6-D Eye Tracking

Researchers work to determine whether the ability to measure and compensate for all aspects of the eye's rolling movement during refractive surgery can impact clinical results.

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The eye trackers in modern refractive laser systems update the laser spot's position on small dislocations of the cornea resulting from ocular movements. Video-based eye trackers determine the position of the eye by measuring the lateral translation of the entrance pupil or the limbus' center. In refractive surgery, however, it is not the position of the pupil or the limbus that is of interest but the exact location of the overlying cornea's front surface. Because ocular movements always consist of rotations of the bulb around the eye's center of rotation (termed *eye roll movement*), a parallax error is always associated with current eye tracking that is based on the rough assumption that the eye is only performing lateral translations (Figure 1).[1] True lateral dislocations of the eye only result from movements of the head. The alignment of any laser treatment relative to the eye is a task with six degrees of freedom (6-D). Besides lateral translations with a horizontal (x-axis) and a vertical (y-axis) component, as well as axial movements along the optical axis (z-axis), surgeons need to take into account the rotations with potential components in the three axes.

A new video-based eye tracking system (SensoMotoric Instruments GmbH, Teltow, Germany), which is ready for implementation in new laser platforms worldwide, is capable of simultaneously measuring real eye roll movements and lateral dislocations of the eye. This technology may eliminate parallax errors, which sometimes occur with earlier modes of video-based eye tracking. We used a specialized software program to determine the degree to which this technology can improve the results of refractive surgery.

CLINICAL RELEVANCE OF EYE ROLL MOVEMENTS

We analyzed the clinical relevance of eye roll movements in refractive surgery using software algorithms developed by the Institute of Refractive and Ophthalmic Surgery (Zürich, Switzerland). The customized software, which has been refined over the years, allows researchers and developers of refractive lasers to simulate an entire laser treatment in a pulse-by-pulse manner, including the real-life effects of variations in fluence resulting from corneal curvature as well as the development of postoperative healing. Measured eye-movement data can be taken into account in each simulated treatment. All algorithms are validated by means of real clinical data in order to provide excellent compliance with real surgical results. Furthermore, the program includes a number of tools for evaluating the clinical relevance of the optical errors introduced by various sources.

Within the scope of a joint project, the clinical neces-

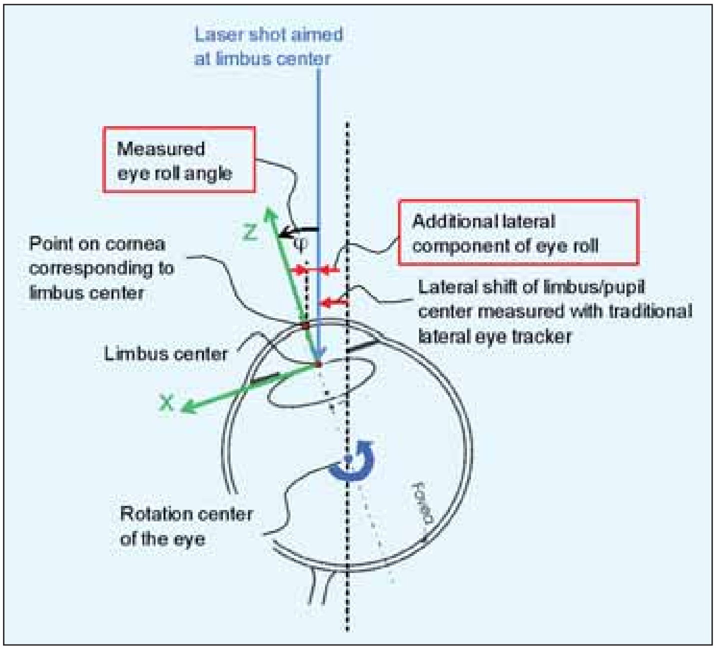

Figure 1. Eye roll movements around the eye's center of rotation cause additional shifts of the corneal surface that cannot be measured by traditional tracking of the limbal/pupillary center. A new eye tracking system from SensoMotoric Instruments GmbH measures the angle of rotation and determines the additional lateral shift.

