Intraocular pressure during phacoemulsification

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PURPOSE: To assess changes in intraocular pressure (IOP) during standard coaxial or bimanual microincision phacoemulsification.

SETTING: Oregon Eye Center, Eugene, Oregon, USA.

METHODS: Bimanual microincision phacoemulsification (microphaco) was performed in 3 cadaver eyes, and standard coaxial phacoemulsification was performed in 1 cadaver eye. A pressure transducer placed in the vitreous cavity recorded IOP at 100 readings per second. The phacoemulsification procedure was broken down into 8 stages, and mean IOP was calculated across each stage. Intraocular pressure was measured during bimanual microphaco through 2 different incision sizes and with and without the Cruise Control (Staar Surgical) connected to the aspiration line.

RESULTS: Intraocular pressure exceeded 60 mm Hg (retinal perfusion pressure) during both standard coaxial and bimanual microphaco procedures. The highest IOP occurred during hydrodissection, ophthalmic viscosurgical device injection, and intraocular lens insertion. For the 8 stages of the phacoemulsification procedure delineated in this study, IOP was lower for at least 1 of the bimanual microphaco eyes compared with the standard coaxial phaco eye in 4 of the stages (hydro steps, nuclear disassembly, irritation/aspiration, anterior chamber reformation).

CONCLUSION: There was no consistent difference in IOP between the bimanual microphaco eyes and the eye that had standard coaxial phacoemulsification. Bimanual microincision phacoemulsification appears to be as safe as standard small incision phacoemulsification with regard to IOP.

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Bimanual microincision phacoemulsification, defined as cataract extraction through 2 incisions of less than 1.5 mm in maximum diameter, has gained popularity worldwide.[1] This procedure and its variants may soon become a new standard, particularly once intraocular lenses (IOLs) capable of insertion through these microincisions become more widely available. Bimanual microincision cataract surgery (MICS) has several advantages over routine small-incision coaxial phacoemulsification, including increased anterior chamber stability, enhanced followability, and complete access to all 360 degrees of the capsular bag.

One challenge of MICS has been designing instruments that provide an adequate rate of irrigation inflow. Inadequate irrigation results in anterior chamber instability and surge. Thus, surgeons have used maximally raised irrigation bottles and pressurized irrigation to maximize inflow. Increased inflow pressure carries with it the risk for elevated intraocular pressure (IOP) if outflow from the eye ceases, even transiently.

This study was designed to document IOP during the course of bimanual microincision phacoemulsification in human cadaver eyes. The pressure fluctuations and maximum IOP were compared with those in coaxial phacoemulsification.

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MATERIALS AND METHODS

The fluid pressure at the base of a column of water can be calculated (in millimeters of mercury, at standard atmospheric pressure) using the following equation:

$$\text{Pressure (mm Hg)} = \text{Column height (cm)} \times 10/13.6$$

where the density of mercury is 13.6 g/cm^3 and the density of water is 1 g/cm^3.

Bimanual microincision phacoemulsification was performed in a series of intact cadaver eyes using the Advanced Medical Optics (AMO) Sovereign phacoemulsification machine with 20-gauge Duet irrigation (MicroSurgical Technology) and phaco tips. Intraocular pressure recordings were made using a pressure transducer (ultra-miniature 3.5F/1.145 mm, single pressure sensor, intravascular Mikro-Tip catheter, Millar Instruments, Inc.) located in the vitreous cavity (Figure 1), connected to a PowerLab 4/25 data acquisition system (ADInstruments) recording 100 pressure readings each second to an IBM ThinkPad T41 notebook computer (International Business Machines). The Chart 5.1 software accompanying the PowerLab system allowed automatic calculation of various parameters of the pressure values for any selected time segment of recorded data, including the mean, standard deviation, maxima and minima, and the peak–peak average (P–P average), which allowed these values to be generated automatically for any segment of the phacoemulsification procedure. Another value automatically obtained from the recording was the cumulative time that the IOP was greater than any defined IOP level. For this study, this level was set at 60 mm Hg. The transducer was multipoint calibrated at the start of each case to 4 readings at 10, 20, 50, and 100 mm Hg on a mercury manometer, as allowed by the software.

