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The Influence of Increased Intraocular Light Scatter on the Contrast in a Confocal Scanning Laser Ophthalmoscope Image

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Introduction

In 1987 Webb and co-workers introduced the Confocal Scanning Laser Ophthalmoscope (CSLO) [1]. This system is similar to the conventional SLO [2] except that a small aperture is positioned in front of the detector, conjugate to the focus of the illumination spot on the retina (confocal). Analogously to the SLO, the influence of scattered light from points other than the point of illumination is strongly reduced. Additionally an ideal confocal scanning laser microscope has lateral resolution 1.4 times better than a conventional microscope [3]. As the aperture blocks any light scattered from layers or points other than the point of illumination, the depth of focus is drastically decreased, permitting optical tomography.

Webb and Hughes published a simple model quantifying the signal-to-noise ratio when imaging through cataractous eyes with a non-confocal SLO [2]. In the CSLO, the confocal aperture rejects scattered light and the image quality is further improved in cases when the optical media of the investigated eye is turbid. This result is a significant clinical improvement when imaging through cataracts without dilation of the pupil[4].

The role of the pinhole in confocal imaging systems has been thoroughly investigated by Wilson [3]. However, his quantitative analysis does not include imaging through strongly light scattering media. It is the intention of the present study to assess CSLO imaging through diffuse scattering media as a model for cataract.

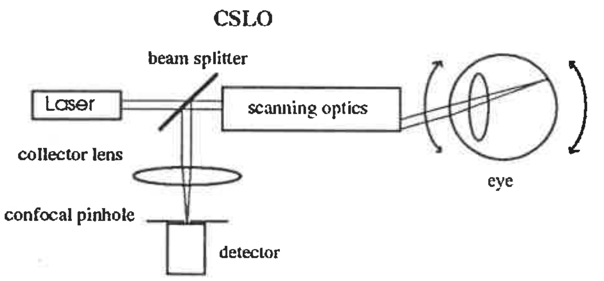

Figure 1. Schematic of the optical arrangements.

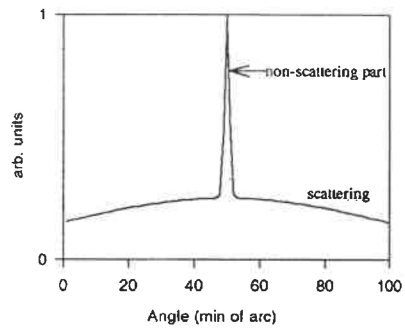

Figure 2. Schematic of the PSF used in the calculations

Methods

The CSLO used in this study is infinity-corrected to minimize scan-induced aberrations in the image. The diameter of the beam entering the eye was 8 mm. The field of view was 5°. With an image matrix of 512x512 pixels, each pixel is 0.6 min of arc wide. A collector lens (see Figure 1) with a focal length of 5 cm focused the light reflected from the retina through the pinhole onto the detector. Five different pinhole sizes were tested (50, 100, 200, 400, and 600µm). A HeNe laser (wavelength: 633nm) was used as the light source and a photo-multiplier tube (PMT) as the detector. Within the range used in the experiments, the PMT detector response was found to be linear with incident light intensity. To simulate an eye, we used a CCD-camera lens (f = 1.6cm, Ø=11.5mm) focused onto an integrated circuit (used to simulate the fine details in a retina). This lens has quite severe spherical aberrations and, for an 8mm pupil its cut-off frequency was measured to be about 40cpd. In order to simulate cataracts we used sand-blasted glass plates, inserted in front of the lens. The set-up simulates cataractous eyes with about 85%, and 95% scattering. For comparison a clear glass plate with little or no scattering (<10%) was used.

The scattering properties of the filters were measured using a 1 mW HeNe-laser (633nm) and a Photodyne detector. First the light transmitted through the filter was measured. Then the fraction of light in the central beam was measured at a distance of 3m, the detector subtending a half angle of 1.7 mrad.

