Porcine Model to Compare Real-Time Intraocular Pressure during LASIK with a Mechanical Microkeratome and Femtosecond Laser

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Purpose. To compare real-time intraocular pressure (IOP) during laser in situ keratomileusis (LASIK) in porcine eyes using two types of microkeratomes.

Methods. An interventional, prospective study of two microkeratomes: a Moria 2 (Moria group) and an IntraLase femtosecond laser (IntraLase Corp., Irvine, CA; IntraLase group). These devices were used to create lamellar corneal flaps in freshly enucleated porcine eyes. The IOP changes induced by the procedures were recorded with a reusable blood pressure transducer connected to the anterior chamber by direct cannulation.

Results. Seven porcine eyes were studied in each group. The IOP increased during the suctioning phase, reaching a mean of 122.52 ± 30.40 and 160.52 ± 22.73 mm Hg during the cutting phase in the Moria group (the total time in this group was 36.42 ± 7.48 seconds; suctioning required 21.42 ± 7.48 seconds and the cutting phase, 15 ± 2.88 seconds). In the IntraLase group, the IOP reached 89.24 ± 24.26 mm Hg during the suctioning phase and 119.33 ± 15.88 mm Hg during the intrastromal laser application (the total time was 92.85 ± 13.49 seconds; suctioning required 40.00 ± 9.57 seconds and the cutting phase 52.85 ± 5.66 seconds). Both IOPs during both phases differed significantly between the two groups ($P = 0.01$ for all comparisons).

Conclusions. Real-time IOP can be measured during LASIK using a transducer connected to the anterior chamber. The results showed a significant increase in IOP during the procedure in both groups, although with the IntraLase the IOP seemed to increase to a lesser extent than with the conventional mechanical microkeratome. (*Invest Ophthalmol Vis Sci.* 2007;48:68–72) DOI:10.1167/iovs.06-0192

Laser in situ keratomileusis (LASIK) has become the most frequently performed corneal refractive surgery for the correction of low to moderate myopia. The procedure involves preparation of a superficial flap by using a mechanical keratome and ablation of the corneal stromal tissue with an excimer laser.[1]

Femtosecond laser technology enables nonmechanical creation of a corneal flap.[2–4] This technology includes a solid-state laser used to create flaps during LASIK. The laser uses an infrared wavelength (1053 nm) to deliver closely spaced 3-μm spots that can be focused to a preset depth to photodisrupt tissue within the corneal stroma. The resultant plasma produces cavitation bubbles, consisting primarily of water and carbon dioxide. The IntraLase femtosecond laser system (IntraLase, Corp., Irvine, CA) relies on a low-pressure (35 mm Hg) suction ring to align and stabilize the globe. A flat lens attached to the laser delivery system is used to applanate the cornea within the suction ring. To create the ideal corneal flap during LASIK, sufficiently high intraocular pressure (IOP) is needed to manage the eye.

Two different ways to measure IOP during corneal refractive surgery have been proposed; both have some drawbacks. Applanation tonometry cannot be performed when the microkeratome is cutting the flap. In addition, the viscosity of the vitreous gel may jeopardize IOP measurement in direct cannulation of the vitreous cavity.[5–7] For this reason, we recorded the real-time IOP by direct cannulation into the anterior chamber, to obtain accurate IOP measurements during LASIK.

The real intraoperative IOP that is achieved during the suctioning and the cutting phases and the differences in IOP that can occur if the flap is created with a mechanical keratome or with the IntraLase femtosecond laser have not been measured during surgery. High IOP and sudden changes in IOP may cause irreversible changes in ocular tissue.

