Evaluating the lateral resolution of the adaptive optics scanning laser ophthalmoscope

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Abstract. We present a statistical assessment of the lateral resolution of the adaptive optics scanning laser ophthalmoscope (AOSLO). We adopt a 2-D Gaussian function to approximate the AOSLO point spread function (PSF), which is dominated by the residual wavefront aberration and characterized by the Strehl ratio. Thus, we derive the lateral resolution in the presence of residual wave aberrations, which is inversely proportional to square root of the Strehl ratio. The modeling, while not sufficient in describing the fine structure of the real PSF, demonstrates good conformance to the lateral cross section of the real PSF. With this model, the lateral resolution of our current AOSLO was computed to be 1.65 to 2.33 \( \mu m \), which agreed well with the actual result. We also reveal the relationships among the lateral resolution and other three measures of the AOSLO imaging property including the Strehl ratio, the PSF, and the root mean square (rms) of wavefront aberration. © 2006 Society of Photo-Optical Instrumentation Engineers.

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1 Introduction

The adaptive optics scanning laser ophthalmoscope (AOSLO) was demonstrated to produce in vivo microscopic views of the living human retina with unprecedented resolution\(^1\) and has emerged as an attractive microscopic imaging modality with promise to improve diagnosis, understanding, and even treatment of blinding retinal diseases. Appropriately assessing the lateral optical resolution of the AOSLO is significant in system performance evaluation and system design as well as optimization.\(^2\) For instance, it can help us to specify a tolerable degradation factor of the system performance so that we can subsequently define a reasonable error budget. It can also help us to reasonably characterize an optimal system bandwidth for AOSLO imaging signal conditioning and processing.

Fundamentally, a scanning laser ophthalmoscope (SLO) is a confocal scanning laser microscope. If it had an ideal objective lens, it should have a better lateral resolution by 27\% than a conventional microscopic imaging system with equal objective-lens pupils, a fact that was very well treated by Wilson and Sheppard,\(^3\) Sheppard and Shotton,\(^4\) Webb et al., and Webb.\(^5,6\) But the fact is that the SLO must employ the optimization.\(^2\) For instance, it can help us to specify a tolerable degradation factor of the system performance so that we can subsequently define a reasonable error budget. It can also help us to reasonably characterize an optimal system bandwidth for AOSLO imaging signal conditioning and processing.

With adaptive optics (AO) correction, the PSF, which is originally dispersed randomly and severely, is forced to concentrate to an approximately Gaussian image point. Although AO correction varies between individual eyes, the root mean square (rms) of the aberration can be statistically compensated to quite a low level. It becomes feasible to evaluate the lateral resolution via mathematical modeling of the PSF, and this is the goal of this paper.

Our paper starts with an analysis of the PSF formation of the AOSLO, which depends on the fact that the static AOSLO images are typically generated from multiple-frame image registration and averaging. Given that a summed frame is a combination of the same image blurred by many instances of a variable PSF, we assume a 2-D Gaussian function to describe the light intensity distribution of the AOSLO real PSF. Thus, we build a statistical PSF model that depends on the presence of residual wavefront aberration, from which we derive the real resolution of the AOSLO. Finally, we assess the PSF models and the lateral resolution with actual AOSLO imaging. The paper will also reveal relationships among four measures describing the AOSLO imaging performance,
namely, the rms of wavefront aberration, the Strehl ratio, the PSF, and the lateral resolution.

2 Method

2.1 Ideal Lateral Resolution of the AOSLO

The PSF of the AOSLO is formed by a double-pass reflection in the human eye. Ideally, if (1) the SLO intermediate optical system was very well constructed, (2) the human eye was a perfect diffraction-limited optical system, and (3) we used a pinhole of infinite small size (a point pinhole), the AOSLO PSF would be

\[ I(v) = I_0 \left[ 2J_1(v)/v \right]^2, \quad (1) \]

where \( I_0 \) is the peak intensity of the image of a point object; \( J_1(v) \) is the first-order Bessel function; and \( v \) is the optical coordinate and is related to the real-space polar coordinate \( r \) on the retina plane, via

\[ v = 2\pi r/\lambda f, \quad (2) \]

where \( a \) is the radius of the eye’s pupil, \( f \) is the focal length of the eye, and \( \lambda \) is the laser wavelength in the eye, which is a quotient of the laser wavelength in air over the eye’s index of refraction.