The study involved 4 eyes. Three eyes had bimanual surgery. The fourth eye had coaxial phacoemulsification through a 2.5 mm incision made with the Rhein 3D 2.5 mm to 3.5 mm diamond blade (Rhein Medical Inc). Of the 3 bimanual eyes 2 (eyes 1 and 2) had the paracentesis incisions made with the Paratrap 0.7 mm to 1.2 mm diamond blade (Mastel Precision Instruments); the third (eye 3) had incisions made using the MST 1.4 mm to 1.6 mm steel blade (MicroSurgical Technology) to assess the effect of incision size and resultant incisional outflow on IOP. One of the bimanual eyes (eye 2) with the Paratrap paracentesis incisions had Cruise Control (Staar Surgical) connected to the aspiration line of the phaco handpiece to assess its effect on chamber stability and surge control. Postocclusion surge (POS) simulation was performed in each eye at the end of nuclear disassembly and before cortical cleanup by having the aspiration tubing of the phacoemulsification handpiece manually kinked and completely occluded while the vacuum built up to the preset maximum (350 mm Hg). After the vacuum level was reached for 5 seconds, the kink in the aspiration tubing was suddenly and totally relieved. If no unacceptable chamber fluctuation occurred, the bottle pole height was lowered 5 cm at a time until unacceptable surge occurred. This pole height and the height of fluid column above the eye were recorded. Unacceptable chamber fluctuation was defined as any movement of the posterior capsule toward the cornea during surge. Bimanual nuclear disassembly and irrigation/aspiration (I/A) were performed with the bottle height set at 75 cm on the machine with a 30 cm pole extension (105 cm). Coaxial nuclear disassembly and (I/A) used a bottle height setting of 60 + 30 cm extension (90 cm). The eye with the Cruise Control had the device taken off after the first round of POS testing and was subjected to a second round of POS testing without the Cruise Control in place to assess the contribution made by the device in the reduction of surge.

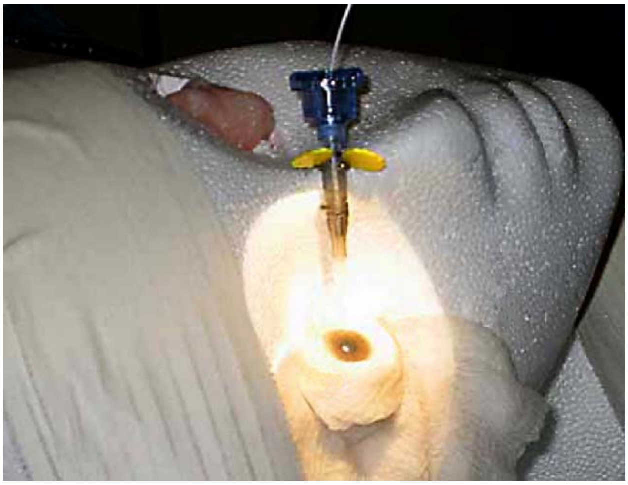

Figure 1. Setup of the vitreous pressure transducer. The transducer is located in the vitreous cavity at the tip of the catheter wire.

The static IOP was measured at the working bottle height at the start of the phacoemulsification procedure to determine whether this correlated with the theoretical IOP, based on the bottle height set. The actual column height of balanced salt solution (BSS) was measured in each case, and the expected working IOP was mathematically calculated. The actual measured IOP was expected to vary from this theoretical value because of incisional outflow, with the actual value being lower than the theoretical IOP.

Phacoemulsification proceeded as usual, and a recording of dynamic pressure changes occurring throughout the procedure. Analysis of the data concentrated on the changes occurring at specific points during the procedure, as follows:

- filling of the anterior chamber with an ophthalmic viscosurgical devices (OVD) (hyaluronate 3.0% [Vitrax]);
- hydrodissection and hydrodelineation;
- nuclear disassembly with a chopping method;
- cortical cleanup; IOL injection using the AMO Clariflex (22.0 D) with the AMO Unfolder Silver cartridge system; hydration of the corneal wound; reformation of the anterior chamber with BSS; final IOP at the conclusion of surgery, with the surgeon aiming for a tension of around 30 mm Hg

Nuclear density was noted at hydrodissection and hydrodelineation, and this was recorded on a scale of 1+ to 4+. The identical sequence of surgical steps was followed in all 4 eyes in the study, except for the coaxial eye, in which the incision size was necessarily different and a single left-handed paracentesis was created.

