Determining the Accuracy of an Eye Tracking System for Laser Refractive Surgery

Natalie M. Taylor, BE; Robert H. Eikelboom, PhD; Paul P. van Sarloos, PhD; Philip G. Reid, BE

ABSTRACT

PURPOSE: Patient eye and head movements during laser refractive surgery may result in errors between the surgical beam position and the desired location for optimum correction. This, in turn, may lead to reduced postoperative vision, including increased higher order aberrations of the eye. Active eye tracking systems are often incorporated into laser delivery systems, which aim to reduce the effect of patient eye movement.

METHODS: In this study, the accuracy of an eye tracking system designed for laser refractive surgery was determined. An enucleated porcine eye was attached to a scanning device and the movement measured using the eye tracking system. The recorded position is compared to the preprogrammed position of the scanning device.

RESULTS: The system demonstrated an accuracy of 0.06 m for an intact cornea and 0.1 mm for a cornea with a thin flap removed. This compares to an average decentration of ablation of 0.4 mm for patients relying on passive fixation, as measured by previous clinical trials.

CONCLUSION: implementation of this eye tracker would lead to improved alignment between the laser and eye during laser refractive surgery. [*J Refract Surg* 2000;16:S643-S646]

Photorefractive keratectomy (PRK) is the removal of tissue from the cornea using laser ablation, to correct refractive errors of the eye. To ensure accurate tissue removal, accurate alignment between the patient's eye and the surgical laser beam is required throughout the procedure. During this time—30 to 90 seconds—micromovements of the eye are unavoidable. Eye and head movements may decenter the ablation, which may result in postoperative astigmatism or glare.[1,2]

From the Centre for Ophthalmology and Visual Science, Lion's Eye Institute, The University of Western Australia, Nedlands, Australia.

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Correspondence: Natalie M. Taylor, BE, Centre for Ophthalmology and Visual Science, Lions Eye Institute, The University of Western Australia, 2 Verdun St, Nedlands 6007, Australia. Tel: 61.8.93810731; Fax: 61.8.93810700; Email: taylorn@cyllene.uwa.edu.au

Several commercial laser systems have incorporated an eye-tracking device in which the eye movement is measured and the laser beam is moved to compensate for this. There is little published information on the accuracy or effectiveness of these systems, or whether the performance is affected by the removal of corneal tissue. Molebny[3] describes an eye-tracker to be used for PRK, which has an accuracy of 0.1 mm for an eye movement range of ±2 mm, without mentioning the method used to ascertain this accuracy. The eye tracking system using in the Excimed UV200 from Summit Technology[4] was claimed to be accurate to 0.1 mm in a 6 x 6mm^2 tracking field. Pallikaris and colleagues give results for clinical trials of the Autonomous Technologies T-PRK excimer laser system.[5] The trial did not include a control group of patients to demonstrate that the device improved the procedure's result, nor did it mention the accuracy or precision of the system. The popularity of LASIK is increasing, yet tracking an eye with a corneal flap removed may be more difficult, due to the increased scattering of light from the resulting irregular surface.

An eye-tracking system is being developed for an existing commercial laser.[6] To assess whether the system will improve centration and reduce drift during the procedure, it is important to know the accuracy with which the eye-tracker detects the patient's pupil. The eye tracker is intended to be used during PRK and LASIK, and so the accuracy should not be affected by the removal of corneal tissue. The aims of this study were to determine the accuracy of the eye tracking system, and to assess the change in performance when the integrity of the corneal surface is compromised.

METHOD

The accuracy was calculated by using this technique to determine the eye movement when the eye movement was already known. The expected eye position and the recorded eye position were compared to find the error at each measurement, and a correlation was made between the two data sets.

The predetermined eye movement was achieved by attaching a pig's eye to a scanning device, which could be programmed to move in two axes. The scanner movement was programmed to resemble a variety of types of eye movements: long fixations, slow drifts, and the occasional saccade—very fast eye movement. The maximum eye movement was 2 mm in both the X and Y direction. The scanner was mounted on an optical bench with the prototype eye-tracking system, and video footage was recorded of the eye moving along the preprogrammed path. Coaxial IR illumination was used. The experiment was performed with an eye with an intact cornea and an eye with a flap of corneal tissue removed. The flap of corneal tissue was removed using a microkeratome, after the anterior chamber had been injected with saline, which increased the rigidity of the eyeball to facilitate the cutting of the flap.

