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Through focus point spread function and modulus transfer function for multifocal lenses

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ABSTRACT

A system for measuring the through-focus point spread function (PSF) for intra-ocular lenses (IOLs) and converting to modulation transfer function (MTF) is developed. The system consists of a light source, eye model, IOL, magnifier, and CCD camera. By capturing the resulting image through a range of focus positions, the PSF is found and converted to MTF. The MTF displays differences in the depth of focus for monofocal, multifocal, and extended depth of focus (EDOF) IOLs. As multifocal and EDOF IOLs evolve, using the MTF to predict the image quality is vital to implanting the most appropriate lens in the patient's eyes.

Keywords: Intraocular lenses, modulation transfer function, multifocal lenses, image processing

1. INTRODUCTION

Cataract surgery is one of the most commonly performed surgeries and can help dramatically improve the quality of life for individuals. During the surgery, the natural lens in the eye which has become cloudy due to the hardening of protein is replaced by an intra-ocular lens (IOL). The original IOLs were known as monofocal IOLs and only focused at a single distance position. For clear sight closer to the eye, the individual would have to use reading spectacles since the implant cannot change power like the natural crystalline lens. In recent years, multifocal IOLs have become more commonplace. Multifocal lenses were initially refractive in nature, having different zones or regions of optical power. Most multifocals now, have shifted to diffractive lens, where two or more diffractive orders are used to create multiple foci. By utilizing diffractive profiles on the lens surface, light can be focused into multiple positions, which allows the individual to have a range of vision without the need for additional eyewear. It is imperative that optical tests be developed to determine the characteristics and performance of monofocal and multifocal lens designs. A system for measuring the through-focus PSF and consequently the through-focus MTF is described here. This system consists of a white light source and a model eye where an IOL can be inserted to be tested. The pupil used in the model eye of the system can easily be interchanged to determine how the lens will perform under different lighting conditions (such as daylight vision and night vision). Light from the source passing through the eye model forms an image. This image is then magnified and relayed to a 16-bit CMOS camera. The image from the camera, which is the PSF, is then run through an algorithm to determine the MTF. When the camera is moved along the optical axis through range of different positions, a series of images of the PSF is captured and run through the algorithm to determine the through-focus MTF. Ultimately, this process allows the performance of monofocal and multifocal IOLs to be measured and compared for object at different distances.

2. METHODS

The optical test bench is compliant with ANSI Z80.35-2018.[1] The experimental setup is shown below in Figure 1. The LED light source is a white light XLamp XP-L LED (Cree, Durham, NC), which emits a spectrum of wavelengths to produce the white light. The object that is imaged through the system is a $10\mu m$ diameter pinhole, in compliance with the ANSI standard. The IOL is submerged in saline in a polished quartz cuvette (Starna Cells, Atascadero, CA) wet cell. Apertures of differing sizes can be inserted into the cell along with the IOL to change the effective pupil size without compromising the IOL alignment. To ensure proper alignment of the aperture, the IOL holder is on a stage which allows for degrees of freedom rotationally, as well as along multiple axes. This allows for IOL performance measurements in the presence of tilt and decentration of the lens. A Mitutoyo 10X Plan Apochromatic Infinity Corrected Microscope Objective is used in combination with a 1X tube lens (both from Edmund Optics, Barrington, NJ) to magnify the image and relay it to a 2.1 MP 16-bit sCMOS camera (CS2100M-USB, Thorlabs, Newton, NJ).

