A simplified dynamic focus method for time domain OCT

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A new optical arrangement for performing dynamic focus in time domain OCT is demonstrated. Unlike previously reported schemes, this method does not require any additional components or impose design constraints on the OCT system. The scheme is tested on a high lateral resolution OCT system (NA = 0.13) and we show that we extend the effective depth of focus from 200 μm to better than 2 mm. The optimum correction is for media with a mean refractive index of 1.4.

Introduction

Optical Coherence Tomography (OCT) is an imaging technique, first reported in 1991 [1], which generates 3D tomograms of optically scattering media. Depth selection is achieved through the 'coherence gate' phenomenon observed in low coherence interferometry. In time domain OCT (TD-OCT), a depth scan (A-scan) is generated by mechanically scanning the coherence gate along the depth range, whilst in spectral domain OCT (SD-OCT) either a spectrometer (Fourier domain OCT) or a wavelength tunable source (swept source OCT) is used to recover the A-scan in a single shot [2]. SD-OCT offers several benefits over TD-OCT, including higher sensitivity and exponentially faster scan rates [3].

However, SD-OCT retains some disadvantages. In particular there is a limited depth range (the 'confocal gate') due to the finite depth of field (DOF) of the imaging optics. While TD-OCT is compatible with dynamic focus schemes which scan the coherence and confocal gates simultaneously, the inherently single-shot nature of the A-scan acquisition in SD-OCT precludes this [4]. TD-OCT therefore continues to have applications where either a large scanning range or high lateral resolution (high NA) are required, a particular example being adaptive optics assisted retinal imaging [4].

The diffraction limited DOF and lateral resolution, Δx, of an OCT imaging system can be defined as [2]:

$$DOF = \frac{2\lambda n}{NA^2} \quad (1)$$

$$\Delta x = \frac{1.22\lambda}{NA} \quad (2)$$

where λ is the central wavelength, n the refractive index of the sample and NA the numerical aperture of the imaging lens. Since high lateral resolution is desirable in many OCT applications, there is a design trade-off between lateral resolution and DOF in SD-OCT or non dynamic focus assisted TD-OCT.

Dynamic Focus

Dynamic Focus is difficult to implement in A-scan based (depth priority) OCT, as the depth scanning is fast and high speed adjustments of the focus are required. Hence, T-scanned based (transversal priority scanning) OCT, where the depth scan is slower, is better suited to dynamic focus [4].

One simple dynamic focus solution is to have both the interface optics and reference arm mounted on separate stages (or similar optical-path-length varying devices). However, this adds complexity and cost to the system, requires synchronisation of the stages and may increase the noise due to mechanical scanning. Other more elaborate systems, using components such as MEMS mirrors [5], will add further costs and/or complexity.

A method has been proposed previously whereby the interface optics and reference arm are mounted on the same stage [6]. This allows correction for media with a refractive index of 1.4 with a single stage. However, this may restrict the design of the OCT system somewhat (a retro-reflector is required) and may be particularly difficult to implement in more complex systems, such as those including adaptive optics.

Method

Our simplified method requires only that the object arm, and not the reference arm as in [6], is placed on the translation stage. By allowing physical separation of the two interferometer arms, our method removes a design constraint which restricts the layout of more complex systems such as those employing adaptive optics. In addition, it permits the design of a probe-head which is both smaller and can be positioned independently of the rest of the OCT system. This allows for much greater flexibility in creating systems which are portable and which can be employed in a wide range of situations.

A TD-OCT setup with the new dynamic focus method is shown schematically in Fig. 1. The system is illuminated by an SLD of central wavelength 850 nm and bandwidth 50 nm, delivering a peak optical power of 700 μW to the sample. The numerical aperture of the imaging system is 0.13, yielding diffraction limited lateral resolution and DOF of 4 μm and 100 μm respectively in air. The theoretical axial resolution, determined by the bandwidth of the source, is approximately 6 microns. Conventional (non dynamic focus) TD-OCT images for comparison were acquired by scanning the reference translation stage, TS2; this stage is not required for dynamic focus assisted imaging.

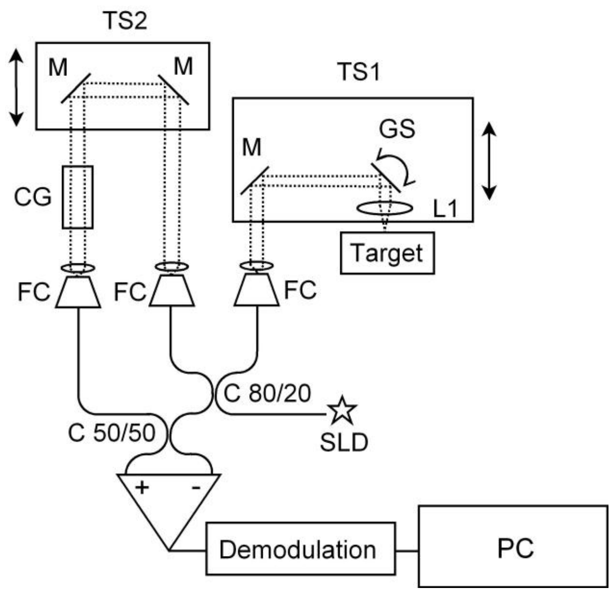

Fig. 1: *TD-OCT with dynamic focus. L1: lens (f = 15 mm), M: mirror, FC: fibre collimator, C: 2x2 coupler, GS: XY galvo scanner head, CG: dispersion compensating glass; SLD: super-luminescent diode; TS1: translation stage for depth scanning with dynamic focus; TS2: translation stage for depth scanning (no dynamic focus).*

