In Vivo Real-Time Intraocular Pressure Variations during LASIK Flap Creation

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PURPOSE. To monitor and compare in vivo real-time intraocular pressure (IOP) in rabbit eyes undergoing LASIK flap creation using microkeratome and femtosecond laser.

METHODS. Thirteen rabbit eyes in each group underwent LASIK flap creation using a microkeratome and a femtosecond laser. In vivo real-time IOP profile was measured using a 30-gauge needle with an IOP catheter sensor inserted into the anterior chamber from the limbus during surgery.

RESULTS. In vivo real-time IOP monitoring was achieved in all cases, showing IOP variations during different phases of LASIK flap creation from docking of the instrument, start of surgery to the end of procedure, and monitoring the post-LASIK stabilization. IOP fluctuations were significantly lower in corneal flaps made with the femtosecond laser than with the microkeratome during globe suction (81.78 ± 10.55 vs. 122.51 ± 16.95 mm Hg), cutting (62.25 ± 3.28 vs. 141.02 ± 20.46 mm Hg), and suction (41.40 ± 2.99 vs. 89.30 ± 12.15). In contrast, femtosecond laser requires double the time (19 ± 2 vs. 10 ± 2 seconds for globe suction and 19 ± 2 vs. 9 ± 2 seconds for cutting) for completion of the procedure.

CONCLUSIONS. The authors describe an accurate and reliable setup to measure and record in vivo real-time changes in IOP measurement from the anterior chamber during laser surgery. Femtosecond laser flap creation exerts less extreme IOP fluctuations with improved chamber stability but requires more procedure time than does microkeratome.

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the microscope but not lifted. The flap was then inspected under using forward and reverse pedals. After flap formation, the vacuum was released, and the ring was removed. The flap was then inspected under the microscope.

Microkeratome dissection was performed in a similar fashion. The eye, and adequate suction was confirmed by a sudden and constant rise in IOP as measured by our intracameral device. Microkeratome dissection was performed with the microkeratome by one surgeon (JSM). Pressure measurements were obtained with a transducer. The transducer was calibrated before each flap creation to ensure that the IOP was accurate. To ensure the transducer was working accurately, after cannulation of the anterior chamber, IOP measurements were also taken with a tonometer (Tono-Pen; Reichert-Jung, Depew, NY) before the experiment was begun (Fig. 2). For the microkeratome and femtosecond groups, the suction ring was applied over the sclera after the insertion of the cannula into the anterior chamber of the eye. During the procedure, the IOP was recorded continuously with the amplifier from the time of the application of suction through to the end of the microkeratome pass.

FIGURE 1. Setup for corneal flap creation and measurement of IOP in anesthetized rabbit eye using the femtosecond laser and the microkeratome. (A) Insertion of a 30-gauge needle through the limbus into the anterior chamber. (B) Setup for the IOP recording to the transducer. (C) Corneal flap created with the femtosecond laser and the suction ring. (D) Microkeratome blade setting for the corneal flap creation with the needle inserted into the anterior chamber.

Intraocular Pressure Measurements

IOP was measured in the anterior chamber using a 30-gauge winged infusion cannula that was inserted through the limbus so that the suction ring could be applied over the sclera without dislodging the cannula. Pressure measurements were obtained with a transducer. The transducer was prepared according to the instructions of the manufacturer to ensure that the seal was tight and that all air was flushed from the system. The transducer was calibrated before each flap creation to ensure that the IOP was accurate. To ensure the transducer was working accurately, after cannulation of the anterior chamber, IOP measurements were also taken with a tonometer (Tono-Pen; Reichert-Jung, Depew, NY) before the experiment was begun (Fig. 2). For the microkeratome and femtosecond groups, the suction ring was applied over the sclera after the insertion of the cannula into the anterior chamber of the eye. During the procedure, the IOP was recorded continuously with the amplifier from the time of the application of suction through to the end of the microkeratome pass.

Statistical Analysis

Data are expressed as mean ± SEM. Statistical comparison of multiple group data was performed using one-way analysis of variance (ANOVA) with Newman-Keuls test where applicable. Statistical analyses between the microkeratome and femtosecond groups comparing the IOP variations with suction on, globe suction, cutting, and suction off during LASIK flap creation were performed with the Student’s t-test. P < 0.05 was considered statistically significant.

RESULTS

In vivo real-time IOP profiles were successfully measured intracameral in all eyes of 13 rabbits during the different stages of LASIK flap creation using either the microkeratome or the femtosecond laser. Under either condition, we observed a steep rise in IOP levels throughout the surgery (P < 0.001). No complications were observed with the insertion of the catheter and the suction ring. No postoperative infections were documented.