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Other studies have been performed with model eyes having different values of spherical aberration. A study with a similar optical bench setup performed by Gatinel and Hubrechts used a model eye with no aberrations.[2] This is the classic eye model design used mainly when IOLs consisted of spherical surfaces and could only induce positive spherical aberration.[1] A more recent addition to the standard are eye models where the "cornea" is a doublet with clinical levels of spherical aberration.[1] These models were developed as aspheric IOL surfaces became prevalent to compensate for spherical aberration of the cornea. The latter models more accurately reflect the response of the human eye, since there are aberrations inherent in the cornea. In this experiment, for a pupil of 6mm, there will be $+0.215\ \mu m$ of Zernike spherical aberration, which compensate most of the spherical aberration for clinically.[3]

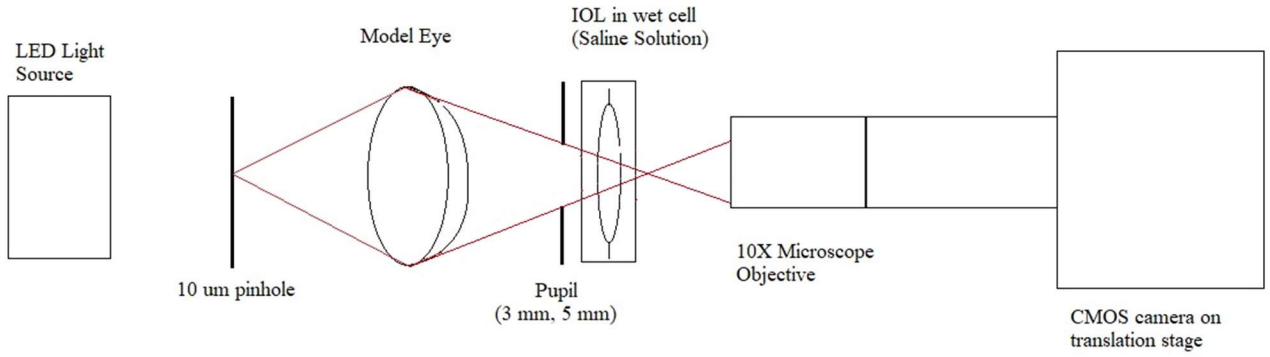

Figure 1. Optical bench setup for finding PSF and through focus MTF

To capture the through-focus MTF, the camera must be shifted along the optical axis to different positions of defocus, which can be measured in diopters (D), or inverse meters. The distance between the object, which is the pinhole, and the start of the model eye doublet must be measured to determine the corresponding vergence of the object using the vergence equation, which determines how the light ray is converging or diverging between in a certain space. This is given by the equation,

$$V = \frac{n}{d} \tag{1}$$

where V is the vergence, n is the refractive index of the medium, and d is the distance between the object and the lens. For this experiment, the distance was 40 mm and the space is air so the refractive index simply equals 1. This vergence, along with the power of the IOL under test, can be used to find the shift in the image plane based on the equation given by ANSI Z80.35-2018 [1],

$$dt = \frac{1315 * V}{(\Phi_{IOL} + 49.17)^2} \tag{2}$$

where dt is the shift in the image plane for the calculated vergence, V, and power of the IOL at that position, Φ. The distance to shift along the optical axis can be determined after finding the position of best focus

$$\Delta dt = dt - dt_{best\ focus} \tag{3}$$

Based on the location of the best focus position of the lens, and the calculated dt at best focus, $dt_{best\ focus}$, it can be determined how far to shift the image, Δdt, for specific dioptric powers. For this study, a range of -3D to 5D was tested in 0.25D increments to fully characterize the behavior of the lenses.

For each pupil size, a series of through-focus PSF images are captures, along with a "dark" frame with the illumination source turned off. This last image captures fixed pattern noise, bad pixels, and non-uniform sensitivity of the camera sensor. Figure 2 illustrates the

processing steps for the image set. Custom code was developed in Matlab (Mathworks, Natick, MA), and is included at the end of the paper. The processing algorithm is as follows:

- Read in the current image.
- Read in the dark image.
- Subtract the dark image from the current image to remove fixed pattern noise.
- Median filter the resulting image to remove isolate speckles.
- Find the peak of the PSF and create a cropped region about this peak. Ensure the tails of the PSF are included.
- Set any negative pixel values to zero. These come from random noise in the dark areas of both original images.
- 2D Fourier transform the cropped image to get the Optical Transfer Function (OTF). The modulus of this result is the MTF.
- Repeat for each image in the series and plot the through-focus MTF.

