Simulation of the OCT-depth signal of homogeneous turbid media via an extended Monte-Carlo model

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We present a simple model to simulate OCT depth signals in weakly and strongly scattering media. A weighting function rescales the photon signal according to its individual number of scattering events. With this function, we are able to implicitly predict the influence of dependent scattering without modelling the process explicitly. In future, our quantitative approach could improve biological imaging.

1 Introduction

Optical coherence tomography (OCT) is widely used in medical imaging, for example in ophthalmology or dermatology, to name just a few, and its potential is not yet fully explored [1]. In the obtained data a lot of information is encoded. Not only the morphology, which can be seen by the naked eye, but also other optical properties can be retrieved from the OCT data. By simulating light propagation via a Monte-Carlo (MC) method and comparing simulations and measurements additional information can be obtained.

The simulation of an OCT depth profile at one spot (A-scan) uses the stochastic MC method presented in [2] taking into account the geometrical constraints of the OCT detection system and proposing a new approach for the incorporation of multiple scattering events by means of a suitable heuristic weighting function. A modification of Alerstams parallel GPU MC approach [3] was used to generate the simulated data with a large number of photons processed in parallel. We systematically studied the influence of various scattering orders on the simulated OCT signal using a virtual homogeneous sample. The simulated data was compared to real OCT data obtained from milk phantoms, prepared as homogeneous liquid samples with known concentration. Our investigations show that simulation and experiment are in reasonable agreement. Even though our approach does not explicitly include dependent scattering, this effect is taken into account implicitly.

2 Experimental measurements

A standard Spectral Domain OCT setup (Thorlabs Telesto II @ 1325 nm central wavelength) was used with axial and lateral resolutions of 5.5 µm and 13 µm in air, respectively. The A-scan is obtained from the interferometric signal and shows directly the depth profile (along the z-direction). A galvanometric mirror set and an F-Theta objective allow for scanning the surface in x and y direction (defining the sample plane) to obtain so called B- and C-scans (2D and 3D). Each measurement was averaged over 50 B-scans with each A-scan averaged over 20 single shots. The left hand side of Fig. 1 illustrates a typical OCT B-scan of a milk-water dilution. By averaging over 20 A-scans a smooth depth profile is extracted (Fig. 1, top right). The profile is described by:

$$i_D(\Delta z) = \frac{\rho}{2} F_D(\Delta z) \underbrace{\exp\left(-\mu_s \Delta z\right)}_{\text{Beer-Lambert}} \qquad (1)$$

where ρ is a factor containing amplitude and offset and Δz is the depth. The exponential function corresponds to the Beer-Lambert law. F_D is the device function where the confocal intensity profile of the Gaussian beam is the main contribution. By using Eq. 1 as fit function the scattering coefficient μ_s can be obtained.

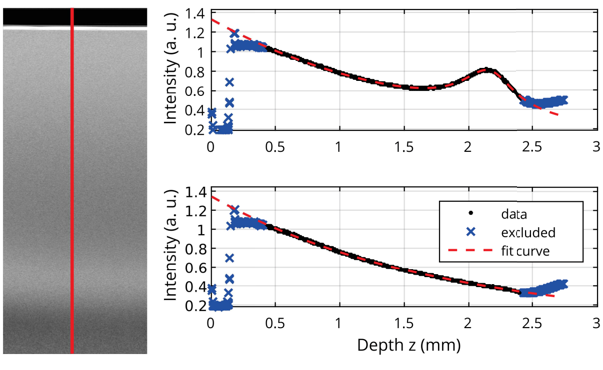

Fig. 1 *From an OCT B-scan (left) an averaged A-scan is extracted (top right) and the device function F_D is deconvolved (bottom right)*

3 Simulations

From a general point of view, the extended MC simulation launches photons which travel through a virtual sample and undergo scattering processes. Only the coherent backscattered photons reaching the detector are contributing to the simulated OCT signal. Also geometric selection rules like numerical aperture of the detection system are considered (see Fig. 2).

