Comparison between a Supercontinuum Source and a Titanium Sapphire laser in achieving ultra-high resolution Spectral Domain Optical Coherence Tomography (SD-OCT)

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ABSTRACT

Corneal B-scan images and signal-to-noise ratio measurements using ultra-high resolution Spectral Domain Optical Coherence Tomography (SD-OCT) are reported. A comparison of results is obtained using a Ti:Sa laser and a supercontinuum optical source, is performed. Beside some differences in the SNR, the images are strikingly similar.
Keywords: OCT, Tear film, Ultrahigh resolution, corneal imaging

1. INTRODUCTION

Optical Coherence Tomography (OCT) is a non-invasive high resolution imaging method. Over the last decade, the progress in light source technology has seen the emergence of ultra-broadband sources such as the Ti:Sa laser and the supercontinuum source (SC). The development of these types of sources allows enhancement of the axial resolution in OCT that enables new applications, such as visualization of small features in the anterior and posterior eye segment with micron resolution. This capability has been shown, for example, by *in vivo* imaging of the precorneal tear film in the human eye [1-6].

Nevertheless, these sources present some drawbacks compared to superluminescent diodes, which are mostly used. Currently, the cost for both light source technologies is relatively high, limiting their wide spread use in commercial OCT systems. On the other hand, SC sources present the ability to access to a large wavelength range from visible to IR. However, so far the SC sources have been considered too noisy to be used for *in vivo* imaging. In this paper, measurements with both Ti:Sa and SC laser are performed using the same experimental set-up in order to analyze their noise performance and to compare *in vitro* and *in vivo* OCT data. Images of the cornea of a healthy human volunteer are presented allowing the visualization of the precorneal tear film.

2. METHOD

The set-up consisted of a Michelson interferometer and a broadband spectrometer [7,8]. For the presented experiments, two sources, a Ti:Sa laser (Integral OCT, Femtolasers Produktions GmbH, Vienna, Austria) and a supercontinuum source (SuperK Extreme Low noise, 320 MHz, NKT Photonics, Birkerod, Denmark) were employed (Fig.1). The Ti:Sa laser emits at a central wavelength of 800 nm and covers a full width at half maximum (FWHM) spectral range of 175 nm. This gives a theoretical axial resolution of 1.7 µm in air and 1.2 µm in tissue. The output spectrum of the SC source covers a wavelength range from 600 to 2400 nm. The spectrum is spectrally filtered by a passive optical filter (SuperK Split from NKT Photonics, Birkerod, Denmark), which limits the spectrum to a FWHM bandwidth of 140 nm centered at 800 nm. This gives a theoretical axial resolution of 2 µm in air and ~1.5 µm in tissue.

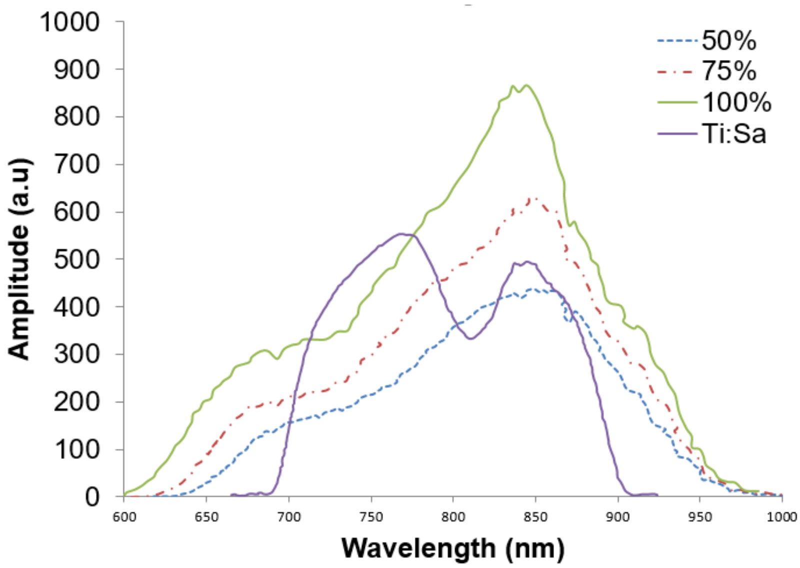

Fig.1. Spectrum at the output of the two sources: SC running at different output power (50%, 75% and 100%) and Ti:Sa laser.