The anterior segment complications of LASIK have been well documented in the literature.[8] In addition, there have been several reports proposing a casual relationship between LASIK and retinal detachments in myopic eyes[9–11]; macular hemorrhages, macular holes, lacquer cracks, and choroidal neovascular membranes developed after LASIK have also been reported.[12] Different hypotheses explain the posterior segment complications, with the first postulating that the mechanical stress is caused by the IOP elevation produced by the pneumatic suction ring, which may induce tangential stress on the posterior segment.[13] Some investigators have proposed that the shockwave generated by the impact of the excimer energy on the cornea can generate pressure of up to 100 atmospheres, which also causes mechanical stress on the eye.[14] Acute damage to the optic nerve after LASIK has also been reported.[15]

Some case studies have reported that this increase in IOP damages the retinal ganglion cells, causing visual field defects.[16] Other studies have reported that the retinal nerve fiber layer thickness decreases after uncomplicated LASIK[17,18] or even that LASIK could cause occlusion of the retinal arteries.[19]

To the best of our knowledge, there are no published studies of the real-time IOP changes during a femtosecond laser procedure compared with IOP changes induced during a conventional mechanical LASIK procedure, especially when the IOP is measured via the anterior chamber.

The purposes of this study were to develop an experimental model to measure real IOP changes using an external manometer connected to the anterior chamber and then to compare these changes when using two well-known methods, a mechanical keratome and low-pressure IntraLase technology, to perform LASIK.

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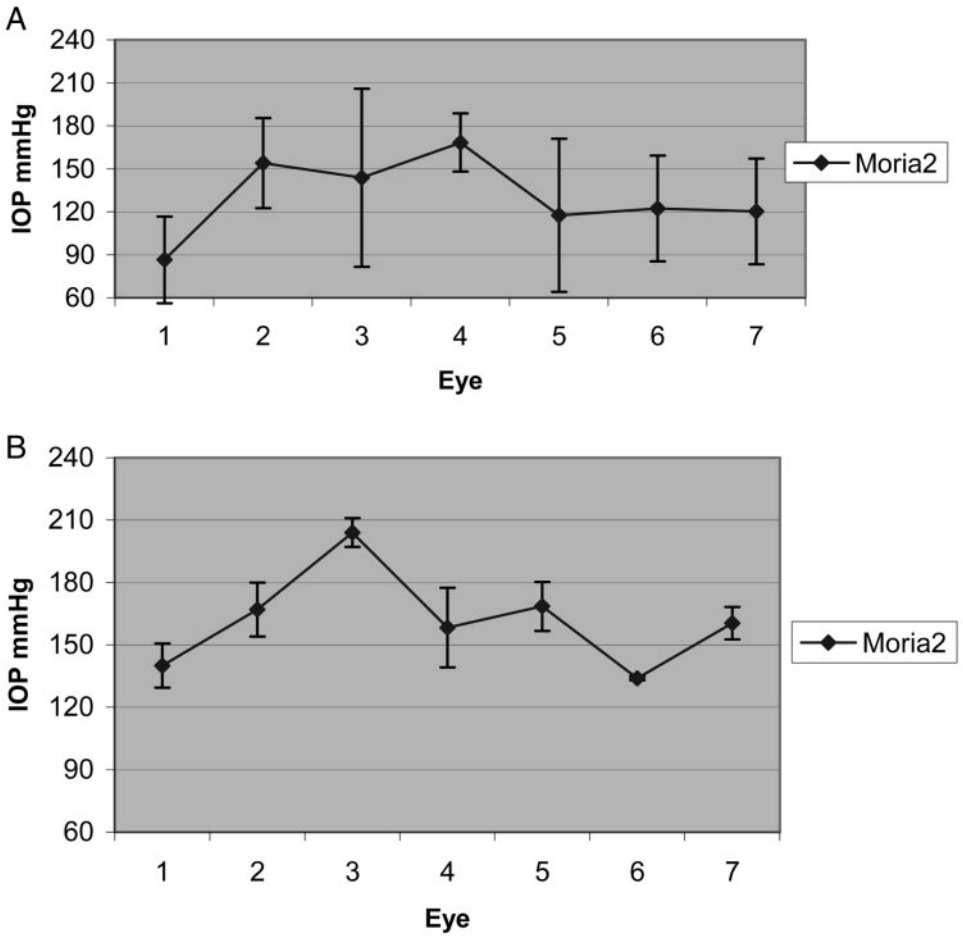

FIGURE 1. Mean IOP ± SD in each eye in the Moria group during the suctioning (**A**) and cutting (**B**) phases. IOPs were recorded every 5 seconds from the exact moment that the suction ring was applied. The mean time was 21.42 ± 7.48 seconds in the suctioning phase and 15.00 ± 2.88 seconds in the cutting phase.