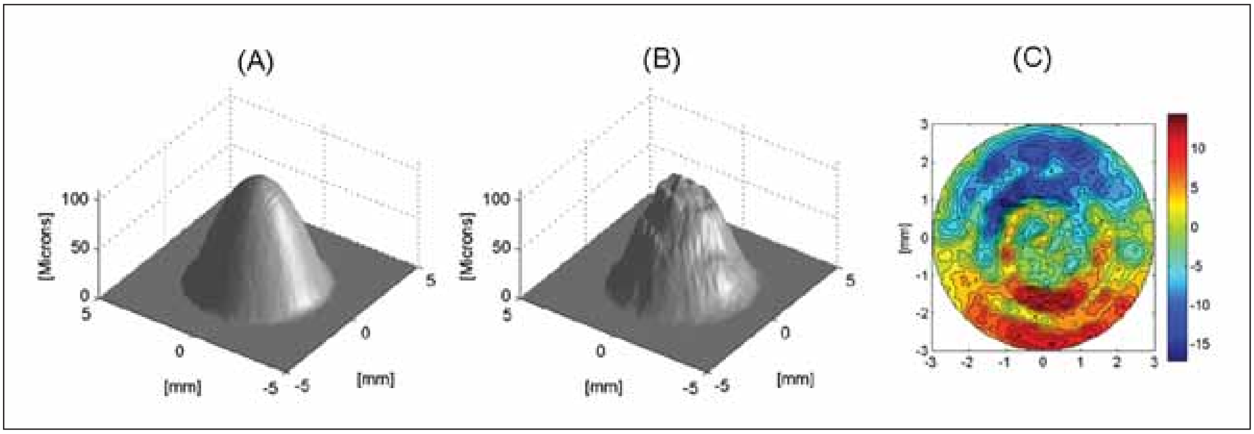

Figure 2. Ablated corneal profiles after the simulated treatment of 8.00 D of myopia are shown. The investigators compared the profiles of a case in which all eye roll movements were compensated for (A) with one in which there was no compensation except for the lateral translations as performed with traditional eye tracking (B). They measured the difference in the profiles (C).

sity of eye roll tracking was evaluated. Dr. Bueeler and colleagues from the Institute of Refractive and Ophthalmic Surgery performed simulations of refractive laser treatments using eye roll data from real eyes measured during refractive surgery. Optical quality metrics that are known to correspond well with patients' subjective visual impressions were used for the final evaluation.

Figure 2 shows two ablated corneal profiles of an 8.00 D myopic correction and the corresponding difference map. The measurement and compensation of eye roll movements lead to a significantly increased quality of ablation in case A compared with case B, where a rolling eye was present during the treatment. The eye roll data that led to case B were measured in a patient during real refractive surgery.

The researchers found that correcting sphere and cylinder can induce significant amounts of higher-order aberrations, mainly coma, if eye roll movements of normal magnitude are present during the treatment (Figure 3). For these, the main lateral eye-movement component (shift of the limbal/pupillary center) was assumed to be already compensated for by traditional lateral eye tracking.

Other investigators have concluded that ocular wavefront errors with root-mean-squared values (RMS) larger than 0.14 µm are clinically relevant.[2] The calculations from the Institute of Refractive and Ophthalmic Surgery have shown that, in the case of myopic and hyperopic corrections of more than 4.80 D and 2.50 D, respectively, clinically relevant amounts (larger than 0.14 µm RMS) of higher-order aberrations (coma) are induced in at least 50% of the treated eyes (Figure 3).

In some cases, highly deleterious aberrations of up to 0.65 mm wavefront RMS were introduced. Hyperopic corrections were more sensitive to eye roll movements than myopic treatments. This susceptibility occurs because more peripheral ablation is required in hyperopia and eye roll movements have a larger effect on the ablation in the periphery.

Nevertheless, Dr. Bueeler found that eye roll movements did not induce significant amounts of aberration

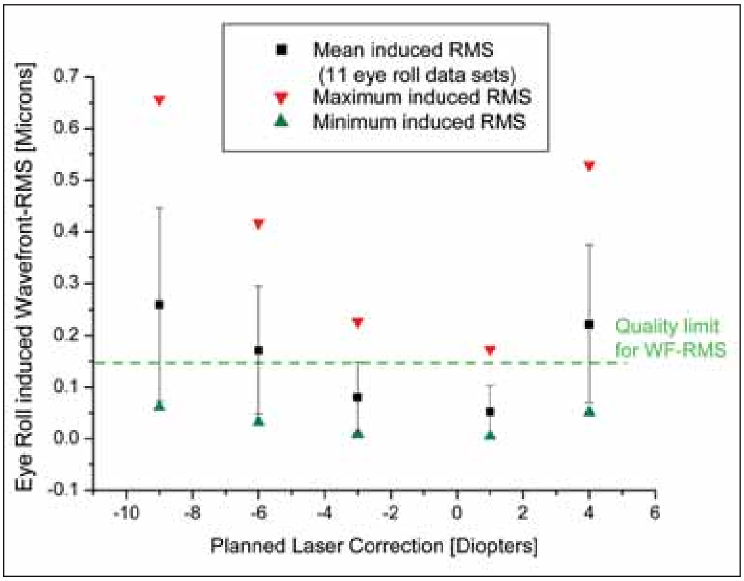

Figure 3. Eye roll movement induced wavefront RMS in dependence of the planned spherical correction in diopters. The mean ± standard deviation out of 11 measured eye roll movement data sets is plotted. The maximum and minimum of the induced values are indicated.

when the laser treatment corrected purely higher-order optical errors such as coma and spherical aberration. Postoperative epithelial healing eliminated most of the effects of rolling eyes in these cases.