RESULTS

Static IOP Correlation with Theoretical IOP

There was good agreement between the static IOP and theoretical IOP except in the eye with the MST 1.4 mm to

1.6 mm paracentesis incisions (Table 1). The static IOP came close (89.9% to 94.9%) to the theoretical IOP based on BSS column height. In the Paratrap eye without Cruise Control, the static IOP reached 98.3 mm Hg instead of the theoretical 109.3 mm Hg, whereas in the Paratrap eye with Cruise Control, it reached 100.1 mm Hg instead of 105.5 mm Hg. In the eye with 1.4 mm to 1.6 mm incisions, the static IOP was 53.0% (55.0 mm Hg instead of 103.7 mm Hg) of the theoretical IOP. Coaxial eye 4 had a lower steady IOP at 87.5 mm Hg (theoretical 96.2 mm Hg) than the other bimanual eyes with the Mastel Paratrap incisions because the set bottle height was 15 cm lower (equivalent to 11.0 mm Hg).

Pressure During Injection of OVD

Mean IOP during Vitrax injection was 42.7 mm Hg in the eye with a 1.0 mm paracentesis and 2.5 mm main incision. The mean pressure was 89.5 mm Hg in the 2 eyes with 2 Paratrap incisions and 163.0 mm Hg in the eye with the 2 MST 1.4 mm to 1.6 mm incisions.

Capsulorhexis

Pressures during capsulorhexis generally followed the pressures at the end of OVD injection. The mean pressure was 38.1 mm Hg in the coaxial eye, 87.5 mm Hg in the Paratrap eyes, and 107.2 mm Hg in the MST eye.

Hydrodissection

The mean pressure during the hydro steps ranged from a low of 78.6 mm Hg in 1 Paratrap microincision eyes to 223.2 mm Hg in the MST microincision eye. The coaxial eye, with a mean pressure of 111.5 mm Hg, did not have the lowest IOP.

Nuclear Disassembly (Phacoemulsification)

Peak pressures measured 66.1 to 196.6 mm Hg, whereas mean pressures varied between 39.9 and 94.3 mm Hg. The standard deviations ranged from 9.3 mm Hg to 20.6 mm Hg. An indication of the amount of pressure fluctuation during nuclear disassembly was given by the P–P average, which varied from 25.7 to 41.7 mm Hg.

Nuclear disassembly (phacoemulsification) made up the longest stage of the procedure, and the lowest mean pressure recorded during the time that the phaco needle was in the eyes occurred in the MST 1.4 mm to 1.6 mm incision eye. The mean pressure in the coaxial eye during phaco was 63.8 mm Hg; the average of the mean pressures in the Paratrap eyes was 91.2 mm Hg (Table 2).

Irrigation/Aspiration

The mean IOP was 55.3 mm Hg in the MST 1.4 mm to 1.6 mm eye and 85.2 mm Hg in the Paratrap eyes. The mean in the coaxial eye was 73.2 mm Hg.

Intraocular Lens Injection

For IOL injection in the Paratrap and MST 1.4 mm to 1.6 mm eyes, a fresh 2.5 mm incision was constructed. The mean pressure was 89.1 mm Hg in the coaxial eye and 121.7 mm Hg in the Paratrap eyes. In the MST 1.4 mm to 1.6 mm eye, it was 110.6 mm Hg.

Wound Hydration

The mean pressure was 9.0 mm Hg in the coaxial eye and 40.0 mm Hg in the Paratrap eyes. In the MST 1.4 mm to 1.6 mm eye, the mean IOP was 32.4 mm Hg.

Reformation of AC

The mean pressure was 47.6 mm Hg in the Paratrap eyes and 70.2 mm Hg in the coaxial eye. In the MST 1.4 mm to 1.6 mm eye, it was 60.9 mm Hg.

Final Pressure, Presumed 30 mm Hg

The tactile IOP, presumed by the surgeon to be 30 mm Hg in each case, varied from 41.8 to 73.2 mm Hg.

Table 1. Balanced salt solution column height and theoretical and measured static IOP in each eye.

	Eye 1 Biman-Paratrap—No Cruise Control	Eye 2 Biman-Paratrap—Cruise Control	Eye 3 Biman-MST 1.4–1.6—No Cruise Control	Eye 4 Coaxial—No Cruise Control
Measured column height (cm)	148.6	143.5	141.0	130.8
Theoretical static IOP (mm Hg)	109.3	105.5	103.7	96.2
Measured static IOP (mm Hg)	98.3	100.1	55.0	87.5
Measured vs theoretical IOP (%)	89.9	94.9	53.0	91.0

IOP = intraocular pressure

Table 2. Intraocular pressures (mm Hg) during nuclear disassembly (phacoemulsification) ex vivo.