MATERIALS AND METHODS

In this experimental model, using porcine eyes, we prospectively evaluated the changes in IOP from the application of the suction ring through the end of the passage of the mechanical microkeratome (M2; Moria, Antony, France) or creation of the nonmechanical flap with the femtosecond laser (IntraLase Corp., Irvine, CA).

Fourteen freshly enucleated porcine eyes were separated into two groups of seven eyes each: the Moria group and the IntraLase group. All eyes were free of corneal damage when inspected by slit lamp microscopy.

The eyes were inflated with a 5% glycosylated solution through the optic nerve (in the same manner described by Kasetsuwan et al.[6]) to obtain an IOP of 8 to 20 mm Hg checked with a Perkins applanation tonometer; the eyes were placed on a stand with sufficient support to withstand the surgical procedure. The IOP was measured in the anterior chamber using a 27-gauge winged infusion (Set REF 387412 Valu-Set BD Biosciences, Hull, UK) that was inserted through the limbus in such a way that the suction ring could be applied over the sclera without touching the needle. Pressure measurements were obtained with a reusable blood pressure transducer (MLT0380 Reusable BP Transducer, Power Laboratory; AD Instruments, Racine, WI). The transducer is an external sensor for coupling to vascular pressure (in our experiment the IOP in the anterior chamber) via a liquid-filled catheter. A saline-filled silicone tube attached to the catheter was connected to the transducer. The transducer was prepared according to the instructions of the manufacturer, to assure a tight seal and that all air was flushed from the system. The recorder was set to 0 to initialize the transducer. Before starting the procedure, the transducer was checked to verify that the pressure would be registered correctly. For calibration, we connected the transducer to a mercury-calibrated column and then checked that the pressure in the mercury column and the display connected to the transducer were the same.

The suction ring was applied, and a flap was created in the eyes in both groups. The same experienced surgeon (JMR) performed all procedures on 1 day under direct microscopy visualization. During the procedure, the IOP was recorded continuously with the amplifier (ML110 Bridge Amplifier; AD Instruments, Castle Hill, Australia) connected to the barometric transducer, from the time of the application of the suction ring through the end of the microkeratome pass. IOP also was measured before and after the suction ring was placed, by using a Perkins handheld tonometer (Clement Clarke, Essex, UK). The IOP level after the procedure had to be at least 6 mm Hg, to rule out any substantial fluid leakage from the eye during the experiment,

Statistical analysis was performed using Student's *t*-test and the nonparametric Wilcoxon signed-rank test. $P < 0.05$ was considered significant.

RESULTS

Seven porcine eyes were studied in each group. In the Moria group, the mean IOP during suction was 122.52 ± 30.40 mm Hg (Fig. 1A) compared with 89.24 ± 24.26 mm Hg in the IntraLase group ($P = 0.001$). During flap creation, the mean IOP was 160.52 ± 22.73 mm Hg in the Moria group (Fig. 2A) compared with 119.33 ± 15.88 mm Hg in the IntraLase Group (Fig. 2B; $P = 0.001$).

