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Enhanced contrast in optical coherence tomography using multiple scattering

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ABSTRACT

Optical coherence tomography (OCT) is a powerful label-free approach for volumetric morphological imaging with numerous applications, especially within biomedicine. The penetration depth of OCT reaches well beyond conventional microscopy; however, signal reduction with depth leads to a rapid degradation of the signal below the noise level. The important pursuit of imaging at depth has been largely approached by extinguishing multiple scattering. This has been valid for many microscopies; however, here, we postulate that in OCT, multiple scattering can enhance image contrast at depth. We demonstrate this using an original geometry that completely decouples the incident and collection light fields by introducing a spatial offset between them. This approach leads to a preferential collection of multiply scattered light with depth, compensating for signal attenuation and enhancing the image contrast at depth. A wave optics model and unified theoretical framework supports our experimentally demonstrated improvement in contrast. The effective signal attenuation can be reduced by over 24 dB. Our approach reveals mesoscale features in images of ex vivo mouse bone. Considering most approaches to date have aimed to minimize multiple scattering, our results suggest that the problem of OCT imaging at depth should be distinguished from optical microscopy at depth. This facile and widely applicable geometry enables a power capacity to dynamically tune for contrast at depth.

Keywords: Optical coherence tomography, optical attenuation, turbid media, spatial offset, contrast enhancement

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1. INTRODUCTION

Morphological imaging with optical coherence tomography (OCT) has made major strides in the past few decades[1]. While advances of using OCT have been spectacular, there are major drawbacks in terms of its depth penetration. The state-of-the-art implementations of OCT use light in the near-infrared range of the spectrum to penetrate deeper into biological matter, however, signal extinction through turbid samples often precludes obtaining discernible signals from depths beyond 1 mm. The conventional wisdom is that the OCT signal is dominated by ballistically scattered light (light which has undergone a single backscattering event) whereas multiply scattered light and diffuse light are detrimental to image formation. Thus, most advances in imaging through disordered media have focused on the enhancement of the single to multiple scattering ratio (SMR)[2]. However, in OCT, these approaches have failed to consider the accompanying limits in the dynamic range and the detection noise. In most practical settings, the high flux from surface-scattered photons will obscure depth information within the detector noise before the fundamental limit in SMR is reached.

Practically, OCT is well-known to retrieve morphological tissue contrast at depths much greater than most microscopy methods. This is because a large proportion of the useful OCT signal also comprises multiply scattered light[3]. In uniformly scattering tissues, multiple scattering dominates the signal past 1 mean free path in the sample. While ballistic scattering attenuates exponentially, the likelihood of multiple scattering increases with depth. Recognizing this phenomenon, we illustrate that we can generate an OCT image by prioritising the multiple scattering signal. By completely decoupling the incident and collection paths of OCT though a facile spatial offset, we can tune the collection of ballistic light and multiply scattered light at different depths in the sample. This leads to substantially enhanced imaging depth and contrast through

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a decrease in the effective attenuation in scattering samples and the preservation of the signal within the dynamic range of the detectors. We term our technique spatially offset OCT (SO-OCT).

In addition to an experimental demonstration of improved contrast, we present a wave-based model of the heterodyne efficiency factor that provides a framework for exploring the impact of offset collection geometries. Using this model, we show that we can significantly enhance the OCT signal contrast at depth and reveal mesoscale features obscured by the limits of detection noise despite favouring multiple scattering. Our approach reveals that improving penetration depth should not be addressed solely from the perspective of eliminating multiple scattering. On the contrary, SO-OCT demonstrates an approach for capturing information about the sample that is carried predominantly by the multiply scattered light.

2. METHODOLOGY

2.1 Modelling framework

Through modelling based on the extended Huygens-Fresnel princple[4] we have derived a unified theoretical framework which allows us to describe SO-OCT with and without a variable angle between the illuminaiton and collection paths[5] . Incorporating both spatial offset and the angle, the heterodyne efficiency factor can be written as:

$$\Psi(z,s,\alpha) = e^{-2\mu_a z}\left[e^{-2\mu_s z}e^{\frac{-(z\alpha+s)^2}{2\omega_H^2}} + \frac{4e^{-\mu_s z}(1-e^{-\mu_s z})}{(1+\mu_a\Delta z_D)(1+\frac{\omega_{SA}^2}{\omega_H^2})}e^{\frac{-(z\alpha+s)^2}{\omega_H^2+\omega_{SA}^2}} + \frac{(1-e^{-\mu_s z})^2\omega_H^2}{(1+\mu_a\Delta z_D)\omega_{SA}^2}e^{\frac{-(z\alpha+s)^2}{2\omega_{SA}^2}}\right], \quad (1)$$

where s is the lateral offset in the lens focal plane and α is the angular offset between the illumination and collection paths, μ_a and μ_s are the absorption and scattering coefficients of the tissue, respectively, and ω_H and ω_{SA} are the the $1/e$ intensity radii in the absence and presence of absorption and scattering, respectively. Modelling was performed using custom software developed in MATLAB R2020a (*The MathWorks, Inc*., MA, USA).