	Eye 1 Biman-Paratrap—No Cruise Control	Eye 2 Biman-Paratrap—Cruise Control	Eye 3 Biman-MST 1.4–1.6—No Cruise Control	Eye 4 Coaxial—No Cruise Control
Nuclear disassembly	*196.6* 94.3 ± 14.8 38.8*	*158.8* 88.0 ± 20.6 41.7*	*66.1* 39.9 ± 9.3 25.7*	*100.6* 63.8 ± 16.0 36.0*

Figures in *italics* are maximum pressures recorded.
Numbers in normal font indicate mean ± SD.
*P–P average pressures representative of pressure fluctuations.

Proportion of Surgery Time During Which IOP Was Greater Than 60 mm Hg

The surgery was timed from the start of the data recording, which began once the transducer was placed in the vitreous cavity. The Chart 5.1 software was programmed to automatically calculate the amount of time the pressure was greater than 60 mm Hg in each eye. Procedure times from the start of recording to the end of the case ranged from 538.3 seconds (9 minutes) to 751.3 seconds (12.5 minutes). The proportion of time that the eyes had an IOP above 60 mm Hg ranged from 47.9% (328.4/686.2 seconds, eye 2, Paratrap) to 84.8% (557.6/657.3 seconds, eye 1, Paratrap).

Postocclusion Surge Simulation

The IOP drop during each episode of POS ranged from 60.9% to 72.3% in the eyes without Cruise Control. With Cruise Control, the mean IOP drop was 50.1%, with a corresponding absolute value of 40.7 mm Hg, whereas it was 59.5 mm Hg in eyes without Cruise Control. The pressure fluctuation during surge took place over a shorter time without Cruise Control, 0.07 to 0.10 seconds; it took 0.14 seconds with the device in place. This consequently caused the pressure change per unit time to be much greater in the eyes without Cruise Control, with a value from 565 to 911 mm Hg/s compared with 290.7 mmHg/s in the eye with the Cruise Control.

DISCUSSION

Intraocular pressure fluctuations during phacoemulsification surgery have not been studied in intact human eyes, although the pressure changes during simulated postocclusion surge have been studied in the phaco test chamber.[2,3] With the advent of bimanual microincision phacoemulsification through incisions smaller than 1.5 mm, new problems and challenges have arisen. Smaller incisions require smaller irrigating tips and phaco needles. These can potentially reduce efficiency, unless high vacuum levels are used. High vacuum in conjunction with the smaller bore irrigators necessary for microincision phaco may lead to chamber instability if the balance between inflow and outflow is upset. Increased infusion pressure by way of increased bottle height or forced infusion has been necessary to avoid unacceptable anterior chamber fluctuations. One potential drawback has been theoretically higher pressures maintained during these surgical procedures, especially in eyes with compromised optic nerves, such as glaucomatous eyes.

The static IOP in the eyes was very close (90% to 95%) to the theoretical value, except in the bimanual eye with larger paracentesis incisions (MST 1.4 to 1.6). In this eye, the IOP was about 50% of the theoretical value based on the fluid column height. This was likely due to the much greater amount of incisional outflow from the 2 larger incisions. These incisions measured 1.6 mm on the Deacon-Steinert incision gauge compared with 1.2 mm to 1.3 mm with the Paratrap 0.7 to 1.2 knife. The chamber stability during nuclear disassembly did not seem compromised by using the larger blade.

In the coaxial eye, the static IOP was 91% of the theoretical IOP. This was most likely because there was little incisional outflow with a 2.5 mm incision with adequate sealing of the wound enhanced by the silicone sleeve. AMO recommends a 2.65 mm to 2.75 mm incision with the 20-gauge sleeved tip.

The pressures recorded during this study were generally higher than expected. Hydrodissection peak pressures in particular exceeded 400 mm Hg (Figure 2) in eyes 1 and 3, whereas the means in these 2 eyes were in excess of 150 mm Hg. Even the coaxial eye (eye 4) had a peak pressure of almost 200 mm Hg, whereas the mean was about 110 mm Hg. The lowest peak and mean pressures (171.8 mm Hg and 78.6 mm Hg, respectively) during the hydro steps belonged to the bimanual eye with the Paratrap knife and Cruise Control. We expected the coaxial eye to have peak and mean hydrodissection pressures less than those in the other eyes because of the larger 2.5 mm incision, but this expectation was not supported by the data. Filling the anterior chamber with an OVD with resultant efficient