The actual IOP immediately before suctioning was 11.5 ± 3.43 mm Hg ($r = 8$–16) in the IntraLase group and 17.28 ± 3.25 mm Hg ($r = 11$–20) in the Moria group. The IOP recorded by the transducer immediately after the maneuvers was 8.85 ±

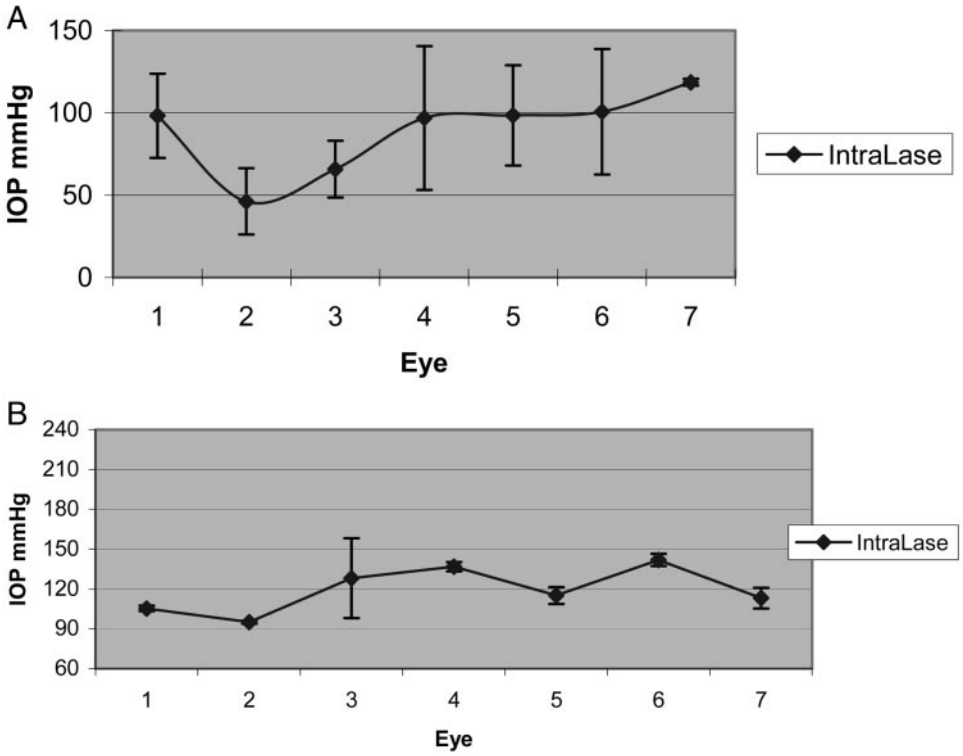

FIGURE 2. Mean IOP ± SD in each eye in the IntraLase group during the suctioning (**A**) and cutting (**B**) phases. The IOP was recorded every 5 seconds from the exact moment that the suction ring was applied. The mean time was 40 ± 9.57 seconds in the suctioning phase and 52.85 ± 5.66 seconds in the cutting phase.

2.11 mm Hg (r = 7 to 12) in the IntraLase group and 13.71 ± 3.63 mm Hg (r = 7 to 18) in the Moria group.

The mean time required to complete the suctioning was 21.42 ± 7.48 seconds (range, 15–35 seconds) in the Moria group compared with a mean of 40 ± 9.57 seconds (range, 30–55 seconds) in the IntraLase group (P = 0.04). The mean time needed to create the flap was 15.00 ± 2.88 seconds (range, 15 to 20 seconds) in the Moria group compared with 52.85 ± 5.66 seconds (range, 50 to 65 seconds) in the IntraLase group (P = 0.008; Fig. 3, Tables 1B, 2B).

The total time needed to complete the procedure in the Moria group was 36.42 ± 7.48 seconds and in the IntraLase group was 92.85 ± 13.49 seconds. The IntraLase procedure took twice as long as the mechanical procedure (P = 0.001).

DISCUSSION

In this animal model, we measured the real IOP in enucleated porcine eyes with two suction and cutting procedures during LASIK. Both groups had an IOP increase immediately after the placement of the suction ring that was maintained during the entire surgical procedure. We found differences both in suction time and in the real IOP levels that were achieved in both groups.