For the cases of no scattering, a clear glass plate, and 85% and 95% scattering glass plates, images of the artificial retina were recorded for each pinhole size. The laser intensity was varied in order to maintain the same image feature brightness throughout the experiment

Theory

An illumination spot is formed on the retina the size of which, ideally, is determined by the point-spread function of the optics of the eye (PSF_{eye}), the PSF of the transfer optics (PSF_{ins}) and the finite size of the laser source (δ_{laser}). The spot is scanned over the retina, and imaged through the confocal pinhole onto the detector. The resulting image intensity, $I(x,y)_{image}$, is then determined by a convolution between the object reflectance, $R(x',y')_{object}$, and the resulting imaging function for the complete system (T_{tot}):

$$I(x,y)_{image} = T_{tot} \otimes R(x',y')_{object} \quad (1).$$

For simplicity we assume the retina to be a perfect diffuser and the PSF_{eye} to be the same both for light entering, as well as, exiting the eye. Furthermore, the transfer optics in the instrument is superior to that of the eye. The T_{tot} may then be estimated by:

$$T_{tot} = (PSF_{eye} \otimes \delta_{laser}) \cdot (PSF_{eye} \otimes D_{pinhole}) \quad (2),$$

where $D_{pinhole}$ denotes the finite size of the confocal pinhole.

In order to calculate a CSLO image of the model retina, a realistic continuos PSF for our artificial cataractous eye is needed. The PSF_{eye} used in these calculations is the sum of two contributions. One part specifying resolution (i.e. including diffraction effects and aberrations) and one part specifying wide-angle scattered light. Both parts are assumed to have Gaussian angular distributions (Figure 2). In order to simulate the resolution of the lens used in the experiment (see above) the angular width of the non-scattering contribution is chosen to give a cut off frequency of 40 cpd (at 1% modulation). The wide-angle scattered light is chosen to have a half width at 1/e height (σ) of 2°. Using equation 2 we calculated the Modulation Transfer Functions (MTF) for different pinhole sizes (50µm, 100µm, 200µm, 400µm, and 600µm) and different fractions of scattered light (0%, 85% and 95%). The calculations were all performed using MathCad™ (Mathsoft).

Results

Figures 3 and 4 present images taken with the CSLO through our artificial eye. In Figure 3 images taken with a) a 600µm and b) a 50µm pinhole are presented. As can be seen, the image quality is improved by the smaller confocal aperture as expected. Figure 4 shows the increase in image quality as the confocal pinhole is decreased (from 600µm to 50µm). In this case the 85% scattering glass-plate was used. As can be seen the added stray-light hardly affects the image when using the 50µm pinhole (compare Figures 4e and 4f).

Table 1

Pinhole	0% scattering		85% scattering		95% scattering	
(µm)	theory	measurements	theory	measurements	theory	measurements
50	0.97	0.84 (0.6-1.0)	0.85	0.87 (0.6-1.0)	0.38	-
100	0.97	0.88 (0.4-1.0)	0.82	0.79 (0.5-1.0)	0.34	0.43 (0.1-0.7)
200	0.96	0.82 (0.5-1.0)	0.71	0.63 (0.4-0.7)	0.24	0.24 (0.0-0.5)
400	0.96	0.71 (0.4-1.0)	0.55	0.60 (0.4-0.8)	0.17	0.24 (0.0-0.5)
600	0.95	0.72 (0.4-0.9)	0.42	0.57 (0.4-0.8)	0.16	0.23 (0.0-0.5)

Table 1. Summary of results from measurements of contrast in CSLO images using 85% and 95% scattering plates and 5 different pinhole sizes. Absolute range of measurements indicated within parenthesis.

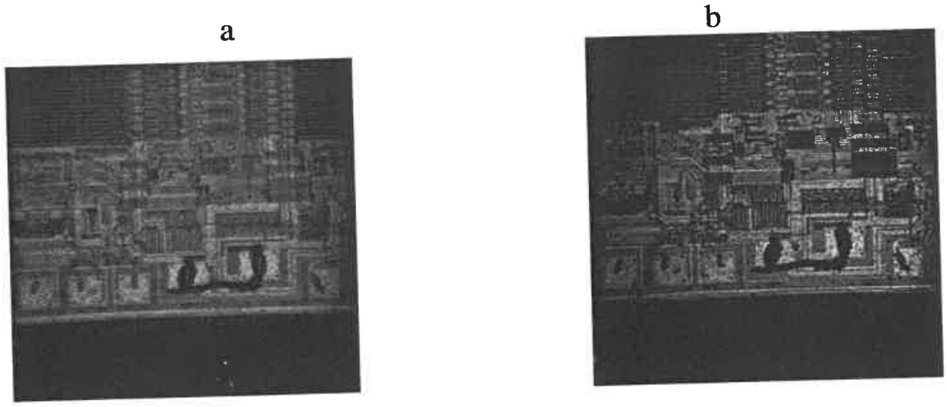

Figure 3. CSLO images of the "model retina" (the IC) in the artificial eye using a) a 600μm and b) a 50μm pinhole. No scattering added. Field of view is 1250x1250 μm.

