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Speckle Size in Optical Fourier Domain Imaging

G. Lamouche^a, S. Vergnole^a, C.-E. Bisailon^{a,b}, M. Dufour^a, R. Maciejko^b, and J.-P. Monchalain^a

^aIndustrial Materials Institute, National Research Council, Boucherville, Québec, Canada

^bEcole Polytechnique de Montréal, Québec, Canada

ABSTRACT

As in conventional time-domain optical coherence tomography (OCT), speckle is inherent to any Optical Fourier Domain Imaging (OFDI) of biological tissue. OFDI is also known as swept-source OCT (SS-OCT). The axial speckle size is mainly determined by the OCT resolution length and the transverse speckle size by the focusing optics illuminating the sample. There is also a contribution from the sample related to the number of scatterers contained within the probed volume. In the OFDI data processing, there is some liberty in selecting the range of wavelengths used and this allows variation in the OCT resolution length. Consequently the probed volume can be varied. By performing measurements on an optical phantom with a controlled density of discrete scatterers and by changing the probed volume with different range of wavelengths in the OFDI data processing, there is an obvious change in the axial speckle size, but we show that there is also a less obvious variation in the transverse speckle size. This work contributes to a better understanding of speckle in OCT.

Keywords: Optical coherence tomography, speckle, biomedical imaging

1. INTRODUCTION

The interfering contributions of the multiple scatterers contained in a biological tissue always lead to speckle in optical coherence tomography (OCT) imaging. Speckle is often seen as degrading the signal and many approaches were devised to reduce its deleterious effect.¹ But speckle also contains information about the underlying structures and some recent papers were targeting at extracting this information in order to differentiate various tissues. The contrast of the speckle pattern was shown to vary with the density of scatterers as demonstrated by measurements performed on liquid phantoms.² Texture parameters were evaluated on renormalized OCT images and artificial intelligence was used for phantom and tissue differentiation.³

In the current paper, we look at the speckle size, a parameter that could also be used for tissue differentiation. Work on speckle size also contributes to a better understanding of speckle formation in OCT. To a first approximation, the axial speckle size is determined by the OCT resolution length and the transverse speckle size by the focusing optics illuminating the sample. This is illustrated in Fig. 1 where a coronary artery of a rabbit is imaged with the same OCT source but different spot sizes. The axial speckle size (vertical on the image) is about the same in both images, but the transverse speckle size (horizontal on the images) is much smaller with the smaller spot size. The speckle size is also affected by the microstructure. This has been demonstrated in our laboratory by performing measurements on optical phantoms with different densities of scatterers using time-domain optical coherence tomography (TD-OCT).⁴ In the low density of scatterers regime, the axial speckle size is the OCT resolution length and the transverse speckle size is the width of the point-spread function. As the density of scatterers increases, both speckle sizes decrease. The sensitivity of the variation in speckle size is similar to what was obtained with the contrast of the speckle field.² The important parameter is the average number of scatterers contributing to the measurement, i.e., the scatterers contained within the probed volume defined by the coherence length of the source and the illuminating spot size.

In this paper, we again investigate the variation in speckle size with the number of scatterers contained within the probed volume. Instead of varying the scatterer density, we modify the probed volume. This can easily be done with an Optical Fourier Domain Imaging system, also called Swept-Source (SS-OCT) system. In an OFDI system, there is no varying delay line as in TD-OCT. The wavelength of a coherent source is scanned and

Further author information: (Send correspondence to G.L.)

G.L.: E-mail: guy.lamouche@cnrc-nrc.gc.ca, Telephone: 1 450 641 5198

spatial information is recovered by Fourier transform.⁹ The probed volume can easily be modified by selecting the wavelength range used in the data processing and thus modifying the OCT resolution length. A single measurement can thus be used to obtain different speckle fields. The spectral range used in the analysis will obviously affect the axial speckle size, but our interest lies in the less obvious variation in transverse speckle size.

Figure 1. Cross-section images of the coronary artery of a rabbit. Images are 0.2 mm wide in the axial direction (vertical) and 0.3 mm wide in the transverse direction (horizontal). The same TD-OCT system was used for both images. The left image was obtained with an illuminating optics characterized by a spot size of 21 microns while the right image was obtained with a spot size of 5 microns.