First, noise performance of the SC has been conducted for different input power levels on a mirror serving as a reference sample. In a second measurement, the SNR value was assessed for signal returned from a sellotape sheet. The sample arm power was set by a neutral density filter implemented in the Michelson interferometer to a fixed incident power of 400 µW in both experiments. The SC source was operated at different power outputs of 50%, 75% and 100% of full power capacity, settings that determine the bandwidth and shape of the spectrum as shown in Fig. 1 and, thereby, influence imaging parameters. The SC generation is more efficient at higher power where a broader spectrum is obtained. The comparison of different configurations is performed by calculating the SNR. The Fourier transform of the interference pattern is taken after multiplication of the spectral signal by a Hanning function. The SNR is given by the formula:

$$\mathrm{SNR} = 20 \text{ x } \mathrm{Log}\left(\frac{\mathrm{Signal}}{\mathrm{RMS}}\right) \tag{1}$$

The signal considered in equation (1) is the amplitude value of the first peak in the A-scan. The RMS (root mean square) noise is defined by:

$$RMS = \frac{1}{N}\sum_{N} x_i^2 \tag{2}$$

where x_i is the noise amplitude at position i. It is estimated by taking the amplitude values in a part of the image where no sample is present – more exactly before the first sample surface. In order to calculate the sensitivity, a neutral density filter was placed in the sample arm to attenuate the signal arising from the back reflection of the tape front surface and had been considered as loss and added to the SNR value.

3. RESULTS

The first experiment was conducted using a mirror as sample. The power on the sample was 400 µW. In Fig.2, the sensitivity is represented as a function of the SuperK output power level (%). The noise is reduced as the power increases. This can be explained by the nature of the supercontinuum generation.

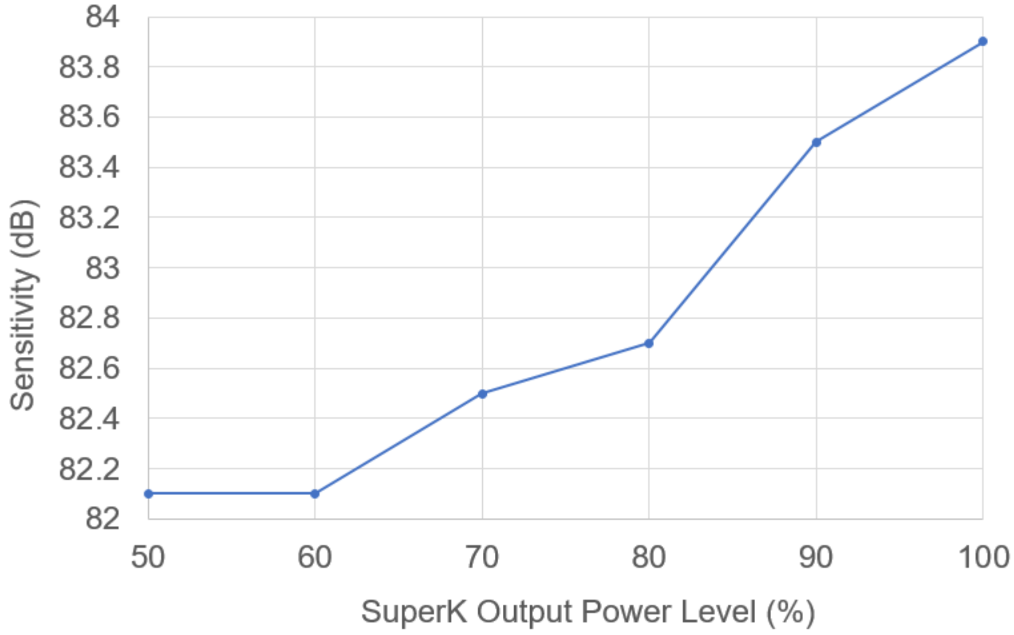

Fig.2 Sensitivity as a function of the percentage output from the SuperK. The power on the sample was 400μW.

