Influence of Exposure Time and Pupil Size on a Shack-Hartmann Metric of Forward Scatter

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ABSTRACT

PURPOSE: To determine the influence of exposure time and pupil size on a Shack-Hartmann (S/H) derived metric of forward scatter (MAX_SD) using a physical model of nuclear cataract.

METHODS: A physical model eye was developed and mounted to a S/H wavefront sensor. The eye model consisted of a lens, variable pupil, simulated cataract, and retina. Located behind the pupil, a cuvette contained one of five polystyrene microsphere solutions simulating five levels of nuclear cataract severity. Cataract severity was described using a S/H derived metric of forward scatter (MAX_SD), which measures aspects of forward scatter contained in the S/H lenslet point spread functions (PSF). To determine the impact of exposure time and pupil size, measurements of MAX_SD were regressed against cataract severity for three different exposure times and three different pupil sizes.

RESULTS: MAX_SD was well correlated to cataract severity. Exposure time had the largest influence, and pupil size had the smallest influence on the forward scatter metric. When pupil size and exposure time were allowed to vary and image saturation was allowed to occur, MAX_SD explained 83% of the variance in cataract severity. Excluding images where saturation occurred, holding optimal exposure time constant, and varying pupil size, MAX_SD explained 97% of the variance in cataract severity.

CONCLUSIONS: The ability of the forward scatter metric derived from S/H measurements to predict cataract severity for a longitudinal study is optimized by selecting a patient-specific exposure at the initial cataract assessment to avoid saturation and maximize the dynamic range of the system. This patient-specific exposure should be used in all future visits. [J Refract Surg. 2005;21:S547-S551.]

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Dr Applegate has proprietary interests in metrics of forward scatter.

This work was supported in part by NIH grant R01 EY05820 to Dr Applegate and CORE grant P30 EY07551 to the College of Optometry, University of Houston, Houston, Tex.

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of cataract and grading (eg, LOCS-III) and Scheimpflug densitometry. These tools (particularly the slit-lamp) are commonly used to assess cataract severity.

A major problem with using backscatter to predict forward scatter in cataract is that with Mie scattering, no direct relationship exists when particle size and density varies over a large range.

Researchers and clinicians are aware that backscatter measures are indirect measures of forward scatter and lacking when used to predict visual performance. Thibos and Hong suggested measuring forward scatter as a new application of S/H technology and Applegate and Thibos were the first to report observations using a S/H wavefront sensor (SHWS) to measure forward scatter.

Shack-Hartmann estimates of cortical and posterior sub-capsular cataract will have less reversibility than nuclear cataract due to their anterior and/or posterior localization. Nonetheless, it is fully anticipated that cortical and posterior sub-capsular cataract will have their unique S/H image signatures. Here we focus on nuclear cataract as a first step in a systematic development of the technique.

A major goal of the laboratory is to develop a physical model that could be used to test and develop a computer model of forward scatter. A computer model that can replicate different physical eyes will facilitate development of better metrics in a time efficient manner. In developing this physical model, we took the opportunity to demonstrate the importance of proper exposure given the fact that current S/H systems purposely favor overexposure or use image processing to accentuate spot centers.

**MATERIALS AND METHODS**

**PHYSICAL EYE MODEL**

To control all parameters during testing, we built a physical eye model (Fig 1). This system was developed in Zemax software (Zemax, San Diego, Calif) and was designed to match other researchers’ modulation transfer function data on real eyes. The main optic was a 19-mm focal length plano-convex silica lens with a diameter of 12.7 mm, n = 1.463. Directly behind the lens was an adjustable pupil. To hold solutions of scattering media, an interchangeable glass cuvette followed directly behind the pupil plane. The cuvette, simulating a cataractous crystalline lens, was filled with various concentrations of 1-µm diameter microspheres in distilled water. A cuvette path length of 5 mm was chosen to approximate a lens thickness equal to that of an older adult aged lens. The retina of the system was a piece of white paper mounted to a locking micrometer drive allowing focus adjustment.

Based on the work of Cox et al, five levels of simulated nuclear cataract were chosen to span the range encountered in a clinical population of nuclear cataract patients. One cuvette contained only distilled water as a non-cataract configuration. Four cuvettes contained 1-µm microsphere solutions of increasing microsphere density to produce the same scatter profile function through a path of one half the length of the cuvette used by Cox et al. This yielded microsphere solutions of 0.00%, 0.08%, 0.16%, 0.32%, and 0.48%.

Figure 1. The physical eye model. This assembly picture was used to model a human eye with various levels of nuclear cataract. The model mounts to the front of the SHWS. Left to right is a Lambertian reflector acting as the retina, a cuvette filled with microsphere solution acting as lens cataract, a sliding adjustable pupil, and a plano-convex lens as the main focusing optic.
MEASUREMENTS

The physical eye model was mounted to the front of the SHWS, and S/H images were acquired for the five cataract levels over 5-, 7-, and 9-mm pupils. Three exposure times were used: 100, 200, and 300 ms. The input source for the retinal guide star was held constant. Lenslet pitch was 400 µm and the lenslet focal length was 24 mm. Cuvettes and pupil size could be changed without disturbing the positioning of the physical eye model. To reduce instrument noise, as in real eye measurements, background images were subtracted from the S/H images.

