First photon detection in transillumination imaging: a theoretical evaluation

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Abstract

This thesis is a theoretical evaluation of the (single) first photon detection (FPD) technique as a limiting case of time-resolved transillumination imaging (TI) for diagnostic purposes. It combines analytic and Monte Carlo (MC) simulation methods to derive the single photon statistics and to solve the radiative transfer equation (RTE) for a given source-medium-detector geometry.

Initially, a standard Monte Carlo (SMC) simulation algorithm for visible to infrared photon transport through a turbid (randomly scattering and absorbing) medium such as soft tissue is developed from first principles. This provides a time dependent solution of the RTE at longer time scales. In order to efficiently simulate very early arriving photons, an Indeterministic Monte Carlo (IMC) technique based on path integrals is devised and validated. The IMC utilizes the SMC algorithm to propagate photon trajectories and extends controlled MC techniques to accelerate and enhance the probability of detecting shorter trajectories thereby improving the statistics.

The IMC technique provides a tool for the construction of a temporal point spread function (TPSF) of the emerging photons for the entire time scale. The computational procedure is validated by reproducing the published spatial resolution results associated with conventional time-gated systems over longer time scales of several hundred picoseconds. It is then used to predict the spatial resolution of these systems for shorter (sub-100 picosecond) time scales.

The calculation of the TPSF at short time scales for a pulse made incident onto the medium enables the mathematical derivation of the temporal probability density functions (p.d.f.) for the first arriving photon, $f_1(t)$. This facilitates the investigation of a first photon detection (FPD) system as applied to a diagnostic TI configuration.
A FPD system produces a signal representing \( f_1(t) \) from which the mean transit time of the first arriving photon, \( \tau_1 \), may then be estimated for a sequence of incident pulses at each scan position. By rectilinear scanning across the medium, a 2-D map of \( \tau_1 \) can be created and displayed as a grey scale image.

The application of FPD to TI is evaluated assuming an ideal detector capable of detecting the first arriving photon with 100% efficiency (infinite extinction coefficient). However, a model for a FPD system corresponding to a non-ideal (single first photon) detector is also considered through the evaluation of the p.d.f. for the later (1\(^{st}\), 2\(^{nd}\), \ldots) arriving photons. This enables a detection time limit to be specified to eliminate the later arriving photons and thereby overcome distortions in the first photon p.d.f. which may be caused by any inefficiency in the response of the detector.

The FPD technique is then applied to obtain \( f_1(t) \) for various laser pulse intensities. The FPD system is also examined for the case of spherical inhomogeneities (representing tumours) embedded in the centre of an otherwise homogeneous medium. The effect of the variations in the embedded inhomogeneity (size and optical density) and optical properties of the medium are also studied. A heterogeneous medium which resembles tissue more realistically is considered.

For a FPD system where the received signal does not change (one photon) per incident pulse, the signal contrast is redefined and is examined as a function of the incident laser power and medium absorption and scattering properties. The signal-noise-ratio is also evaluated for the FPD system as the error in the estimation of \( \tau_1 \).

Based on the analysis of the SNR, the number of incident pulses (per scan position), needed to achieve a required SNR, is also derived.

It is shown that the p.d.f. of the first arriving photon for a \( \sim 3 \text{mm} \) totally absorbing inhomogeneity located at the mid-plane of a 50mm thick tissue-like medium may be distinguished (95% confidence level) from the p.d.f. of a medium without the inhomogeneity. This theoretical study provides an introduction aimed at assisting further experimental research into the limits of transillumination imaging employing a first photon detection (FPD) system.