A pulsed laser at 1064 nm is injected into a non-linear fibre. Due to interplay between dispersive effects and non-linear effects in the nonlinear fiber, such as modulation instability, self-phase modulation and soliton fission, the bandwidth of the peak is enlarged and a broadband spectrum of several hundreds of nanometres is observed at the output of the fibre. The larger the input power of the pulsed laser, the larger the non-linear effects and the broader the spectrum. On the other hand, the intensity noise is most prominent at the edges of the SC spectrum. Increasing the width of the spectrum by increasing the pump power leads to a reduction of the noise at a fixed wavelength (Fig.3) [9]. The relative intensity noise (RIN) of the SuperK has been measured using a spectrometer with 0.15 nm resolution and an integration time of 13 μs. The RIN is calculated as the standard deviation divided by the average value for each pixel.

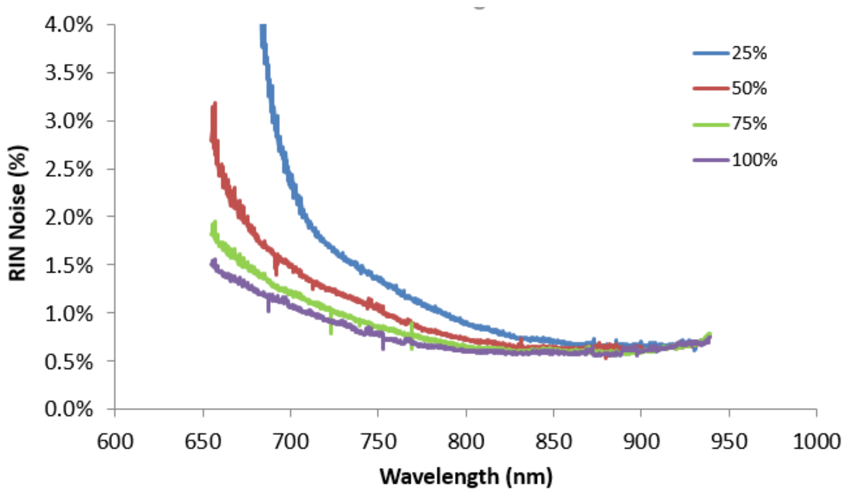

Fig.3. Relative Intensity Noise (RIN) versus wavelength for different output power levels of the SuperK.

The data on SNR performance are shown in Table 1. For the SC source, the higher the pump power, the larger the bandwidth and therefore the lower is the noise, as shown earlier. At this level, the SNR is 1.8 dB lower than that calculated from the OCT data yielded from measurements with the Ti:Sa laser.

Table 1. Calculations of the RMS noise and SNR for both sources

Source	Signal ($x10^5$)	RMS	SNR (dB)
SuperK at 50%	1.07	44.19	67.68
SuperK at 75%	1.35	47.20	69.14
SuperK at 100%	1.95	46.55	72.44
Ti:Sapphire laser	2.47	46.97	74.43

Despite the difference in SNR calculated from the OCT data of the measurements with the different sources, the sellotape images shown in Fig.4 reveal similar image features and the difference in image quality is barely noticeable.