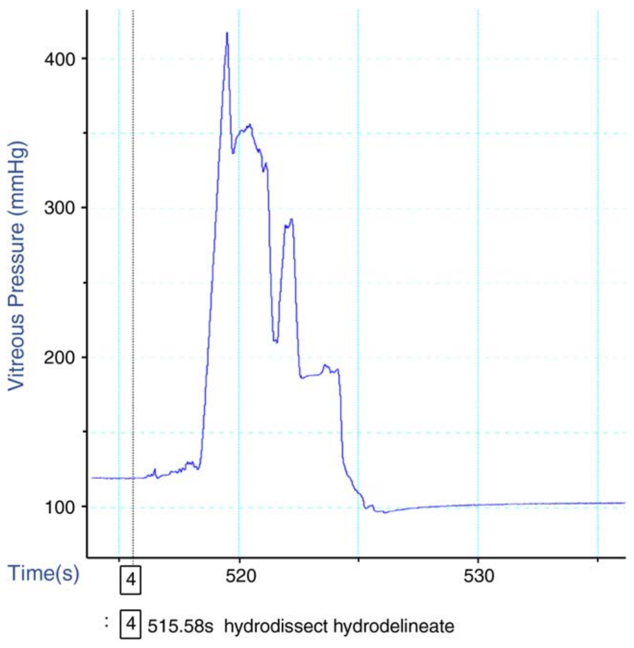

Figure 2. Hydrodissection pressure tracing shows peak pressures exceeding 400 mm Hg.

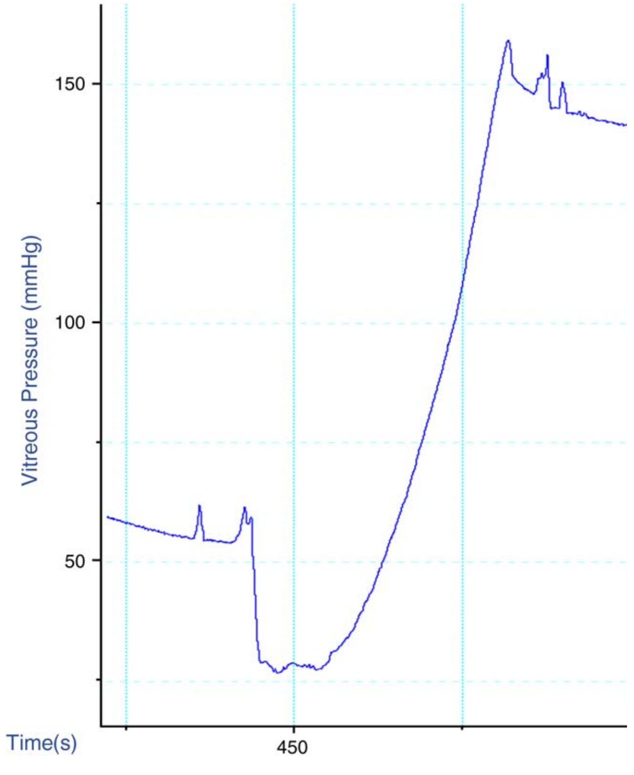

Figure 3. Curve of OVD injection.

sealing of the incisions may have accounted for the higher-than-expected pressure in this eye.

Injection of an OVD (Figure 3) and IOL implantation also generated high transient pressures. The pressure reached a peak of 343.5 mm Hg in eye 3, which was slightly overfilled, and OVD was observed streaming through the paracentesis incisions. Two other eyes (1 and 2) had peaks in excess of 100 mm Hg, whereas coaxial eye 4 had a lower peak pressure of 89.6 mm Hg. During IOL implantation, peak pressures reached 172.4 mm Hg in eye 1, whereas the lowest was 117.9 mm Hg in eye 4. It was interesting to be able to discern the biphasic pressure pattern (Figure 4) during IOL injection, with the first peak as the optic was delivered, followed by another smaller peak during delivery of the trailing haptic. Clinically, the high pressures correlated well with the clinical experience that some patients have discomfort during hydrodissection and IOL injection when cataract surgery is performed under topical anesthesia.[4] In general, it was found that the pressures during capsulorhexis reflected the pressure at the end of OVD injection and hydrodissection produced pressures about 2 to 3 times greater than this baseline.