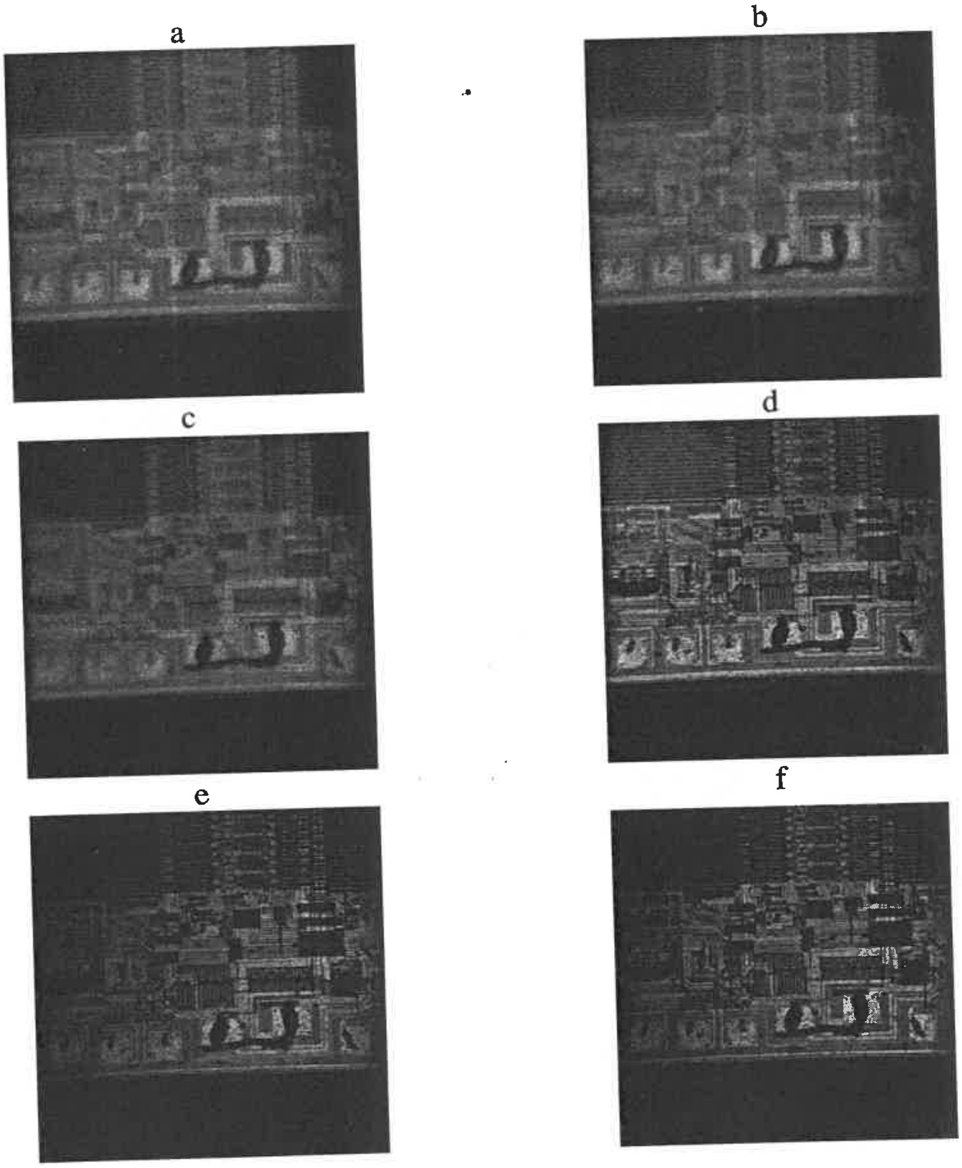

Figure 4.. Images a) to e) are all taken through a glass-plate, scattering about 85% of the transmitted light, using different pinhole sizes: a) 600μm b) 400μm c) 200μm d) 100μm and e) 50μm. For comparison image f) is taken through a glass-plate with no scattering (<10%) using a 50μm pinhole.