We first provide information about the optical phantoms that are used. We then briefly review our work done using TD-OCT showing that the speckle size varies with the density of scatterers in optical phantoms. We follow with a description of our OFDI system. We finally present measurements showing that the transverse speckle size indeed varies when the spectral range used in the OFDI analysis is modified.

2. OPTICAL PHANTOMS

It is quite a challenge to fabricate a solid and deformable optical phantom with a controlled density of scatterers that are homogeneously distributed. Our elected solution is the use of silica microspheres in a silicon matrix. Silica microspheres are often sold in aqueous solution which raises the problem of the evaporation of water. We work with dry silica microspheres that are introduced directly in a mixture of silicon and solvent, mixed in an ultrasonic bath to break microsphere aggregates, the procedure being followed by the evaporation of the solvent. The sample is then left alone for the polymerization of the silicon to occur. Figure 2 presents an electron micrograph of silica microspheres along with the picture of a phantom.

Figure 2. Electron micrograph (left) of the silica microspheres that are introduced in a silicon matrix to fabricate a solid and deformable optical phantom with a controlled density of scatterers (right).

3. VARIATION OF SPECKLE SIZE WITH TD-OCT

We performed measurements using TD-OCT on phantoms with different density of scatterers.⁴ The details of this work will be published elsewhere. In Fig. 3 we present an excerpt of the results. It shows the transverse speckle size measured by transverse Fourier transform of the speckle fields for phantoms with different density of scatterers. The horizontal axis is the effective density of scatterers (ENS) that corresponds to the scatterers contained within the probed volume, the latter being defined similarly to Ref. 2 based on the coherence length of the source and the illuminating spot size. Two series of phantoms with microspheres of diameter $1.86 \mu\text{m}$ and one with microspheres of diameter $2.34 \mu\text{m}$ were fabricated. Simulation results were also obtained by modeling the phantom as an ensemble of discrete scatterers. The source of the TD-OCT system was a Covega superluminescent diode providing an OCT resolution of $14.4 \mu\text{m}$. The focusing optics in the sample arm provided a spot size of $7.4 \mu\text{m}$ (measured at $1/e^2$ for the intensity). The speckle size values in Fig. 3 are full-width-at-half-maximum values measured in the focal region. The transverse speckle size decreases as the effective number of scatterers increases as shown by both the simulations and experimental results. The values evolve between an upper limit given by the point-spread function of the focusing optics and a value that can be evaluated from a statistical analysis in the case of a dense collection of scatterers.

Figure 3. Variation of the transverse speckle size as a function of the Effective Number of Scatterers (ENS) measured on various phantoms along with simulation results.

4. OPTICAL FOURIER DOMAIN IMAGING

It is recognized that Fourier Domain OCT presents some advantages over TD-OCT: there is no moving parts and it is more sensitive.⁶ The signal is collected as a function of the wavelength in FD-OCT and the spatial information is recovered by Fourier transform. Two kinds of setups can be used. The first one is called Spectral Domain OCT (SD-OCT) and uses a broadband source and relies on the detection with a spectrometer to separate the spectral components.^{7,8} The second one is Optical Fourier Domain Imaging (OFDI)⁹ also known as Swept Source OCT (SS-OCT). In this case, the spectral components are separated at launch with a wavelength-swept source. We opted for the second design and Fig. 4 illustrates our setup. It is a Mach-Zehnder fiber-based interferometer. It uses a Thorlabs swept-source (SL1325-P16) with a 1325 nm center wavelength and a 85 nm FWHM. The wavelength sweep repetition rate is 16 kHz. Using the full spectrum available in the OFDI data processing, the theoretical axial resolution is $9.1 \mu\text{m}$. It must be noted that the setup is fitted with acousto-optic

modulators to remove the mirror image and autocorrelation noise generated in the computation of the Fourier Transform.^{10,11}

Figure 4. Optical Fourier Domain Imaging setup.