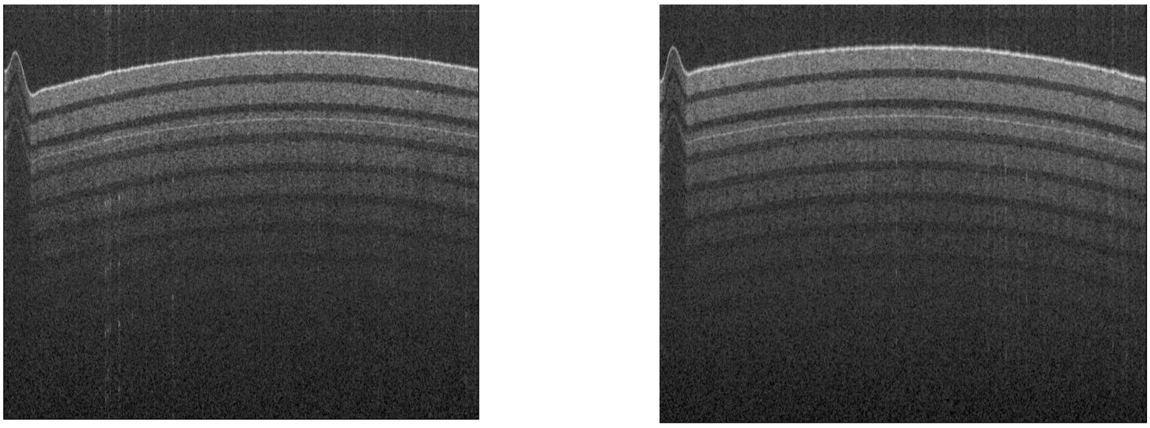

Fig.4. Performance comparison of the supercontinuum source from NKT Photonics running at 100% (left image) and Ti:Sapphire (right image) showing a B-scan with 512 A-scans on a sellotape sample after dispersion compensation at the post-processing stage. The power on the sample was 400 µW.

Finally, images of the cornea from a healthy human volunteer have been acquired. The SC source was operated at 100% power level and the power on the sample was set to 2 mW, which is below the maximum permissible exposure (MPE) given by the IEC 60825-1. The data acquisition is done by a Labview programs. After post processing steps, using matlab for the dispersation compensation and ImageJ, images in Fig.5 (a) and (b) are obtained. Even though, the sensitivity of the SC is worse, the precorneal tear film could be visualized using both the SC and the Ti:Sa laser. The reflection of the first layer from the SuperK appears brighter because the image was acquired closer from the central part of the cornea (where the reflexion is higher) compared to the one taken with the Ti:Sa which is more at the cornea periphery. By drawing an A-scan, the tear film can be identified and variation between both measurements can be seen in Figure 5 (c) and (d). Indeed, the distance between the first two peaks is the thickness of the tear film. In both cases, the tear film can be resolved and measured.