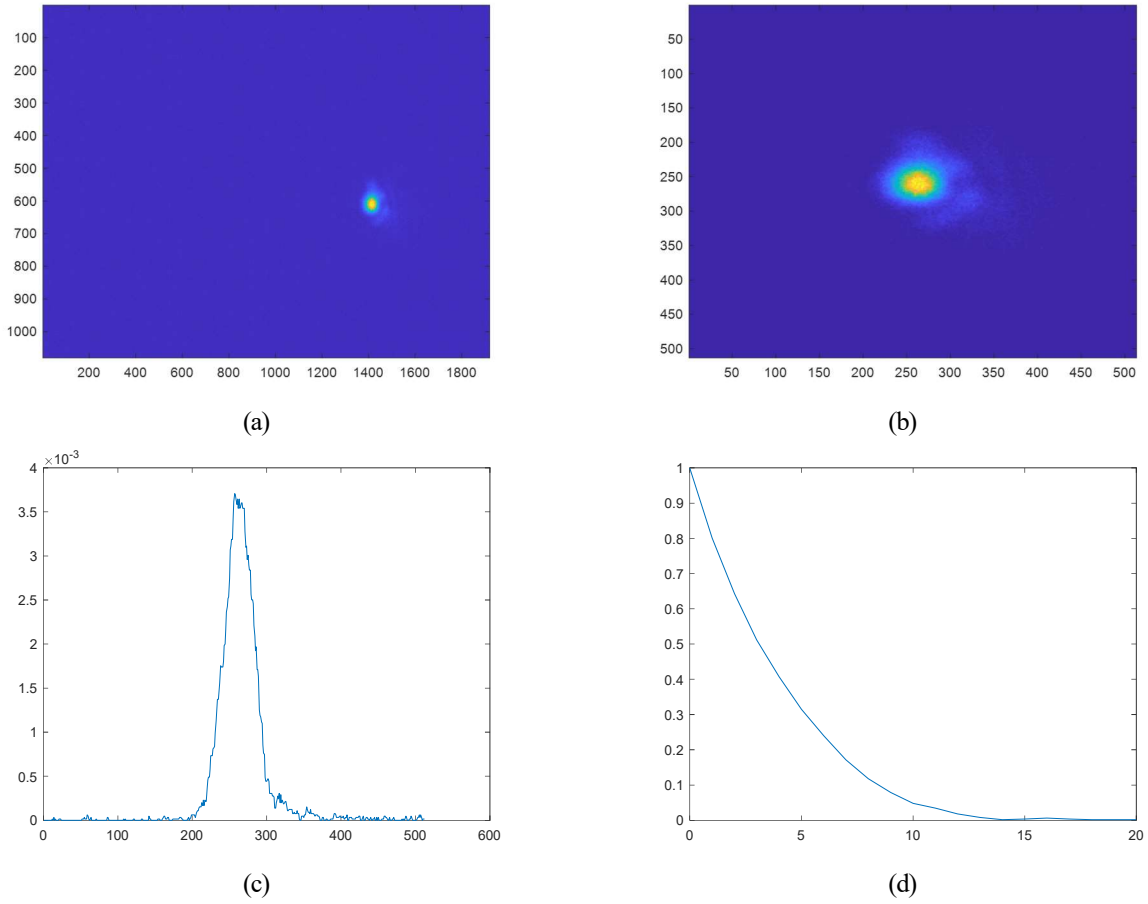

Figure 2. (a) PSF image after the dark image has been removed, and median filtering applied (b) Cropped image of the PSF with negative pixel values set to zero. (c) Cross-sectional plot through the PSF. (d) MTF (horizontal) associated with the PSF.

3. RESULTS

The technique was applied to an multifocal IOL (SN60D3, Alcon, Fort Worth, TX). The lens has a base power of 20D with an additional power of 4 D. PSF images were captured over a defocus range of -2.5D to 5D to fully capture the through focus MTF, though this distance could be shortened depending on the additional power of the multifocal lens. Figure 3 shows the resultant through-focus MTF after processing. The spatial frequency is $50\ cyc/mm$.