In the microkeratome group, the mean IOP before flap creation (baseline IOP) as measured with an intracameral catheter was 13.45 ± 1.65 mm Hg, which increased significantly up to 141.02 ± 20.46 mm Hg during cutting. Pressure was maintained at a mean high value of 89.30 ± 12.15 mm Hg until the suction was removed (Fig. 3). In contrast, the femtosecond group showed a more stable and subtle increase in mean IOP values during the entire LASIK flap creation procedure (Fig. 3). Mean IOP values at baseline level and during the application of suction were 16.47 ± 1.27 mm Hg and 73.11 ± 10.0 mm Hg, respectively. During globe suction and cutting of the corneal flap, IOP levels remained steady (81.78 ± 6.55 mm Hg and 62.25 ± 3.28 mm Hg, respectively) and decreased to 41.40 ± 2.99 mm Hg when the suction was removed.

Although the two groups showed similar patterns of fluctuation in the IOP levels recorded in each stage of corneal flap

FIGURE 2. Correlation between in vivo IOP and tonometer IOP measurements showing good correlation (r = 0.94) between the two devices before commencement of the flap formation.
creation, there were clear differences in several respects. Corneal flaps made with the microkeratome showed significantly high IOP values at globe suction \( (P = 0.035) \), cutting \( (P = 0.0009) \), and suction off \( (P = 0.0008) \) stages compared with the femtosecond group. The IOPs recorded in all animal eyes during the study—preoperative, globe suction, cutting, and suction off—in the microkeratome and femtosecond groups are depicted in Figures 4A and 4B. Individual IOP changes observed from application of the suction ring to the end of the flap creation ranged from 34 to 53 to 100 to 179 mm Hg in the microkeratome group compared with 21 to 76 to 126 mm Hg in the femtosecond group.

The mean total time required for the corneal flap procedure in the femtosecond group was 38 \( \pm \) 2 seconds, approximately twofold higher than the mean time of 19 \( \pm \) 2 seconds observed in the microkeratome group \( (P = 0.0001; \text{ Fig. 5}) \). The mean time required for globe suction was 19 \( \pm \) 2 seconds in the femtosecond group, approximately twofold higher than the 10 \( \pm \) 2 seconds observed in the microkeratome group \( (P = 0.0009) \). Similarly, the mean time required for cutting was 19 \( \pm \) 2 seconds in the femtosecond group, approximately twofold higher than the 9 \( \pm \) 2 seconds observed in the microkeratome group \( (P = 0.0001) \).

**DISCUSSION**

In the present study, we provided a method to successfully measure in vivo real-time IOP in a rabbit model undergoing LASIK flap creation. During the entire surgical procedure of corneal flap creation, there was an initial surge in IOP levels as the suction ring was placed that persisted during globe suction and cutting and later subsided to baseline presurgery levels. In this study, we also compared IOP variations observed during the different stages of surgery, including the time required for the entire procedure using the two major forms of flap creation, namely a microkeratome or a femtosecond laser. There were differences both in the procedure time and in the real-time IOP surge observed in both the groups with a very different pattern.

Increased intraocular pressure is considered one of the major risk factors for the development, progression, and evaluation of glaucoma. Little is known about the potential long-term damage to the eye caused by the sudden spike in IOP observed during surgery.\(^{12,15-17}\) At present, no clinical technique is available to monitor in vivo IOP fluctuations during LASIK surgery. Two previous studies have investigated the IOP changes during LASIK using animal\(^ {24} \) and human cadaveric eye\(^ {25} \) models.

These studies had weaknesses in their designs and in their IOP measurement methods. First, they were performed on enucleated eyes, and IOP was achieved by infusion of a glycosylated solution. Second, the IOP measurements were made by inserting an intravenous pressure sensor into the vitreous cavity through a pars plana incision. Therefore, these studies did not represent actual IOP because the pressure was transmitted in a fluid-filled tube that was dependent on fluid viscosity and thus did not represent the true values based on IOP measured directly in the anterior chamber. Recently, Hernandez-Verdejo et al.\(^ {23} \) reported real-time measurement of IOP changes on enucleated porcine eyes during LASIK flap creation with a reusable blood pressure transducer connected to the anterior chamber by direct cannulation. Although this study added insight into IOP measurements during LASIK, it lacked the response of a living biological system in vivo during surgery.