The ideal lateral resolution can be measured by the full width at half maximum intensity (FWHM) of the PSF. Calculating the value of \( v_0 \), at which the intensity falls to one half of its value at \( v = 0 \), we obtain the ideal lateral resolution \( 2v_0 \) at the retina.

\[ 2v_0 = 2.32. \quad (3) \]

However, Sheppard and Shotton\(^7\) and Wilson\(^8\) pointed out that this resolution would quickly deteriorate to that of conventional microscopes with enlarging pinhole size. To take advantage of the superior lateral resolution from the confocal configuration, we should have a pinhole size with dimension \( v \approx 0.5 \), which leads to the optimal pinhole diameter that is much smaller than the Airy disk that is formed by the collection lens. This is hard to adopt in the AOSLO because the human retina only reflects, on average, about 1 of 10,000 incident photons.\(^9\) Furthermore, given that our incident exposures are limited by laser safety thresholds for the human eye, the signal photons are too sparse and too precious to lose. We must compromise to a relatively large pinhole size to collect enough photons for imaging. If the pinhole size is sufficiently large, we may treat the AOSLO as a conventional microscope. Under this situation, the PSF will be

\[ I(v) = I_0 \left[ 2J_1(v)/v \right]^2, \quad (4) \]

which leads to an ideal resolvable distance at the retina

\[ 2v_0 = 3.24. \quad (5) \]

Thus, allowing for a practical size of the pinhole that is larger than the optimal one, the AOSLO lateral resolution will be most likely within the region that is defined by Eqs. (3) and (5).

Note that an AOSLO using a large pinhole may not be able to take advantage of enhanced lateral resolution via the confocal mechanism. But its depth discrimination ability is much more forgiving to the enlarged pinhole. Although a relatively large pinhole compared with that required for improving lateral resolution is adopted, a satisfactory axial sectioning performance is still attainable.\(^5\)\(^6\)\(^7\)\(^8\)

2.2 Approximation of the Real AOSLO PSF with the Gaussian Function

Distinctly, from Fig. 1 without AO correction, the PSF is highly scattered and it is difficult to assess the actual resolution. After wave aberration compensation, the PSF becomes well concentrated, making it feasible to define the resolution mathematically.

To generate a decent static AOSLO image, we first do multiple-frame image registration to correct the image translation that is caused by translational eye movements, and then we select and average many frames to eliminate the imaging noise. In the image, each pixel actually appears with its statistical expectation brightness. So, we assume a 2-D Gaussian function to approximate the light intensity distribution of the PSF. When the system is aberration-free, the PSF takes the form

\[ I(\rho, \sigma) = I_0 \exp \left( -\pi \rho^2 \right). \quad (6) \]

This Gaussian function centers at the origin point and has a variance \( \sigma \) that equals \( 1/(2\pi\sigma)^{1/2} \); \( \rho \) is a normalized polar coordinate, and \( I_0 \) represents the peak intensity of the diffraction-limited image spot. With aberration this is broadened to\(^17\)

\[ I(\rho, \sigma) = \frac{1}{2\pi \sigma^2} I_0 \exp \left( -\frac{\rho^2}{2\sigma^2} \right). \quad (7) \]

The \( 1/(2\pi\sigma^2) \) is required to conserve energy so that \( \int I(\rho, \sigma) \rho d\rho d\theta = I_0 \) and is equal to the Strehl ratio \( S_R \). Thus, we get an equation that links the PSF and the Strehl ratio:

\[ I(\rho, S_R) = S_R I_0 \exp \left( -\pi S_R \rho^2 \right). \quad (8) \]

The next step is to relate the normalized polar coordinate \( \rho \) to real space. Expanding the diffraction-limited PSF, i.e., Eqs. (1) and (4), as a power series in \( \rho \) and matching up \( \rho^2 \) with a Gaussian function,\(^18\)\(^19\) we obtain, for the ideal point pinhole case:

\[ I(\nu) = I_0 \exp \left( 0.5 \nu^2 \right). \quad (9) \]

And, for a large pinhole,

\[ I(\nu) \approx I_0 \exp \left( 0.25 \nu^2 \right). \quad (10) \]