The results of the calculations together with the measured CCD-lens data are presented in Figure 5. As can be seen the MTFs both with and without intraocular light scattering are indeed improved with reduced confocal aperture size, the latter result confirming the findings in Figure 4. For a 50µm pinhole (Figure 5e) the resolution is about 55cpd (cycles per degree) approaching the confocal limit of 1.4 times the resolution of conventional imaging (Figure 5f).

Finally, we measured the image contrast (modulation) of a black contact in the foreground of the IC. This feature has a fundamental angular frequency of about 2 cpd. For comparison, the theoretical contrast at 2 cpd was calculated from our model (Table 1). As can be seen in figure 5f, at that spatial frequency our model overestimates the contrast in images with no scattering. For 85% and 95% scattering the theory agrees well with the results from measurements.

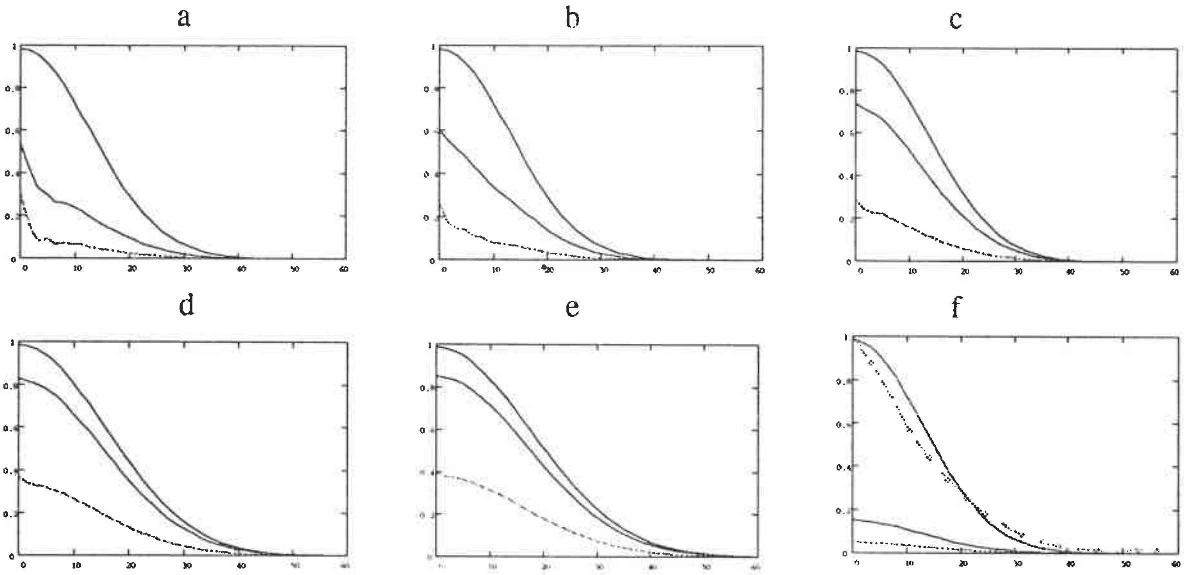

Figure 5. Calculated CSLO MTFs for a) 600µm, b) 400µm, c) 200µm, d) 100µm and e) 50µm pinholes. Each diagram presents functions for 0%, 85%, and 95% intraocular light scattering. In f) the measured MTF of the CCD-lens is plotted (diamonds) together with the MTFs used for our model eye in the calculations.

Discussion

In spite of the simplifying approximation of the form of the PSF of our model eye, our theoretical predictions of CSLO performance when imaging though a diffuse-scatterer, agree well with our measurements. Both theory and experiment confirm quantitatively that SLO and CSLO imaging are relatively insensitive to large amounts of light scatter even in the presence of aberrations. The advantages of the CSLO over the SLO increase with decreasing confocal pinhole size. However, in ophthalmoscopy the improvement given by using the smallest possible confocal pinhole, will be limited by the low intensity of the retinal reflection through cataracts.

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