The videotape was then analyzed using the eye-tracking software. Each video frame was processed sequentially. The frame was digitized by a Matrox Meteor frame grabber (Matrox Imaging, Quebec, Canada), and then processed to find the pupil center. The separation of the pupil from the rest of the image in each frame is facilitated by illuminating the eye during the videotaping with a low powered infra-red (IR) laser diode, which is coaxial to the pupil and the camera. The IR light is reflected off the retina, which causes the pupil to be imaged as a bright disc against a dark background. The image is binarized using a predetermined threshold value and the pupil is detected using a pattern-matching algorithm. The algorithm uses a model—a filled white circle of a predetermined radius against a dark background—and searches for the best match for this model in the image. The center of the matched model is the center of the pupil in the image. This algorithm has been successfully tested on subjects with different iris colors.[6] The time in microseconds and the pupil center in pixels were then written to a file, before the next frame was digitized.

The recorded pupil positions and the predetermined positions were then plotted on the same graph. First, the recorded eye movement and the predetermined eye movement had to be registered and identical units used. The scanning device used encoder units for measuring position and the eye tracking software used pixels, so a conversion factor had to be applied to compare the two data sets. The scanning device updated the position at 10 Hz, whereas the non-optimized eye tracking software ran at a frequency varying from 10 to 12.5 Hz. To ensure that corresponding positions were being compared, the scanner path was linearly interpolated to find the expected pupil position at each recorded pupil position. The error between each recorded point and expected point and the correlation between the two data sets was measured.

RESULTS

Figure 1 shows images of the pig's eye before image processing. This eye had a pupil diameter of approximately 10 mm—30% larger than a human pupil. The injection of saline, intended to facilitate the cutting of the flap, increased the ellipticity of the eye and pupil. In images of the eye with an intact cornea, one axis was 4% longer, compared to a 9% difference in perpendicular axes in the pupil image of the eye that had been injected with saline.

Figure 2 and Figure 3 show the pupil position in pixels as a function of time for the pig's eye with an intact cornea and cornea with the flap removed. Each pixel represents 40 µm at the cornea. It can be seen in Figure 3 that the eye tracking system does not capture images at a sufficient rate to capture all the saccadic movements. The graphs for the y-axis produced similar results.

The Table gives the average error and correlation factor between the measured eye position and the expected eye position for an intact porcine cornea, and a cornea that has had a flap removed. The correlation factor was calculated using the correlation analysis tool in Microsoft Excel 97 (Microsoft, Seattle, WA), which returns the covariance of two data sets divided by the product of their standard deviations.

There is no relationship between the correlation factor and the average error. A small number of large errors would have a greater effect on the

Table
Error and Correlation Between Expected Position and Recorded Position

	Cornea Intact Average error (pixels)	Cornea Intact Correlation Factor	Flap Removed Average Error (pixels)	Flap Removed Correlation Factor
Run 1 x direction	1.43	0.970	2.39	0.903
Run 1 y direction	1.50	0.979	1.56	0.916
Run 2 x direction	1.51	0.979	2.81	0.959
Run 2 y direction	1.43	0.963	3.05	0.961

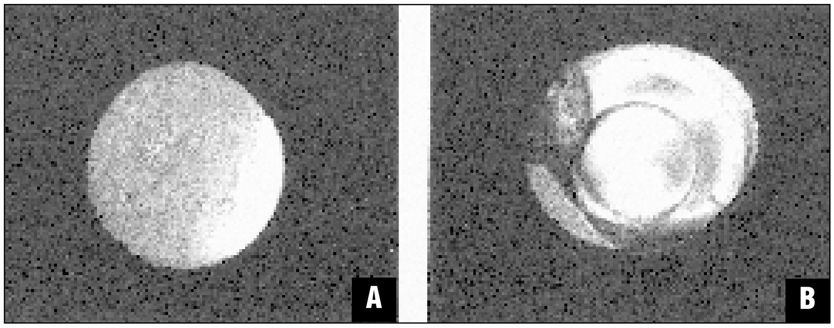

Figure 1. Pig's eye. **A)** intact cornea, **B)** cornea with flap removed.

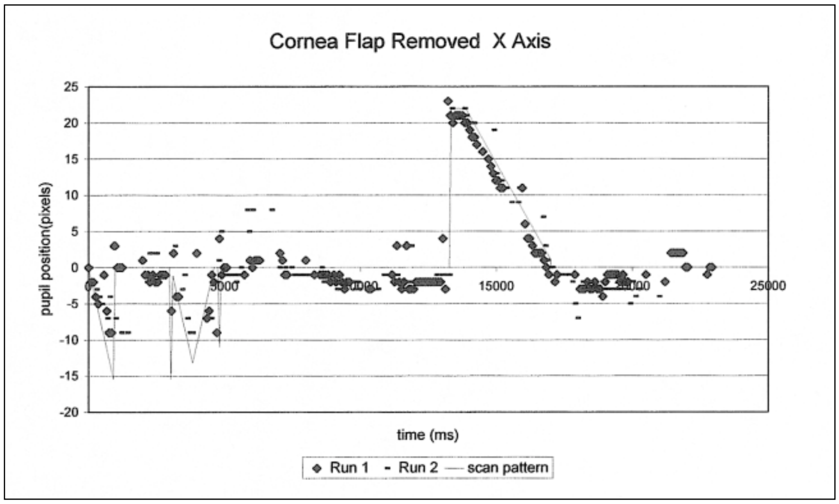

Figure 2. Pupil position versus time in the x direction for the cornea with flap removed.