2.2 Experimental implementation

SO-OCT images were acquired using an adaptation of a commercially available OCT system (TELESTO-II, Thorlabs Inc., NJ, USA), with a custom-built add-on enabling spatially offset detection (Figure 1). An offset is introduced between the illumination and collection paths by translating the position of a pinhole in the collection path.

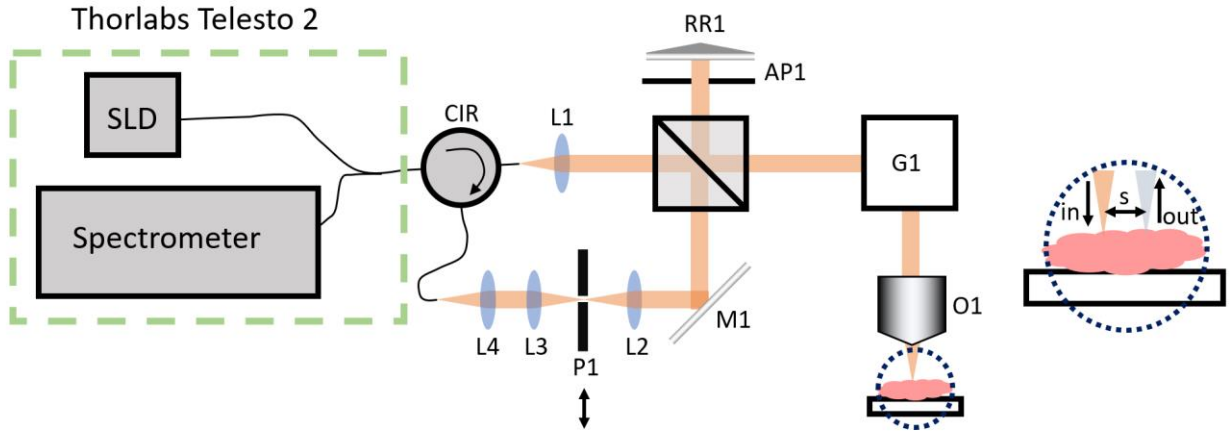

Figure 1. Experimental diagram of the spatially offset OCT system. SLD: superluminescent diode, CIR: circulator, RR1: retroreflector, G1: galvo mirror, O1: objective lens, L1-4: lens, AP1: variable aperture, P1: pinhole. Offset is introduced by translating the pinhole in the collection path.

3. RESULTS

3.1 Modelling

Fig. 2a indicates the relative contribution of single and multiply scattered light to the OCT signal with a separation of s = 0. Already from Fig. 2a it is quite clear that multiply scattered light dominates the OCT signal acquired from deeper in the sample. Indeed, the OCT signal is *mainly* composed of multiply scattered light, especially as the depth in the sample increases. The depth at which the multiply scattered light dominates the OCT signal depends on the scattering coefficient, as shown in Fig. 2b. As a consequence, variation of the offset *s* between the illumination and collection paths allows for tuning of the relative contribution of single and multiply scattered light to the collected signal. In the case where sensitivity is not a limiting factor, the dynamic range of the detector can be likewise optimized to a range relevant to the multiply scattered signals which have travelled deeper into the sample. This is illustrated in Fig. 2c, wherein the heterodyne efficiency factor has been normalized to the peak efficiency. Practically, this demonstrates that the optimization of *s* and the detector dynamic range can lead to an optimal contrast for a selected depth.