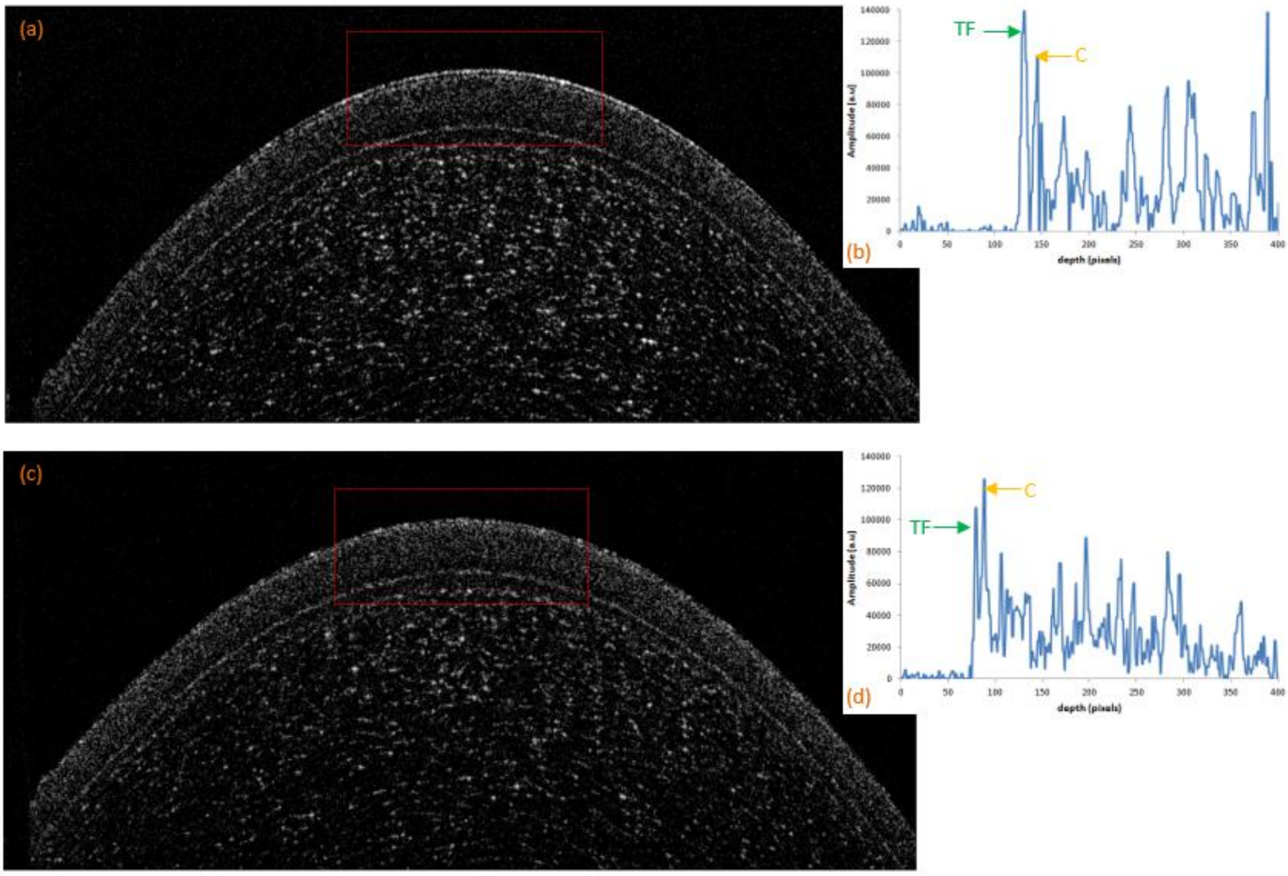

Fig.5. B-scans of human precorneal tear film using a supercontinuum source from NKT Photonics ((a), (b)) and the Ti:Sa laser ((c),(d)) acquired at different positions of the cornea. The power on the sample was 2 mW. (a) and (c) are the B-scans. Graphs (b) and (d) representative A-scan of the region indicated by the red rectangle shown in (a) and (c). TF, tear film front and C, cornea front surface.

CONCLUSION

High resolution OCT images of sellotape phantoms and *in-vivo* human cornea have been obtained using a supercontinuum source and a Ti:Sapphire laser. For the phantom, the signal to noise ratio performance was approximately 2 dB better for the Ti:Sapphire laser than for the SuperK. The optimal performance of the SC was obtained when operating at the maximum power level, yielding an improvement in SNR of 4.8 dB when operated at 100% power compared to when operated at 50% power. However, despite the difference in SNR, the images from the sellotape as well as *in vivo* images of the precorneal tear film appear to be similar. All corneal layers, as well as the tear film can be resolved via both the Ti:Sapphire and the supercontinuum source. Both sources are suitable for ultrahigh resolution corneal OCT imaging, visualization of the precorneal tear film and evaluation of the tear film thickness and show potential for the diagnosis and treatment monitoring of various corneal pathologies [10,11].

ACKNOWLEDGMENT

S.Caujolle, A.Podoleanu and T. Feuchter are supported by the European Commission under the European Industrial Doctorate “ultrawide bandwidth photonics devices, sources and applications”, UBAPHODESA 607624, Marie Curie FD7-People-2013-ITN. S.Caujolle and A.Unterhuber acknowledge the European Commission under the FAMOS project FD7-ICT-317744. R. Werkmeister acknowledges Austria Federal Ministry of Economy, Family and Youth, National Foundation of Research, technology and Development for their help and support. A. Podoleanu is also supported by the NIHR Biomedical Research Centre at Moorfields Eye Hospital NHS Foundation Trust and the UCL Institute of

Ophthalmology, the Engineering and Physical Sciences Research Council (EPSRC) (‘REBOT’ EP/ N019229/1), European Research Council (‘AMEFOCT’ 680879) and Royal Society Wolfson Research Merit Award.

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