In the present study, we measured in vivo real-time IOP variations in a rabbit model using microneedle cannulations of the anterior chamber under general anesthesia and compared the corneal flaps made with the two most commonly used techniques in the LASIK field, the microkeratome and the femtosecond laser. Both groups of eyes showed significant spikes in IOP levels as soon as suction was applied. This sudden spike in IOP levels during LASIK may induce perma-
ment changes in the posterior segment of the eye. Complications including retinal tears,\textsuperscript{15} retinal detachments,\textsuperscript{16,17} optic neuropathy,\textsuperscript{18} macular holes,\textsuperscript{19} and choroidal neovascular membranes\textsuperscript{20} have been reported. Nonarteritic ischemic optic neuropathy\textsuperscript{26} and visual field loss\textsuperscript{27} after LASIK have been attributed to the sudden surge in IOP levels caused by the suction ring placed during surgery.

The maximal IOP differences comparing the two groups were observed during the globe suction and cutting stages; the mechanical microkeratome group showed more than a twofold increase in IOP values than the femtosecond laser group, which theoretically would put eyes at higher risk for the posterior segment complications described here. We also observed that the corneal flaps made with the femtosecond laser facilitated more stable and lower IOP than with the surge and irregular pattern observed in the microkeratome group. During LASIK, a lamellar flap is made using a microkeratome blade or a femtosecond laser, followed by intrastromal ablation with an excimer laser. Stabilization of the cornea by a suction ring placed just before the limbus is a prerequisite. This helps to suck the anterior segment into a vacuum device, firming the cornea to obtain a consistent flap of optimal thickness. A transient increase in IOP induced during globe suction contracts the anterior segment rapidly, which results in anterior-posterior compression and expansion of the globe. These events may cause extreme damage to the eye along the anterior-posterior axis and may result in the development of peripheral retinal tears\textsuperscript{10,11} or macular disease.\textsuperscript{15}

The mean procedure time required for globe suction and cutting by femtosecond laser is twice that required for the microkeratome-created flaps, putting into question the superiority of the corneal flaps made with the former technique. The longer precut suction time can be attributed to the mechanism by which the femtosecond laser achieves suction and can vary depending on the contact between patient interface and corneal surface during surgery. Similar observations have been made in enucleated pig eyes.\textsuperscript{25} At present, it is not possible to predict what is better for the eye—a longer and more stable IOP increase during LASIK, as observed with the femtosecond laser, or a shorter but higher surge obtained during the microkeratome cut. However, newer upgrades, such as the 500-kHz femtosecond laser (VisuMax; Carl Zeiss Meditec), enable LASIK flap creation at twice the speed of the laser used in our study. We now use the 500-kHz femtosecond laser from Carl Zeiss Meditec (VisuMax) clinically and complete the flap cutting procedure in 17 seconds, even shorter than the 19 seconds with the microkeratome. Results regarding the durations of different stages were statistically different, but the relevance of such parameters requires further investigation. Ultimately, faster lasers, such as the 500-kHz femtosecond laser from Carl Zeiss Meditec (VisuMax), will resolve this issue.

A limitation of our study was that we used a rabbit model instead of a primate model because the rabbit cornea is biomechanically more unstable and the anterior chamber is shallower than that of the human.\textsuperscript{24} Hence, the rabbit cornea may be more susceptible to changes induced by raised IOP. The age of the rabbit will also have an effect on the biomechanical properties of the rabbit cornea. To minimize this effect, we performed a paired eye study so that the effects of age and biomechanical variation were minimized. The present study could have been strengthened if we had been able to make comparisons with other commercially available femtosecond lasers used for LASIK (e.g., Intralase [Abbott Medical Products, Abbott Park, IL], LDV [Ziemer, Port, Switzerland]). However, we did not have access to these lasers for animal experimentation, and the aim of our study was to examine the IOP variations in the new-generation, low-pressure femtosecond lasers.

In vivo intraocular pressure measurement during LASIK is not practiced in clinics around the world. This may be partially attributed to the lack of instruments measuring precise and accurate IOP levels with greater reproducibility. Our study corroborates our clinical experience with the Carl Zeiss Meditec laser (VisuMax), during which patients do not experience a blackout in vision during flap creation. They are able to fixate for 90% of the procedure, indicating the pressure increase must be lower than the retinal arterial pressure. This is different from microkeratome flap creation in which patients experience complete blackout. Our present findings suggest that further improvements and studies are required to evaluate the long-term impact of IOP spikes during LASIK, and they highlight the importance of in vivo real-time IOP measurements during developments to improve the safety of contemporary LASIK surgery.

**References**