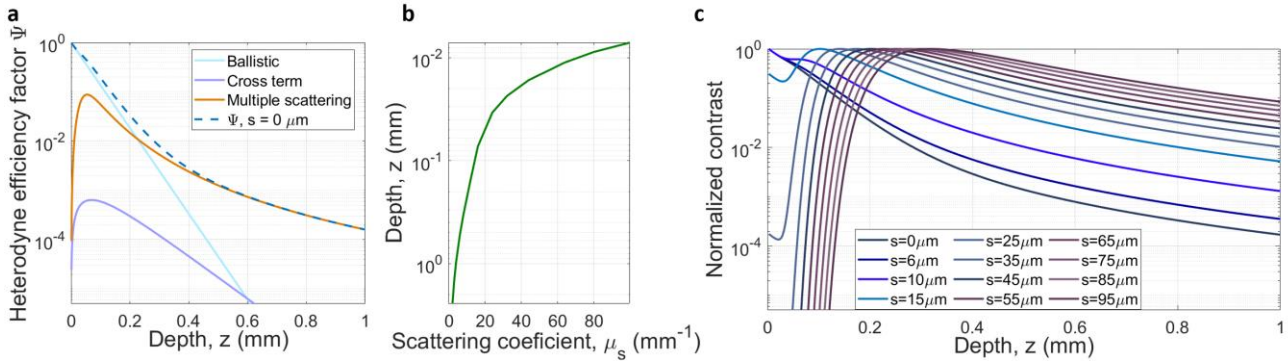

Figure 2. Calculations of heterodyne efficiency factor (Ψ) and normalized OCT contrast in conventional and SO-OCT. Here, the normalized OCT contrast is represented by the normalized heterodyne efficiency factor. (a) shows the relative contribution of ballistically scattered and multiply scattered light in image formation in conventional OCT. While the ballistic signal dominates superficially, the multiply scattered component rapidly dominates the signal at depth. (b) shows the depth at which the multiply scattered light dominates the OCT signal for various scattering coefficients. (c) is the normalized OCT contrast in SO-OCT with $\alpha = 0$ and various offsets.

3.2 Experimental results

One of the main potential advantages of SO-OCT is the opportunity to improve contrast and imaging depth in highly scattering media for example, hard tissue like bone and cartilage. Only a few studies have investigated OCT in bone since the high multiple scattering severely limits the imaging depth[6,7]. In order to demonstrate the contrast improvement in SO-OCT, we imaged an ex vivo mouse femur. Images of the bones with conventional OCT and $s = 40$ μm offset are shown in Fig. 3a and b, respectively. Visually, it is evident that the attenuation of the signal in the SO-OCT image is significantly less than in the conventional OCT image. Indeed, the attenuation between the top and bottom surface of the bone was reduced by over 24 dB for an offset of $s = 40$ μm. The boundary between the hard bone and marrow are much more clearly defined, and the bottom surface of the bone is revealed.

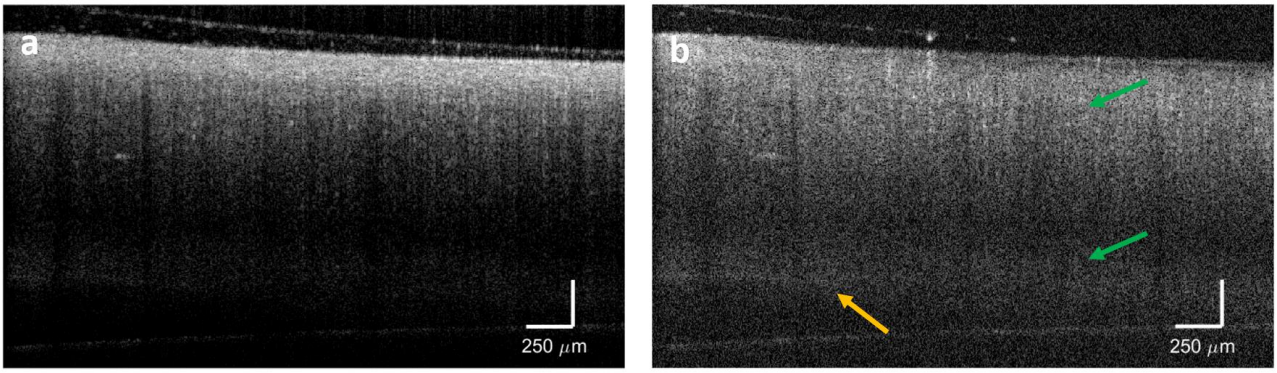

Figure 3. OCT B-scan images of a ex vivo mouse femur with SO-OCT. (a) conventional OCT and (b) s = 40 μm. SO-OCT demonstrates enhanced contrast between tissue layers. The green arrows indicate the boundary between the hard bone and marrow, and the orange arrow indicates the bottom surface of the bone, which is revealed by the enhanced contrast in the SO-OCT image.

4. CONCLUSIONS

Using both modelling and experimental results, we have demonstrated that multiple scattering dominates the OCT signal at depth. We have shown that selectively collecting multiply scattered light using SO-OCT can can significantly enhance the OCT signal at depth and reveal mesoscale features obscured by the limits of detection noise. SO-OCT is a promising new approach for overcoming the limitations of OCT imaging in turbid media.

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