The pressures during nuclear disassembly were more moderate by comparison. The mean generally hovered slightly below the static IOP for the set bottle height, with fluctuations above and below this point as nuclear material alternately occluded and cleared the tip by ultrasound bursts or chopping (Figure 5). Two bimanual eyes (1 and 2) had mean pressure between 88.0 mm Hg and 94.3 mm Hg during nuclear disassembly, whereas eye 3 (also bimanual, but with more leaky incisions) had a mean pressure of 39.9 mm Hg. The only coaxial eye had a mean of 63.8 mm Hg. These pressures, close to the central retinal perfusion pressure of around 60 mm Hg, might explain some of the intermittent visual phenomena that patients report during topical phaco surgery.[5–7]

The I/A phase produced mean pressure readings similar to those during nuclear disassembly in both bimanual and coaxial eyes, with the exception of eye 3 (MST 1.4 to 1.6) which had lower peak and mean pressures than the others because of excess incisional outflow.

The IOP was greater than 60 mm Hg between 50% and 85% of the duration of the phacoemulsification procedure. However, these figures represent the cumulative time that the pressures were greater than the central retinal artery perfusion pressure, rather than the time the pressures were continuously greater than 60 mm Hg. Despite this, it is the common clinical experience that most eyes do outstandingly well after surgery.[8] However, these transient high pressures are not completely innocuous, as they have been documented to cause increased disc cupping[9] and acute reversible visual field depression, the degree of which is greater in those with glaucoma.[10]

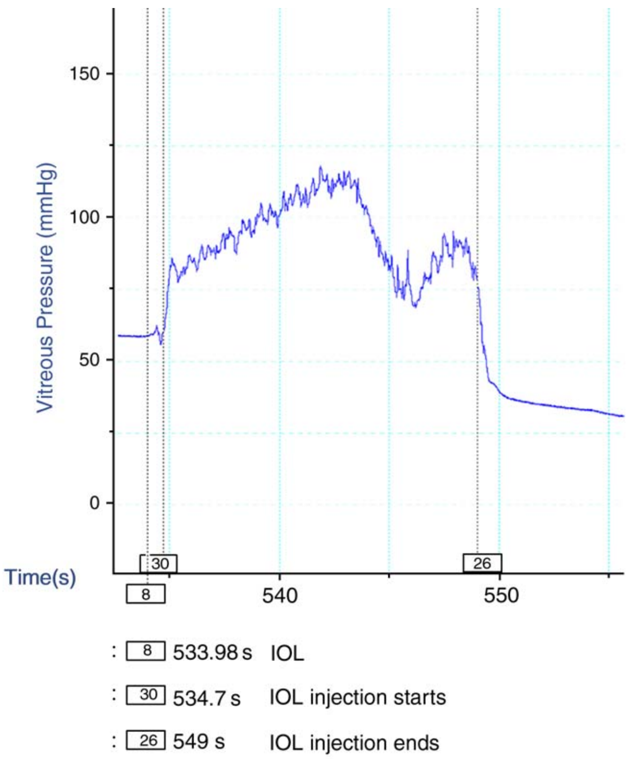

Figure 4. Lens injection pressure tracing shows biphasic pattern. Label 30 indicates start of lens injection, whereas label 26 indicates end. Time on horizontal axis is from the start of the case (in seconds).

The ability of the Staar Cruise Control to diminish simulated postocclusion surge was well demonstrated in eye 2. Without the flow restrictor, the peak pressure drop per second was between 565 mm Hg and 911 mm Hg with substantial trampolining of the posterior capsule even at the maximum extended pole height. With Cruise Control placed in the aspiration line, the peak pressure drop per second was reduced to between 290 mm Hg and 314 mm Hg, approximately one third to one half the velocity of the pressure fall without the device. Significant anterior chamber instability was seen only when the bottle pole was lowered 20 cm on the machine to 85 cm. The Cruise Control device reduced the magnitude of the pressure drop and the velocity of the IOP reduction (Figures 6 and 7). The Cruise Control has also been shown to be effective by other investigators.[11] It is worth noting that the pressure within the eye during POS is not actually negative, as we previously thought. The lowest pressure in the trough of the POS curve was 38.2 mm Hg, well within the positive range, although it represented about a 60 mm Hg drop from the pressure of around 100 mm Hg during full occlusion (eye 1).

Whether Cruise Control was attached did not seem to affect the magnitude of the IOP fluctuation during nuclear disassembly, as indicated by the standard deviation of the pressure values and the mean peak-to-peak pressure values. We also failed to see a trend with increasing nuclear density and greater IOP fluctuation.