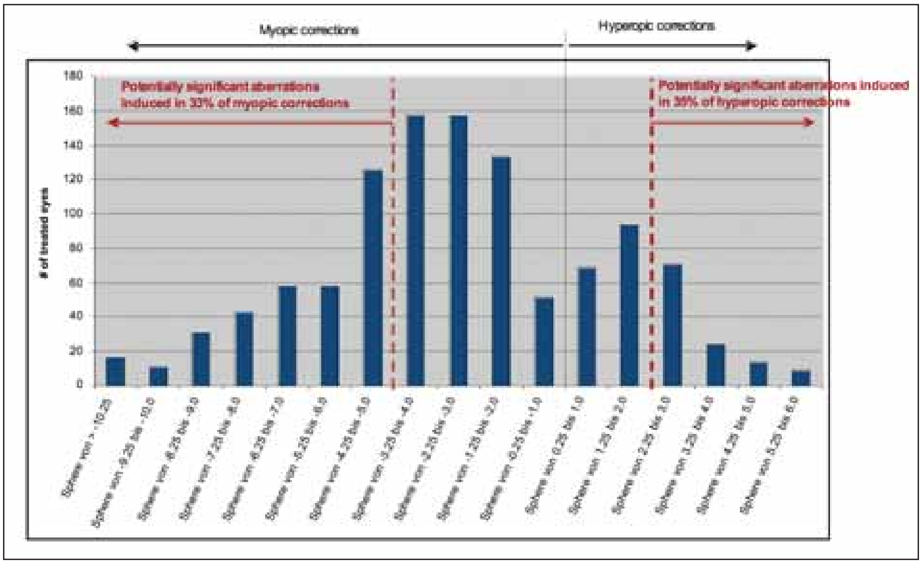

Figure 4. This distribution of different myopic and hyperopic corrections is representative of a large laser center. Thirty-three percent of all patients are at risk of suffering from clinically relevant, eye-roll–induced aberrations after the treatment. These ocular movements cannot be measured with traditional eye tracking of the limbal/pupillary center.

EXPECTED NUMBER OF PATIENTS AFFECTED

Figure 4 shows the distribution of different myopic and hyperopic corrections at a standard laser center in Switzerland. Most myopic treatments normally range from -1.25 D to -5.00 D, and hyperopic corrections commonly are between +0.25 and +3.00 D.

Approximately 280 of 844 eyes that received a myopic treatment had a refractive error greater than 4.80 D. Approximately 95 of 281 eyes that underwent a hyperopic treatment had a refractive error greater than 2.50 D.

Out of all patients in the two aforementioned refractive ranges, 33% have a potential risk of suffering from clinically relevant, eye-roll–induced aberrations postoperatively.

COMPENSATION FOR EYE ROLL MOVEMENTS IN REFRACTIVE SURGERY

Eye roll movements cause two types of ablation errors. First, an additional lateral displacement of each laser pulse occurs due to the geometrical parallax (shift of the apex relative to the limbal/pupillary center). This displacement adds to the lateral shift of the pupillary or limbal center that is already detected by conventional video-based eye tracking. Second, an angular distortion of the ablation cavity results when a laser pulse is absorbed under a different angle than originally planned.

Future laser systems will compensate for the additional lateral displacement by redirecting the laser beam according to conventional lateral eye tracking. The compensation for the angular distortion is not trivial, because the laser system would have to adjust the incidence angle of the laser beam to each movement (eg, through a dynamic recalculation of the laser shot list in real time).

Further simulations performed by researchers at the Institute of Refractive and Ophthalmic Surgery, however, showed that compensating for the lateral component of the measured eye roll movements significantly reduced the induced optical errors even for the highest refractive corrections expected in a laser center. In our investigation, the optical errors all decreased to below the limit of 0.14 µm RMS and thus were no longer clinically relevant. Compensation for the lateral eye roll component reduced the eye roll-induced optical errors in all eyes by 85% to 95%.

Additional compensation for the angular component of eye-roll–movement therefore is not necessary in refractive surgery.

CONCLUSION

Correcting spherical error and cylinder can induce significant amounts of higher-order aberrations if the patient's eye rolls to a normal degree during the treatment, even if traditional eye tracking compensates for the main lateral component of the eye's movements. This finding is most clinically relevant for myopic treatments greater than 4.80 D and hyperopic treatments greater than 2.50 D.

The clinical results of wavefront-guided refractive surgery are generally not as good as originally expected[3-5] due to clinically relevant amounts of residual or induced spherical aberration or coma. These errors are mainly owing to an inaccurate transfer of a theoretically calculated ablation profile to the cornea. Our study shows that the failure of traditional laser platforms to track rolling eyes contributes to poor surgical results. Surgeons will have the ability to compensate for the additional lateral shift of the corneal surface caused by a rolling eye with the 6-D eye tracking system, which was found to significantly reduce the induction of higher-order aberrations. ■


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