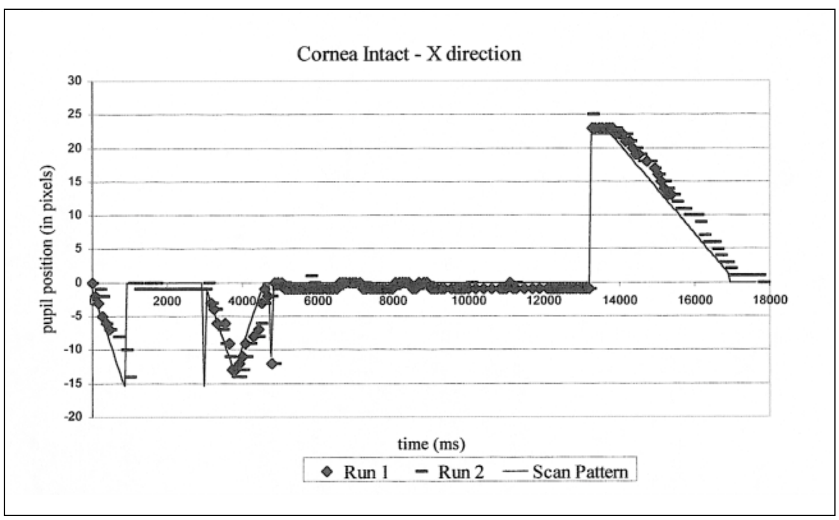

Figure 3. Pupil position versus time in the x direction for the intact cornea.

average error than on the correlation, whereas a consistent error, such as always 1mm to the right, would have little or no effect on the correlation. It is desirable for the eye-tracker to have both a low average error and a correlation factor approaching one.

DISCUSSION

To achieve the aim of reducing the effects of decentration and drift during PRK and LASIK, the eye-tracker would have to perform better than the present technique used to maintain alignment. Cavanaugh and coworkers[7] measured the decentration of ablation of 49 PRK patients who maintained alignment by fixating on a light. The mean decentration from the pupil center, measured using corneal topography, was 0.4 mm and ranged from 0.11 to 1.10 mm. The eye tracking technique in this study had an accuracy of approximately ±1.5 pixels (Table) or ±0.06 mm when tracking an intact cornea. Using this eye-tracker to control the laser alignment would therefore improve surgical reliability, compared to passive fixation.

This eye tracking technique did not accurately follow every eye movement. Figure 3 shows that several of the sudden eye movements were undetected by the current eye tracking software. This occurred because the frequency of the saccade was higher than the frequency response of the eye-tracking sensor and software. Also, small eye tremors of the order of 30 µm[8] would be undetected as the system had a resolution of 40 µm.

The average accuracy of the eye tracker was ±2.5 pixels (Table) or ±0.1 mm when tracking an eyeball that had a corneal flap removed. While this still compares favorably with the alignment error of the present technique and published data of eye-tracking systems, it is less accurate than tracking an intact cornea. The accuracy could be influenced by the change in the shape of the pupil. The saline injection, which facilitated the cutting of the flap, deformed the eyeball causing the pupil to be more elliptical. A pattern-matching algorithm searching for a bright circular disc would less accurately detect an ellipse. Although saline injections are not part of refractive surgery, patients' pupils do vary in size and shape and most pupils are slightly elliptical. Programming the computer to automatically generate a model for the pattern-matching algorithm, and dynamically adjust for the patient's pupil size and shape could reduce potential errors.

While decentration and drift during refractive surgery can affect the patient's visual outcome, the amount that is clinically significant has yet to be determined.[7] Both clinical trials[2,7,9,10] and computer simulations[8,11] have been used to either correlate or quantify the effect of patient eye movement during refractive surgery on visual outcome. While generalizations can be made, such as decentration greater than 1 mm will increase astigmatism[10] and random eye movement may affect contrast sensitivity[8,11], the effect of an uncorrected saccade or tremor is unknown. Until there is a greater understanding of the effect of eye movement on postoperative vision, the accuracy required to compensate for any eye movement that will affect the success of the procedure is unknown. Therefore, it cannot be concluded that the accuracy of this particular eye tracking technique is adequate to eliminate the effect of eye movement. The only criteria on which it may be assessed are whether it is better than patient fixation and more accurate than the published data for other eye-tracking systems. This eye-tracker succeeds on both counts.

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