ANALYSIS

Each lenslet point spread function (PSF) was individually analyzed and statistics were calculated on all lenslet data in the S/H image to extract a metric of forward scatter—MAX_SD. To determine MAX_SD, the standard deviation is calculated from pixel values over a defined square area centered on a lenslet PSF peak. The sides of the square are equal to the average distance between adjacent lenslet peaks. MAX_SD is the maximum of all standard deviations from all lenslet PSFs in the image. If desired, greater detail of the calculation of MAX_SD can be found in Donnelly et al.1

MAX_SD was regressed against cataract severity, represented as % microspheres in solution. To appropriately apply regression, the independent variable needs to be well distributed with respect to the dependent variable. To achieve such a distribution, the independent variable (cataract severity expressed as % microspheres in solution) was transformed by taking the square root of percent of microspheres in solution.

OVEREXPOSED IMAGES

Overexposure caused pixel saturation in the S/H image, causing many pixels to have values near 255 (maximally white), artificially widening the lenslet PSFs (Fig 2C). To identify which S/H images were saturated (overexposed), we used an image histogram. An image histogram is a plot of the number of pixels having a particular value in a S/H image (after background subtraction) as a function of image value. Saturation can be observed in a S/H image histogram as a third peak near value 255, ie, an excessive number of pixels having many values near 255 (Fig 2A). Shack-Hartmann images without saturation (Fig 2D) do not exhibit a third peak (no excessive white pixels) in the histogram near 255 (Fig 2B).

RESULTS

Figure 3 plots MAX_SD at three pupil diameters and increasing exposure time including data from saturated images (Figs 3A-3C) and without saturated images (Figs 3D-3F). When the regression analysis included saturated images (see Figs 3A-3C) over all pupils, R² is
Figure 3. MAX_SD regressed against cataract level (square root microsphere solution). Pupil diameters were 5, 7, and 9 mm (solid circles, open circles, and solid triangles, respectively) at 100, 200, and 300 ms. A-C) Graphs contain some data points derived from overexposed (saturated) images. D-F) Graphs have data points derived from saturated images removed. The regressions that contain points derived from overexposed images have $R^2$ that decrease with increasing exposure time. Without saturation, slopes between exposure times (D-F) remain similar, indicating that if MAX_SD is normalized such that the y intercept is 1 then each normalized value would correspond to a given level of cataract severity.
best for the lowest exposure, 100 ms (average $R^2=0.955$). $R^2$ decreased for increasing exposure times (average 200 ms $R^2=0.925$, and average 300 ms $R^2=0.856$). If overexposed images are excluded, low to high exposure time caused the data to shift to increased values of MAX_SD for all pupil diameters (see Figs 3D-3F). All coefficients of determination improved and were similar in value once overexposed images were excluded from the analysis (see Figs 3D-3F).

**DISCUSSION**

The results of this study indicate that the ability of MAX_SD to predict cataract severity or forward scatter in a longitudinal study of nuclear cataract is optimized by avoiding overexposure and maximizing the dynamic range of pixel values in the S/H image at the first visit for each patient. A possible downside of this approach would be if the forward scatter decreased in severity with time, future images will likely be overexposed, for instance, following a therapy for cataract that not only slows down cataract progression but actually causes the cataract to regress. If this is a concern, instead of maximizing the dynamic range at the initial visit, a cushion to prevent overexposure at future visits should be considered in the process to decrease exposure time. In either case, once a particular exposure time is determined for an individual it should be maintained for the duration of the experiment.

It is good photographic practice to neither underexpose nor overexpose an image when detailed contrast information is the goal. However, S/H wavefront sensing is relatively insensitive to overexposure and is very sensitive to underexposure. As a result, S/H images are typically overexposed, or if underexposed, image processed to add brightness to the spots. Here we wish to make the point that if good photographic practices are followed (optimize dynamic range without saturation), then scatter detection is optimized at no cost to wavefront analysis.

It is useful to note that the rule for optimizing a S/H image for MAX_SD is easy to implement in software such that the user would simply need to take a few (likely one or two) S/H images and let the software adjust exposure time to optimize the image for MAX_SD extraction. The optimization parameters would then be stored in the patient record and on subsequent visits called up for use.

In a SHWS, the limiting aperture is the aperture of each lenslet, not the eye’s pupil. Consequently, we did not expect pupil size to have a significant impact on MAX_SD, and as predicted, it did not.

Exposure time matters when extracting forward scatter metric MAX_SD from a S/H image. By properly choosing exposure time, simulated nuclear cataract is well predicted by the forward scatter metric MAX_SD.

Cataract is only one application of this technique. Forward scatter caused by any of the mechanisms described in the introduction can also be measured using MAX_SD.

**REFERENCES**