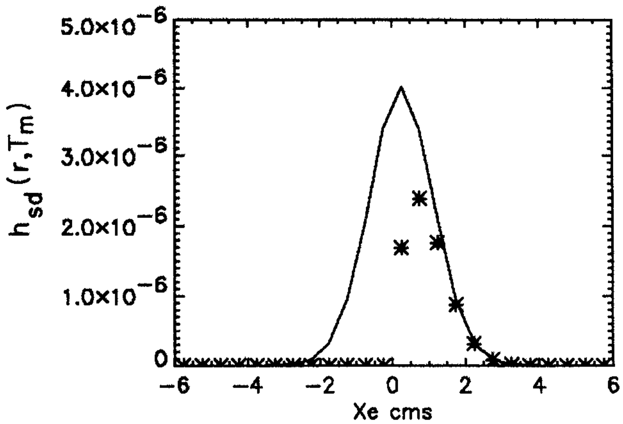

Fig 6. Plot of the hitting density distribution $h_{sd}(r,Tm)$ along a line normal to the imaging axis.
Solid line - imaging axis far from the edge.
Stars - imaging axis strikes the edge.

At present we are investigating this phenomenon further. We are not yet able to describe analytically the relationship between the lateral migration of the photons, the width and offset of the ESF and the migration time. Nonetheless, we have investigated the relationships empirically.

Fig 7 displays the time dependance of (i) the half width of the hitting distribution (ii) the width of the ESF (defined as half the 10% - 90% transmission width (iii) the offset of the point of the ESF with 50% transmission. The two width functions have similar, non - linear time dependances, while the offset appears to be linearly dependant on migration time Tm.

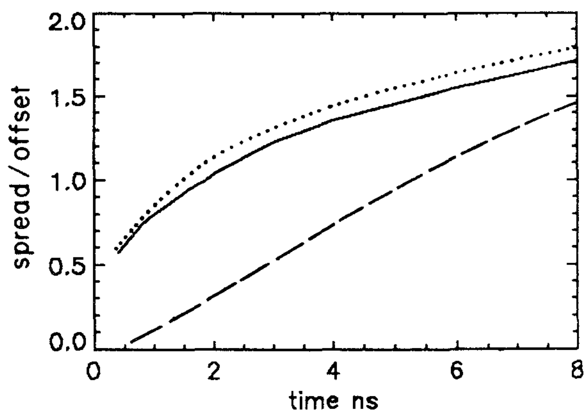

Fig 7. Time dependance of : -
solid line - width of the edge spread function.
dotted line - width of the lateral spread of photons described by the hitting density.
dashed line - offset of the 50% transmission point from the edge

DISCUSSION

We have used the diffusion description of the motion of light in a highly scattering medium to investigate computationally the effect of scattering on the transillumination imaging of an absorbing edge. Our results confirm the experimental observations of Hebden (6) that the edge spread function depends on the migration time of the photons. Hebden's results were made by collecting all photons arriving at the detector before a time Δt, while we have investigated the intensity of photons arriving at a particular time. Nonetheless, this difference in protocol will make no difference to the qualitative conclusions. The width of the ESF increases with the migration time Tm. Moreover, the ESF is offset from the true position of the edge by a distance which is linearly dependant on Tm. This effect is a result of the random nature of the photon transport. The implications of these results for imaging are that the time used for the collection of the 'near- ballistic' photons should be kept short as possible. While it may be possible to correct for the width of the spread by some form of deconvolution, the position of the resulting edges will be offset from the true edge positions. Absorbing objects will appear to be larger than they really are. We are in the process of investigating how this effect depends on the relative absorption coefficients of the wall and the medium when the wall is not a total absorber. We anticipate that an object with an increased absorption (relative to the medium) will appear larger, while an object with a reduced absorption will appear smaller.

ACKNOWLEDGEMENTS

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