Comparing with Eq. (6), we have, for a confocal point size pinhole,

\[ \pi \rho^2 = 0.5 \nu^2, \quad (11) \]

and for a large pinhole,
Putting $\pi \rho^2 = 0.25 \nu^2$.\r
\r
Putting $\pi \rho^2$ back to Eq. (8), we obtain the real PSF for ideal point pinhole case:

$$I(v, S_R) = S_R I_0 \exp(-0.5 S_R \nu^2), \quad (13)$$

and for the case of a large pinhole:

$$I(v, S_R) = S_R I_0 \exp(-0.25 S_R \nu^2). \quad (14)$$

When $S_R=1$, we calculate the PSF difference between Eq. (13) and Eq. (1), which results in a maximum relative error is as low as 2.4% of the peak intensity, as shown in Fig. 2(a). For the difference between Eq. (14) and Eq. (4), the maximum relative error is 5.5% of the peak intensity, as shown in Fig. 2(b). The models conform to the PSF shapes very well.

### 2.3 AOSLO Real Lateral Resolution

Calculating the PSF FWHMs from Eqs. (13) and (14), we acquire the AOSLO resolution $2\nu_{rd}$ when ocular aberrations are present. With an ideal point-sized pinhole,

$$2\nu_{rd} = 2.36/\sqrt{S_R}. \quad (15)$$

while for a large pinhole,

$$2\nu_{rd} = 3.34/\sqrt{S_R}. \quad (16)$$

Normalizing Eqs. (15) and (16) with their corresponding diffraction-limited resolution values, we obtain a general expression of the AOSLO real resolution:

$$r_a \approx 1/\sqrt{S_R}. \quad (17)$$

### 2.4 Assessing the AOSLO Resolution

The laser wavelength of the AOSLO (then at the University of Houston) was 0.660 μm. The eye was dilated and the pupil radius was 3 mm. The eye’s focal length and refractive index, taken from the Gullstrand-LeGrand model eye, are 22.27 mm and 1.337, respectively. Statistically, after the AO correction, the residual aberration was lower than 0.1 wave. For the example case demonstrated in Fig. 1, before AO correction, the Strehl ratio was measured to be about 0.015. When AO was turned on, the measured Strehl ratio increased to 0.70. From Eqs. (15) and (16), the lateral resolution of Fig. 1(b) is estimated to be between 1.65 and 2.33 μm. Figure 3(a) shows the real PSF, which is an average of a series of PSFs that were computed from continuous recordings of the wave aberrations that remained after best AO correction. Figure 3(b) shows the PSF cross sections, which are indicated in Fig. 3(a) along with
the PSF models of Eqs. (13) and (14). This demonstrates good
agreement between the estimation and measurement. It also
agrees well with the images in Fig. 1. Although absolute reso-
lution levels are difficult to assess with an image, the AO-
corrected image does show a well-resolved cone mosaic.

Figure 3 also serves as a further evaluation of the PSF
modeling accuracy. The models maintain good conformance
to the lateral cross section of the real PSF. The maximum
relative error for the large-pinhole model is 19.5% of the peak
intensity. For the point-pinhole model, this error is 18.4%.
Note that the real PSF is not symmetric, and that the model is
not sufficient in describing the sidelobes and the asymmetric
local structure of the PSF.

Fig. 2 PSF modeling errors.

3 Discussion
We derived relationships between the primary metrics that
define optical quality in the AOSLO imaging system. To ap-
ply the formulas, the Strehl ratio for Eqs. (15) and (16)
could be obtained from a real measurement, but that proves difficult
in the human eye. The PSF and resolution are also difficult to
assess from real data. In fact, the simplest metric to directly
measure during imaging is the wave aberration. After AO cor-
rection, the Strehl ratio is generally greater than 0.1, so we
may simply relate the Strehl ratio to the rms of the residual
wavefront aberration. Therefore, given the rms of the wave
aberration, we can calculate the Strehl ratio and lateral reso-
lution and approximate the PSF. Figure 4 plots these relation-
ships.

4 Conclusion
We derived an objective assessment of the real lateral resolu-
tion of the AOSLO imaging via a statistical Gaussian PSF
model. The resolution and PSF models supply a set of quan-
titative relationships for the design, optimization, and evalua-
tion of the AOSLO. But, based on the Gaussian approxima-
tion, the PSF model is unable to describe the fine structure of
the real PSF. So while the model may predict resolution, it is
not recommended for image postprocessing such as deconvolu-
tion in restoring image quality.

Fig. 3 AOSLO real PSF and modeling errors.

Fig. 4 Strehl ratio as a function of rms wave aberration (solid curve)
and the normalized lateral resolution varying with the rms wave ab-
erration (dashed curve).
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