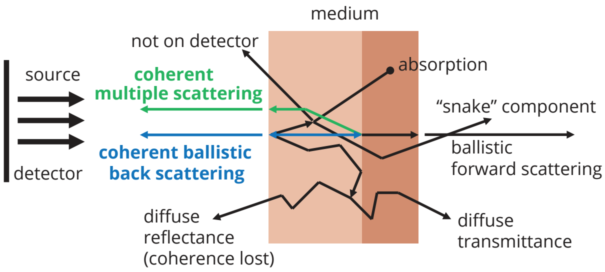

Fig. 2 *Light propagation scheme of simulated photons in a scattering medium. The contributing trajectories are highlighted in blue and green.*

Each photon reaches a certain maximum depth $z_{\max}$ and has a total path length L_p, as well as a corresponding expected depth $d_{\max} = L_p/2n_2$ and a number of scattering events N_{se}. All these values are recorded for post-processing. Subsequently the photons are categorized in two groups according to Ref. [4]: least scattered photons (LSPs), which are scattered only a "few" times and for which the penetration depth can be reconstructed reliably, and multiple scattered photons (MSPs), which, due to their path length L_p, appear to be from the expected depth but in fact never reached it (see Fig. 3).
The depth is divided into interval bins of size Δz, which is chosen to match the axial resolution of the OCT system. All photons fulfilling the coherence condition (Eq. 2) are collected into these bins:

$$|L_p - 2n_2 d_{\max}| < \frac{L_c}{2}, \tag{2}$$

L_c is the coherence length of the light source and n_2 is the refractive index of the medium.

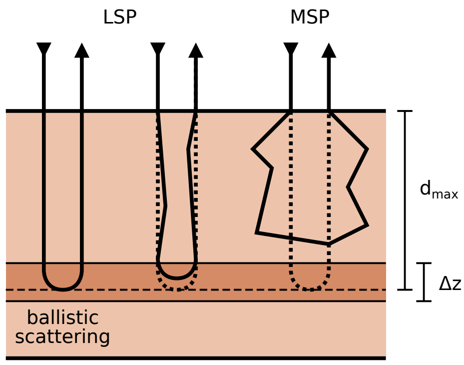

Fig. 3 *Scheme of photon categorization and simulated coherence gating.*

While all coherent photons contribute to the OCT signal, the coherence might actually get lost due to scattering. To mimic this process a weighting function based on the number scattering undergone is defined:

$$F_W(N_{se}) = \left[1 + \exp\left\{a\left(N_{\text{se}} - b\right)\right\}\right]^{-1}. \tag{3}$$

The parameter b determines how many scattering events are accounted for and a defines the "sharpness" of the selection. A parameter study reveals a linear dependence of parameter b on the milk concentration. Hence, for a given concentration the scattering coefficient μ_s becomes predictable.

4 Results and discussion

In the low concentration regime, the dependence of μ_s on the concentration is linear (see inset of Fig. 4). But for high concentrations the measured μ_s (red asterisks) are lower than expected (extrapolated black line). This is due to so called dependent scattering. The latter is not considered by the model explicitely, although the use of the weighting function allows to correct this difference.

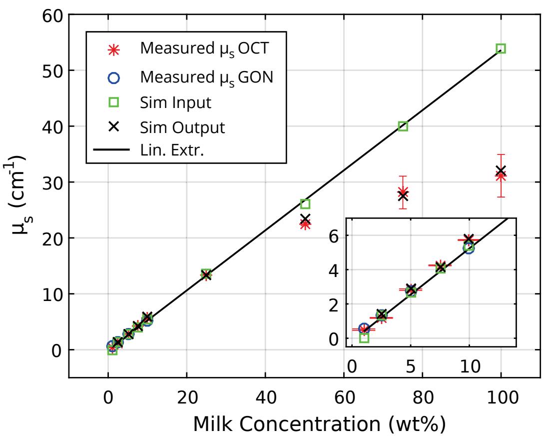

Fig. 4 *Comparison of simulation and measurement of the scattering coefficient μ_s. The inset shows the linear regime for low concentrations.*

The simulation output is represented by the black crosses and corresponds well with the measurements. For increasing concentrations it is harder to retrieve μ_s from the OCT measurements, thus the error is increasing.

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