5. SPECKLE SIZE

Measurements with our OFDI system are performed on a phantom with a density of 9.3×10^8 microspheres per milliliter. The diameter of the silica microspheres is $1.86 \mu\text{m}$. The focusing optics provides a spot size of $7.4 \mu\text{m}$. When the full spectrum of the OFDI system is used, the measured axial OCT resolution is about 11 microns. At the focal point, the probed volume and the scatterer density provides a effective number of scatterers of about 0.65. Figure 5 shows the speckle fields obtained from the phantom but with different spectral ranges, as modified during the OFDI data processing. A-scans were recorded with a transverse step size of $0.25 \mu\text{m}$. Note that all the images are obtained from the same measurement, only the post-processing varies from one case to the other. Cases are full spectrum (d1), half of the spectrum (d2), a third of the spectrum (d3), and a fifth of the spectrum (d5). Every spectral reshaping provides a gaussian spectral shape but with a reduced spectral width. The same notation will be used in the following figures. The resulting OCT axial resolution measured from the reflection from the front facet of the phantom (not shown in the graphs) is provided above each cross-section in Fig. 5. One clearly sees that the axial speckle size increases as the spectral width is reduced. The probed volume varies with the OCT resolution length, and the effective number of scatterers values are estimated to 0.65 (d1), 1.4 (d2), 2 (d3), and 3 (d5), as evaluated with the same definition as in Ref. 2. As a result, the transverse speckle size is also affected, as is shown below.

Figure 6 shows the intensity profiles as a function of depth, it corresponds to the average of the all A-scans recorded over a width of 1 mm. The top of the phantom is not shown, but is on the right of the graph. From Fig. 6, one can measure the depth of field in the sample. We obtain a value of $185 \mu\text{m}$ that is in good agreement with a spot size of $7.4 \mu\text{m}$ taking into account that the refractive index of the phantom is about 1.4. Structures are apparent in the d1 curve, a result of the discrete nature of the scatterers. These structures are less apparent for the other cases, a consequence of the averaging over a larger probed volume.

Figure 7 presents the contrast measured as a function of depth. Away from the focal point, we obtain a value close to 0.52, the limiting value of a high effective number of scatterers.⁵ It is a consequence of the increase of the size of the probed volume as the spot size increases away from the focal point. Near the focal region, the higher values indicate that there is a net decrease in the effective number of scatterers due to the smaller probed volume.^{2,4} The effective number of scatterers increases as the spectral range in the OFDI data processing is decreased, leading to a reduction in contrast from case d1 to case d5.

Figure 8 presents the transverse speckle sizes (full width at $1/e$) evaluated from the Fourier transform over a width of 1 mm (transverse) and averaged over a depth of about $50 \mu\text{m}$. For the d1 case, there is a decrease in

Figure 5. Speckle fields evaluated from an OFDI measurement performed on a phantom but with different spectral ranges used in the OFDI data processing: full spectral width (d1), half of the spectral width (d2), a third of the spectral width (d3), and a fifth of the spectral width (d5).

speckle size as we go from the top of the sample (from the right of Fig. 8) towards the focal point. This is mainly a consequence of the decrease in illuminating spot size as we get closer to the focal point. For the other cases, near the focal point, the speckle size is smaller although the spot size is expected to have a similar value. This is the effect sought, it is due to the larger probed volume, a consequence of the larger OCT coherence length, and thus to the interference between an increased number of effective scatterers. Note that the focal point does not appear to be located at exactly the same depth for all cases. This is attributed to dispersion since we have verified that for a given fraction of the spectrum, the apparent location of the focal point varies with the central wavelength.

Away from the focal point, there are two counteracting effects. The speckle size is expected to increase with the spot size, but to decrease since the effective number of scatterers increases as the probed volume increases. This is clearly demonstrated by cases d2, d3, and d4; as we move away from the focal point (towards the right in Fig. 8), the speckle size first increases due to the increase in spot size, but then decrease due to the increase in number of effective scatterers. Figure 8 also shows that there is some asymmetry around the focal point in the speckle size values. This is yet to be explained.

Figure 6. Intensity profiles as a function of depth for the speckle fields illustrated in Fig. 5.

Figure 7. Contrast as a function of depth for a speckle fields illustrated in Fig. 5.

6. CONCLUSION

We have shown that tailoring the OCT resolution in Fourier-Domain OCT affects not only the axial speckle size, but also the transverse speckle size since the probed volume and effective number of scatterers are affected. This work on speckle size contributes to a better understanding of speckle phenomena in OCT. Like the contrast measurements reported in Ref. 2, the speckle size measurement is sensitive to the low densities of scatterers and could be used for tissue differentiation in specific cases. A better control of the speckle size is also of use when planning elastography measurements relying on speckle tracking.

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Figure 8. Transverse speckle sizes as a function of depth evaluated for the speckle fields illustrated in Fig. 5.

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