If the object translation stage, TS1, is scanned a distance d towards the sample (of average refractive index $\bar{n}$), the coherence gate will move a distance $2d/\bar{n}$ into the sample, while the focus position moves a distance $d\bar{n}$. Matching of the coherence and confocal gates therefore requires:

$$dn^2 = 2d \tag{3}$$

and hence they are matched when $\bar{n} \approx 1.4$. This calculation is equivalent to that used in [6]. When $\bar{n} \neq 1.4$, a good quality image will still be obtained when the gate mismatch is smaller than half the DOF, i.e. when $d\bar{n}^2 - 2d < \left|\lambda\bar{n}/NA^2\right|$, and so when the imaging depth ($2d$) is in the range:

$$2d < \left|\frac{\lambda\bar{n}}{NA^2}\frac{2}{\bar{n}^2 - 2}\right| \tag{4}$$

Results

The system was initially tested for a 2 mm deep B-scan (cross-section) of milk diluted with water, a highly scattering but deeply penetrable media with $\bar{n} \approx 1.4$. Fig. 2 (a-c) shows B-scans acquired in the conventional way (driving one mirror of the XY galvo-scanner head at 500 Hz along with TS2 at 2 mm/s), with the focus placed at different positions. It can be observed that only a small depth range is in focus (and hence imaged) in each frame. The measured FWHM of the confocal profile is 200 μm which is in reasonable agreement with the theoretical DOF calculation above, allowing for the refractive index of the media and some aberrations. Fig. 2(d) shows a B-scan acquired with dynamic focus (TS1 scanned at 1 mm/s, TS2 not scanned), but with all other imaging parameters identical. Scattering can now be observed at all depths, showing that the depth range is greater than 2 mm.

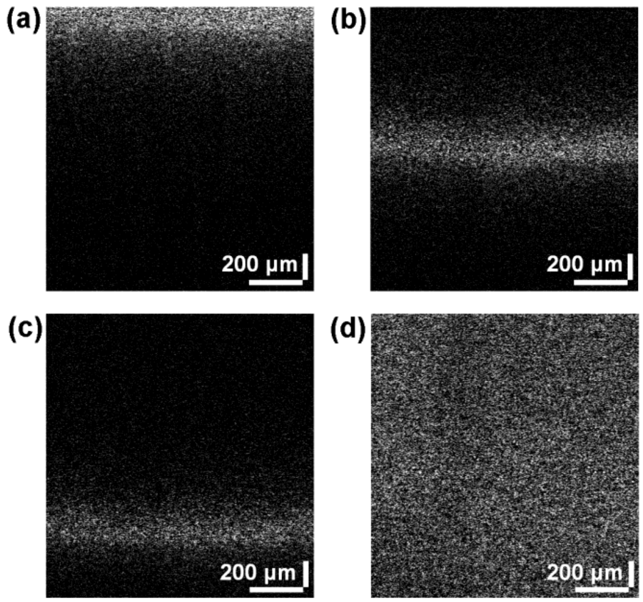

Fig. 2: *B-scan of diluted milk shown without dynamic focus with focus at (a) top of scan (b) centre of scan, (c) bottom of scan, and (d) with dynamic focus.*

Fig. 3 show OCT images collected from tooth enamel (n ~ 1.6) and dentin (n ~ 1.5). Since n ≠ 1.4 , the focus correction will not be as efficient as for the ideal case in Fig 3; nevertheless Eq. 4 still predicts a large increase in imaging range in comparison with conventional TD-OCT. The images in the top row are B-scans (cross sections), obtained (a) without dynamic focus and (b) with dynamic focus. The bottom row shows C-Scans (*en-face* slices) at a depth of 400 μm (obtained by driving one of the XY scanners at 500 Hz and the other at 1 Hz) without (c) and with (d) dynamic focus. As expected, a clear improvement is observed.

In both cases the improvement is the same as that which would be obtained by the method in [6]. For media where n varies significantly from 1.4, methods such as [4] and [5] can in principal obtain a better improvement, but only when one has *a priori* knowledge of the object's refractive index structure and at the expense of cost and simplicity.

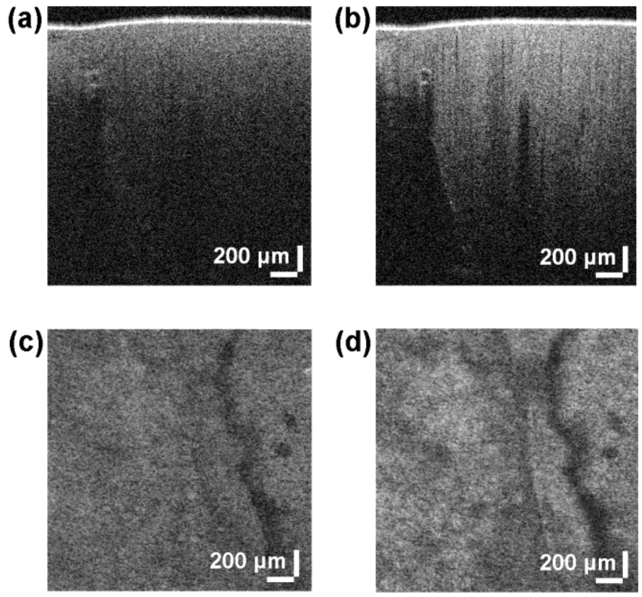

Fig. 3: *Scans of tooth enamel layers; (a) B-scan without dynamic focus, (b) B-scan with dynamic focus, (c) C-Scan (en-face) without dynamic focus, (d) C-scan with dynamic focus.*

Conclusion: We have demonstrated a simple, low-cost and effective TD-OCT dynamic focus solution improved from previously reported methods in that it requires no additional components and allows physical separation of the object and reference arms. This method would be suitable for use in applications requiring large depth scanning as well as those providing requiring high lateral resolution.

References

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