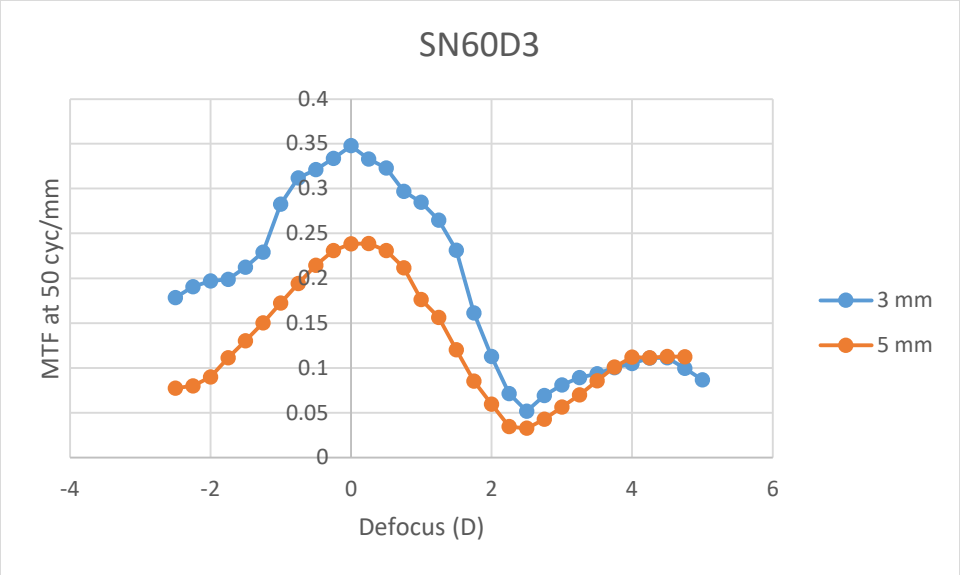

Figure 3. (a) Through-focus MTF at 50 cyc/mm of Alcon SN60D3 20 D lens for 3 mm and 5 mm pupils.

From Figure 3, it is evident that there are two peaks in the through-focus MTF. The first peak is at zero diopters, which equates to an object at infinity, or distance vision. The second peak has lower contrast, and appears at $+4$D of defocus. This corresponds to an object at 250 mm from the eye, or near vision.

4. DISCUSSION

A system and method for measuring the through-focus PSF of IOLs and calculating the through-focus MTF has been demonstrated. There are some practical issues in creating a system directly measuring the PSF that need to be taken into account to ensure accurate results. PSFs tend to have a bright central core surrounded by dim, but strongly structured tails. These tails contain all the information regarding the aberrations of the system and consequently encode the deterioration of the MTF. Traditional 8-bit sensors are inadequate for capturing the fine details of the PSF. Typically, one of two things will happen when capturing a PSF with an 8-bit camera. Either the tails of the PSF will be lost in the noise floor of the sensor, making the PSF look narrower than it actually is, or the central peak of the PSF is saturated, leading to a flat top PSF and incorrect MTF. Alternative means for measuring the MTF are often used to avoid such issues. These include measuring the Line Spread Function (LSF) or the Edge Spread Function (ESF), and using standard Fourier techniques to calculate the MTF.[4] These techniques have advantages over directly measuring the PSF in that they effectively integrate the PSF along one direction causing the faint tails to become more pronounced. However, these techniques also have disadvantages in that they only represent a slice through the MTF. This slice is fine for rotationally symmetric systems, as the slice should be the same in all directions. However, in non-rotationally symmetric systems, the MTF will change depending upon the orientation of the slit or edge used to capture the LSF or ESF. In ophthalmic optics, toric lenses are routinely used, and toric multifocal IOLs are commonplace to provide multiple foci and simultaneously correct for ocular astigmatism. Even more exotic non-rotationally symmetric multifocal designs exist. In these cases, the direct PSF measurement is advantageous because it calculates the full MTF and not simply a slice.