No observable trend could be described with wound hydration and anterior chamber reformation at the end of surgery, and the pressures in different eyes tended to vary widely. Although we aimed for an IOP of about 30 mm Hg during the close of the procedure, the actual IOP within the eyes ranged from 41.8 mm Hg to 73.2 mm Hg, higher than anticipated.

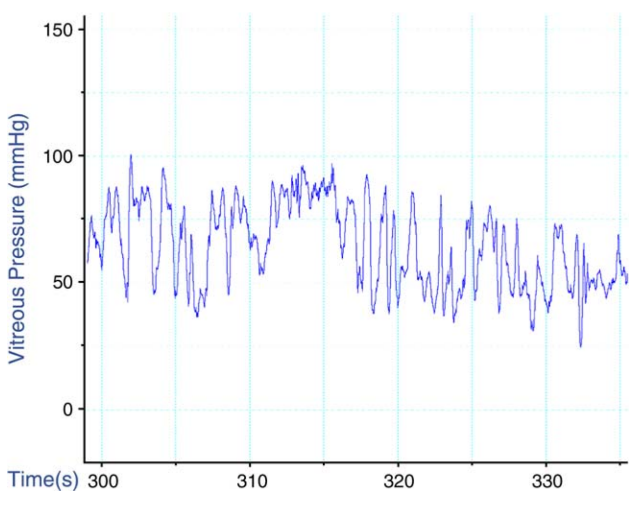

Figure 5. IOP fluctuation during nuclear chopping. Bottle height setting 105 cm.

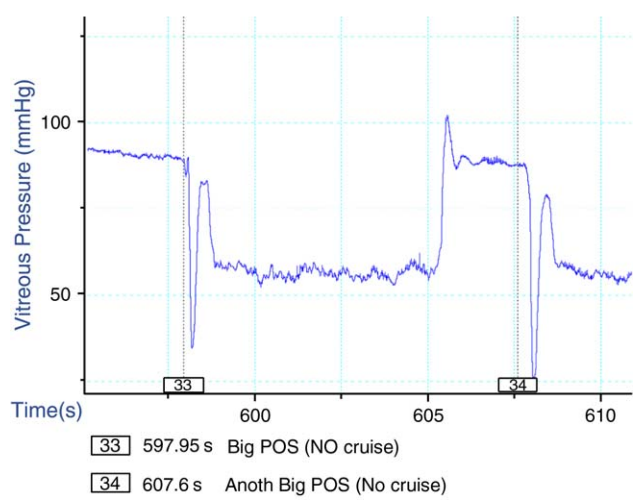

Figure 6. Postocclusion surge tracing (no Cruise Control) shows a large, steep decrease in pressure after occlusion break. Bottle height setting 105 cm.

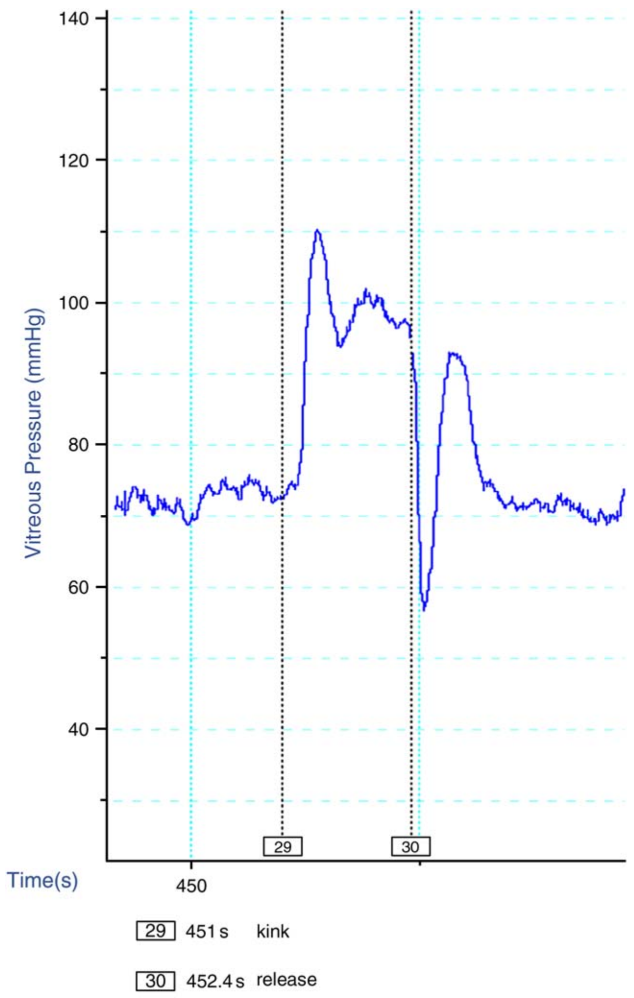

Figure 7. Postocclusion surge tracing (with Cruise Control) shows a less steep, more moderate decrease in pressure after occlusion break. Bottle height setting 105 cm.