Bissen-Miyajima et al.[5] measured the IOP changes during LASIK using a direct method in porcine eyes. In that experiment, an intravenous pressure sensor was inserted into the vitreous cavity, whereas in our study the sensor was introduced into the anterior chamber. Despite this design difference, the study performed by those investigators showed a mean IOP increase of 99.1 ± 6.1 mm Hg, measured by a single-port suction ring and 99.0 ± 6.5 mm Hg using a dual-port suction ring during mechanical microkeratome use. In another study performed in human cadaveric eyes,[6] the measurements were obtained by entering the vitreous cavity through a pars plana incision. The results at two vacuum-pressure settings (488 and 600 mm Hg) after application of the suction ring alone were 93.3 ± 2.6 mm Hg for the 488-mm Hg

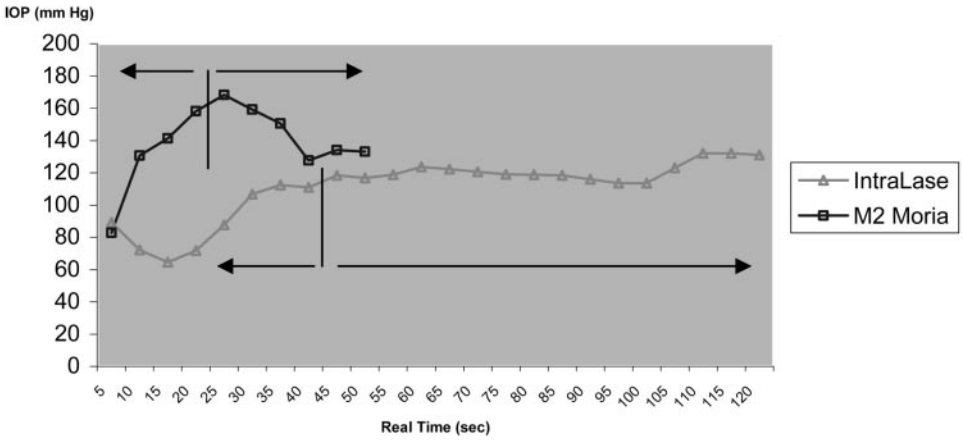

FIGURE 3. IOP increases in mm Hg over time, measured every 5 seconds, in both groups of seven eyes each, in the Moria mechanical microkeratome group and the IntraLase group. *Vertical lines*: the exact moment at which the cutting began. Suction time, 21.42 ± 7.48 seconds in the Moria group and 40 ± 9.57 seconds in the IntraLase group; cutting or flap time, 15.00 ± 2.88 seconds in the Moria group and 52.85 ± 5.66 seconds in the IntraLase Group.

TABLE 1. Moria Group

A. IOP Increases in IOP in Each Eye from Application of the Suction Ring to the End of Flap Creation

Eye	Mean (mm Hg)	SD	Range
1	106.5	±36.39	40–148
2	160.5	±22.66	120–182
3	173.83	±51.52	72–208
4	161.67	±21.52	127–182
5	140.75	±52.94	60–219
6	125.8	±30.61	47–147
7	131.71	±36.09	62–166

B. IOPs Recorded during the Study

Eye	IOP Pre	IOP Suction	IOP Cut	IOP Post	Suction Time (s)*	Cutting Time (s)*
1	15	86.4	140	11	25	15
2	20	154	167	14	15	15
3	20	89	204	16	15	15
4	18	168.3	155	15	15	15
5	11	117.5	164	7	20	20
6	18	122.28	134	15	35	15
7	19	120.2	159.66	18	25	10
Mean	17.28	122.52	160.52	13.71	21.42	15
SD	3.25	30.4	22.73	3.63	7.48	2.88

Initial IOP (IOP pre), mean IOP (in mm Hg) of the suctioning phase (IOP Suction), mean IOP of the cutting phase (IOP Cut), and final IOP (IOP Post) immediately after the cutting phase for each of the seven eyes.

* The two columns on the right show the suctioning and cutting time for each eye expressed as the mean ± SD.

group and 108.0 ± 22.1 mm Hg for the 600-mm Hg group; during the microkeratome pass, the mean IOP was 82.0 ± 15.0 mm Hg for the 488-mm Hg group and 92.5 ± 38.8 mm Hg for the 600-mm Hg group. The pressure changes during the microkeratome pass were not statistically significant. The lower levels of IOP found in those two studies may reflect the fact that the velocity at which the pressure is transmitted in a fluid-filled tube depends on the fluid viscosity, and it therefore seems reasonable to consider that the measurements registered through the anterior chamber, as in the present study, should be more precise than those obtained through the vitreous chamber.