To overcome the limitation of the 8-bit camera, the system described here used a 16-bit camera. While more expensive, the extra bit depth enables far more details to be recovered from the PSF including the tails, and without saturating the peak. The are several additional issues the arise in the PSF measurement. The first is the sensor. The sensor can have bad pixels(either dead, or pegged to its maximum value), as well as non-uniformity in the sensitivity or fixed pattern noise across the sensor. These issues can be largely addressed by capturing a dark image and subtracting it from the captured PSF image. Both the dark and PSF images contain the aforementioned errors, so the subtraction effectively nulls them. One final issue though is random noise. Both the dark and PSF images will have random noise, and in regions of low light level, the subtraction of these images can lead to negative values. While mathematically, this is fine, and the processing algorithm will calculate an MTF. However, the MTF will be inaccurate. There clearly cannot be negative PSF irradiance

values, but the prior processing can lead to negative values. The best strategy here is to set these negative values to zero. Figure 2(c) shows a cross section through the PSF. In the tails of the PSF, some of the random noise can be seen, but only positive values. The negative values have been clipped to zero.

The final challenge with the system described here is alignment. Dealing with small optics in wet cells is challenging, so sufficient degrees of freedom in being able to manipulate the components of the system are essential. Even with these degrees, it is still challenging to align all of the components as can be seen in Figure 2b. In this case, the IOL and the remaining components are all rotationally symmetric, but the PSF is slightly asymmetric. The like cause of this effect is one or more of the components is slightly tilted or decentered, inducing small amounts of coma into the PSF image. Finally, the microscope objective and imaging tube are long and need to be supported through defocus measurements to limit vibrations from causing the PSF to move about. Armed with these insights, the system is going to be further tested and aligned to minimize these effects, and a broader range of IOLs tested. We also have a commercial system which measures the MTF of IOLs (PMTF, Lambda-X, Nivelles, Belgium). This system uses the more traditional ESF measurements to calculate MTF. Future work will be to compare the results of different IOLs with the two measurement systems.

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[4] Schwiegerling, J., [Optical Specification, Fabrication, and Testing], SPIE Press, Bellingham, WA (2014).


```
clear all
clc
clear variables
close all

%load an image and display
img =im2double(imread('C:\Users\jschw\Dropbox\Research\Aberrations\Thru
PSF\Image10.tif'));
imgdark = im2double(imread('C:\Users\jschw\Dropbox\Research\Aberrations\Thru
PSF\Dark.tif'));
img2 = img - imgdark;
img3 = medfilt2(img2); %imadjust ended up clipping the top of the PSF
imagesc(img3);

%crop the image
dim=512;  % FFT is fastest for power of 2 dimensions
maximum = max(max(img3));  % find peak of PSF
[x0,y0]=find(img3==maximum);
img4 = imcrop(img3,[y0-dim/2 x0-dim/2 dim dim]);

%set negative values to zero
[m n]=size(img4);  % set negative values to zero since irradiance
for i=1:m  % probably a better way to do this
    for j=1:n
        if img4(i,j)<0
        img4(i,j)=0;
        end
    end
```

```
end
figure;
imagesc(img4);

xPSFprofile=img4(dim/2,1:dim);  %horizontal profile through PSF
x=1:length(xPSFprofile);
figure;
plot(x,xPSFprofile);


%find the OTF/MTF of cropped image and display
figure('Name','2D MTF')
OTF=fftshift(fft2(fftshift(img4)));  % use the filtered image here
MTF=(abs(OTF));
imagesc(MTF);

%find max value of MTF and plot cross section of row
min=dim/2+1;
max=min+20;     %range of values to graph over
MTF_attempt= MTF(dim/2+1,min:max);      %cross section of MTF at max row across
max to min columns
MTF_norm=MTF_attempt./MTF(dim/2+1,dim/2+1);      %normalize
x=1:length(MTF_norm);
x=x-1; %shift to start at zero, still need to scale to cyc/mm
figure('Name','MTF Cross Section Row');
plot(x,MTF_norm);
```

Figure 4. Matlab algorithm used to find through focus PSF and MTF for multifocal IOLs.