Eye 3 had a posterior capsule (PC) rupture with a dropped nucleus during the later stages of nuclear disassembly, and it was interesting to be able to document and analyze the pressure pattern in this case. During the initial PC opening, the transducer recorded a small increase in the vitreous pressure (Figure 8) as the pressure in the AC was transmitted directly to the vitreous cavity. This was followed by a gradual decrease to subatmospheric pressure of −69.5 mm Hg over 5.23 seconds. We believe this gradual decrease to negative pressures was caused by unrecognized vitreous being caught by the phaco needle, with vitreous traction causing a volume to be removed from the vitreous cavity. This negative pressure was then replaced by an increase to a positive pressure of 63.6 mm Hg over 0.89 seconds. The static pressures in this eye also increased after the PC tear. We believe this was caused by a reduction in incisional outflow in the previously leaky incisions from

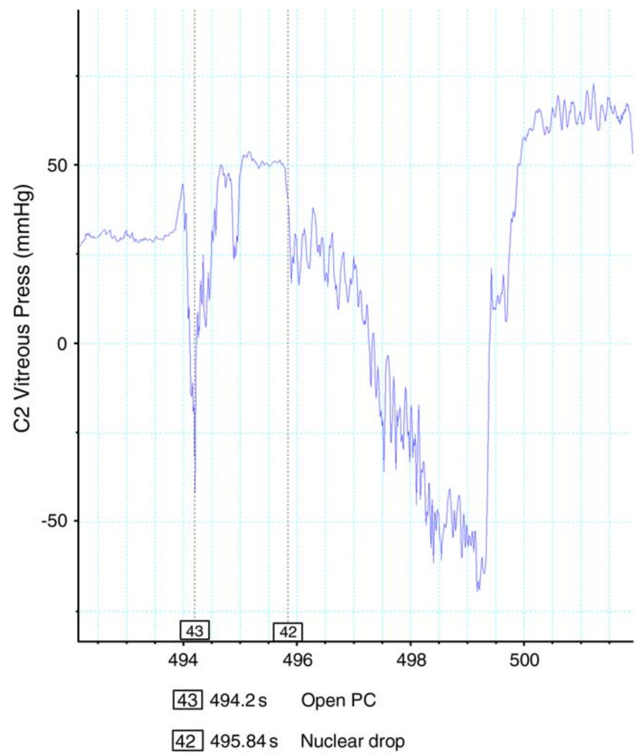

Figure 8. Pressure tracing at the moment of PC break and subsequent nuclear decrease shows pronounced gradual shift to subatmospheric pressures, followed by quick climb to higher steady pressures. Bottle height setting 105 cm.

vitreous plugging of the paracentesis incisions. Simulated postocclusion surge in this eye was also much less than that in the other eyes. The magnitude of POS was between 7.8 mm Hg and 16.0 mm Hg, much less than that encountered in the other eyes. The value for pressure drop per second in this eye was thus also much lower than in the other eyes, 156 mm Hg/s to 320 mm Hg/s. One possible reason for this very limited amount of POS is vitreous plugging of the phaco needle acting as a flow restrictor.

CONCLUSION

This study provides a new understanding of pressure dynamics within the eye. Both bimanual and coaxial phacoemulsification caused high mean pressures greater than 60 mm Hg to be generated within the eye during nuclear disassembly and I/A. The highest pressures occurred during hydrodissection, which produced transient mean pressures in excess of 100 mm Hg with both bimanual microincision and coaxial techniques. The average mean pressure during the hydro steps in the microincision Paratrap eyes (114.3 mm Hg) was surprisingly similar to that in the coaxial eye (111.5 mm Hg). The eye with the smallest proportion of time with an IOP greater than 60 mm Hg during surgery was 1 of the bimanual microincision eyes (47.9%, or 5.5 minutes of 11.4 minutes). The long-term success of both bimanual microincision and coaxial phacoemulsification techniques suggests that transient high IOPs are not harmful to the eye.

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