In our study, the IOP increased in both groups, although it followed a different pattern. For example, in the Moria group, the mean IOP increase during suctioning was 122.53 ± 30.40 mm Hg and reached a mean 160.52 ± 22.73 mm Hg during the creation of the lamellar corneal flap. We also observed a great deal of fluctuation in the IOP levels. However, in the IntraLase group, the mean IOP during suctioning was 89.24 ± 24.57 and 119.0 ± 17.01 mm Hg during the flap creation. In this case, the

TABLE 2. IntraLase Group

A. IOP Increases in IOP in Each Eye from Application of the Suction Ring to the End of Flap Creation

Eye	Mean (mm Hg)	SD	Range
1	101.75	±18.02	(59–129)
2	76.69	±35.72	(34–114)
3	99.54	±33.84	(36–132)
4	109.06	±35	(45–160)
5	107.72	±21.54	(70–141)
6	127.35	±30.1	(72–157)
7	115.35	±3.18	(112–122)

B. IOPs Recorded during the Study

Eye	IOP Pre	IOP Suction	IOP Cut	IOP Post	Suction Time (s)*	Cut Time (s)*
1	13	98.2	105.3	11	50	50
2	9	46.16	95	9	30	50
3	8	65.72	128.15	6	55	65
4	8	96.87	136.8	7	40	50
5	15	98.5	115.1	9	40	50
6	16	100.66	141.9	12	30	55
7	9	118.57	113.1	8	35	50
Mean	11.5	89.24	119.33	8.85	40	52.85
SD	3.43	24.26	15.88	2.11	9.57	5.66

The initial IOP (in mm Hg; IOP Pre), mean IOP of the suctioning phase (IOP Suction), mean IOP of the cutting phase (IOP Cut), and the final IOP (IOP Post) immediately after the cutting phase for the seven eyes.

* The two columns to the right show the suctioning and cutting time for each eye expressed as the mean and standard deviation.

IOP increase was more stable throughout the procedure, especially during the cutting of the flap.

Previous studies have reported that the LASIK flap may induce higher-order aberrations (HOAs) and advocate the use of photorefractive keratectomy for wavefront-guided treatments.[20] Recently, Durrie and Kezirian[21] reported that the IntraLase femtosecond laser induces fewer HOAs, less residual spherical equivalent, and less residual astigmatism, and has better predictability than does photorefractive keratectomy. Kasetsuwan et al.[6] showed that the pressure setting for the suction ring is an important variable in determining consistent corneal flap thickness during LASIK. An interesting aspect of our study was that the IOP levels achieved during the IntraLase procedure were lower and more stable than those achieved when creating a flap with a mechanical microkeratome.

Sudden increases in IOP, although well tolerated, may induce changes in the peripheral retina, as described by Charteris et al.,[10] Krueger et al.,[14] and Flaxel et al.[13] These possible posterior segment complications, among others, make the knowledge of the exact IOP increase induced by surgical procedures such as laser refractive surgery increasingly important.

In our experiment, the IntraLase group had lower IOP increases, although the time needed for the surgical maneuver was almost twice that of the Moria group. It would be interesting to determine which of these factors is more reliable for ocular safety, the time for which the eye is subjected to increased IOP levels or simply the level of the IOP.

There are limitations when using enucleated porcine eyes, because the corneas, although freshly enucleated, were slightly edematous and because the IOP was achieved by an infusion of a glycosylated solution. Clearly, further research is needed in this field.

Real-time IOP can be measured during LASIK with a transducer connected to the anterior chamber. Our results showed a significant increase in IOP during the procedure in both groups, although IntraLase seems to increase the IOP to a significantly lesser extent than does the conventional mechanical microkeratome.

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