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Optical Coherence Tomography – Variations on a Theme

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1 Abstract

Optical Coherence Tomography (OCT) has developed extensively over the last 23 years. This paper reviews some of the imaging techniques based on OCT with particular reference to the trade-offs between lateral and axial resolution, working distance, imaging depth, acquisition speed (enabling real time observation and 3D imaging), imaged area/volume, contrast enhancement – including velocity measurement, and system complexity – including detectors, light sources and the optical path.

Time domain OCT was the original system[1] and required a simple detector, a depth scanning mirror and a short duration pulsed laser light source. Resolution was good but multiple samples were required for each A-scan which made acquisition slow. The development of spectral domain or Fourier domain (SD-OCT), and subsequently swept source (SS-OCT) methods greatly enhanced acquisition speeds. This provided a much better patient experience for retinopathy as well as enabling the possibility of real time 3D imaging. Intra-vascular OCT could also compete with intra vascular ultra-sound (IVUS) by providing both higher resolution and faster draw back times combined with the advantages of a smaller fibre-optic catheter minimizing vessel occlusion.

Various techniques have been introduced to improve image acquisition times, including the use of spatial coherence, alone or in conjunction with temporal coherence, in order to allow simultaneous sampling across multiple sites. Spectral Encoded Endoscopy (SEE) also provides sampling from multiple lateral sites within a single sample sweep, but each location only uses a part of the total bandwidth thus reducing axial resolution. Interleaved OCT on the other hand can sample from several locations simultaneously while employing almost the full bandwidth at each location by using a more complex multi-band demultiplexer (MBDX)[2].

Ultimate resolution is essentially diffraction limited laterally, and source bandwidth limited axially. In practice it is often necessary to work with low numerical aperture optical systems, such as in retinal imaging, and typical lateral resolution is around 15µm, axial resolution around 5µm. A number of high resolution OCT scanners are also available which can give an axial resolution down to around 3µm, but it is debatable whether the increased resolution actually enhances the diagnostic ability. Some improvement in lateral resolution may be achieved through the use of sources with low spatial coherence, or through virtually structured detection (VSD)[3].

OCT may be combined with other detection modalities in order to overcome some of the inherent limitations. Basic contrast enhancement can be provided through the use of polarization sensitive OCT or Doppler OCT. More advanced processes may use magnetomotive nano-particles in a modulated magnetic field for Magneto-Motive OCT[4]. Photo-acoustic microscopy (PAM) has similar penetration and resolution to OCT, but observes optical absorption rather than scattering. By using a transparent Fabry-Perot interferometer as a detector OCT can be implemented coaxially providing a complementary image. Doppler OCT can be implemented in several different ways – phase resolved Doppler (PR-DOCT), resonant Doppler flow imaging, joint spectral and time domain imaging, optical micro-angiography (OMAG) or single pass volumetric bidirectional blood flow imaging (SPFT).

Choice of light source is crucial to good OCT performance. Time domain OCT was dependent on the use of femto-second pulsed lasers. The introduction of SD-OCT and SS-OCT allowed the widespread use of super-luminescent diodes (SLD) sources with longer lifetimes and far lower cost. SLDs are readily available at wavelengths of 800nm with a bandwidth of 30nm, or at wavelengths of 1300nm providing axial resolutions down to 3µm. For ultra-high resolution systems the use of photonic crystal fibres in conjunction with sub-15fs Ti:sapphire lasers has enabled resolutions down to 0.9µm in air and 0,6µm in biological tissue. It remains to be seen whether recent developments in attosecond pulsed lasers[6] will enable resolution limits to be pushed even further.

The majority of applications of OCT are biomedical, especially ophthalmology, endoscopy and intravascular imaging. However, some industrial applications are emerging particularly for non-destructive testing and quality control, such as in the production of MEMS devices[5], or the non-destructive detection of sub-surface strain fields in injected moulded polymer parts[6].

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