Intraocular Pressure and Calculated Diastolic Ocular Perfusion Pressure during Three Simulated Steps of Phacoemulsification In Vivo

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PURPOSE. To investigate the fluctuations of directly measured intraocular pressure (IOP) and induced diastolic ocular perfusion pressure (DOPP) during three simulated steps of phacoemulsification in vivo.

METHODS. Twenty-five eyes of 25 patients who underwent phacoemulsification were evaluated. A pressure transducer was inserted into the anterior chamber to measure IOP directly. The cortical cleanup and viscoelastic removal, nuclear disassembly, and anterior capsular polishing phases of phacoemulsification were simulated. Baseline, static, and dynamic IOP measurements at each stage were conducted before a routine phacoemulsification procedure was performed. DOPP was determined as the difference between diastolic blood pressure and IOP.

RESULTS. The directly measured IOP fluctuated from 13 ± 4.7 to 96 ± 6.2 mm Hg during the simulated steps of phacoemulsification (repeated-measurement ANOVA, P < 0.001). It was elevated more than 39 mm Hg compared with the baseline in static and dynamic measurements (post hoc, P < 0.001). Static DOPPs were lower than 0 mm Hg in all cases during simulated cortical cleanup and viscoelastic removal and in 19 cases during simulated nuclear disassembly. Dynamic DOPPs were lower than 0 mm Hg in 14 cases during simulated cortical cleanup and viscoelastic removal.

CONCLUSIONS. IOP and DOPP fluctuate widely during simulated steps of phacoemulsification. Further studies may be needed to establish the effect of the transient fluctuations in DOPP on visual function. (Invest Ophthalmol Vis Sci. 2009;50: 2927–2931) DOI:10.1167/iovs.08-2996

The introduction of phacoemulsification by Kelman in 19671 was the beginning of a revolution in cataract surgery. With the continued development of phacoemulsification equipment, many cataract surgeons now use maximum vacuum to complete the surgery rapidly. However, one of the potential complications associated with increased vacuum is unacceptable anterior chamber instability. To maintain anterior chamber stability during surgery, more infusion is provided, resulting in transient elevations of intraocular pressure (IOP). Several studies have been conducted to assess the ocular damage due to the temporary high IOP.2–5 Findl et al.2 reported that a 20-mm Hg increase in IOP for 5 minutes caused reduced blood flow to the optic nerve, retina, and choroid in healthy subjects.2 Acute IOP elevations for less than 1 minute may inhibit the retrograde transport of essential neurotrophins from the brain to the retina.2 In addition, there maybe a causal relationship between the high IOP associated with cataract surgery and nonarteritic anterior ischemic optic neuropathy (NAION) that can occur within 24 hours after surgery.3,5 These reports documented the possible adverse effects of transient IOP fluctuations on retinal and optic nerve function and visual acuity recovery. Although real-time IOP fluctuation has been reported in cadaveric eyes during phacoemulsification,6 there is no adequate information about the duration or magnitude of IOP fluctuations during in vivo procedures. Furthermore, the dynamic changes in ocular blood flow induced by IOP fluctuations remain unclear. The purpose of this study was to directly measure IOP changes and to assess changes in induced diastolic ocular perfusion pressure (DOPP) during three simulated steps of phacoemulsification.

METHODS

This study was approved by the Institutional Review Board for Human Research of Eye Hospital at Wenzhou Medical College (Wenzhou, Zhejiang, China). All subjects signed informed consent forms after the implementation of IOP measurement was explained, and all were treated in accordance with the tenets of the Declaration of Helsinki. Twenty-five patients (15 men and 10 women) with ages ranging from 33 to 88 years (70.7 ± 12.3 years, mean ± SD) were recruited for the study (Table 1). Twenty-three patients had age-related cataracts, and two had congenital cataracts. Eligibility criteria included no history of systemic or ocular diseases, no previous eye surgery, and no history of using eye drops or taking systemic medications that could modify IOP or blood pressure. All operations were performed by the same surgeon (YZ) on right eyes (Infiniti Vision System; Alcon Laboratories, Inc, Fort Worth, TX).

IOP was measured directly with a system similar to that described by Grinbaum et al.7 A pressure transducer with a precision of 1 mm Hg (Duckworth & Kent, St. Louis, MO) was connected to a digital monitor8 and inserted into the anterior chamber (Fig. 1). The IOP was transmitted to the transducer by the balanced saline column, and the transducer response was simultaneously displayed digitally. Reset of the IOP measurement instrument was made with the transducer in a cup of the balanced saline which was held at the level of the eye before IOP measurements were made.

The baseline IOP was obtained when the pressure transducer was inserted into the anterior chamber with its sharp steel tip at the 11-o’clock position of the limbus. Then the incision was enlarged to 3.0-mm wide as the main incision to accommodate the irrigation/aspiration (I/A) tip with a silicone sleeve. Next, a 1.0-mm wide side s
port stab was created at the peripheral cornea at the 2-o’clock position. Static and dynamic IOPs at the three settings of column height, vacuum, and flow rate described later were assessed via this side port incision.

Baseline IOP was recorded first. After that, IOP measurements were made under static conditions representing irrigation, followed by dynamic conditions representing irrigation and aspiration. Three settings of infusion column heights, vacuums, and flow rates were used to simulate different steps during phacoemulsification (Table 2). A routine clinical phacoemulsification procedure takes approximately 10 minutes. The cortical cleanup and viscoelastic removal stage, nuclear disassembly stage, and anterior capsule polishing stage take approximately 5 minutes for a lens nucleus graded III to IV. The duration and proportion of time for cortical cleanup and viscoelastic removal, nuclear disassembly, and anterior capsule polishing stages are approximately 2 minutes (20%), 2 minutes (20%), and 1 minute (10%) respectively. The static IOP at the three settings was measured when aspiration was not yet activated. The vacuum was then turned on, and when it reached the maximum level for each of the three settings, the dynamic IOP was measured. Without the I/A tip occlusion, the actual vacuums achieved were 325 mm Hg on setting A, 253 mm Hg on setting B, and 75 mm Hg on setting C. After static and dynamic IOPs were measured, routine coaxial phacoemulsification and other surgical steps were performed for all patients.

Blood pressure was assessed with an electrocardiogram monitor (MP2 Intellivue, Philips Co., Eindhoven, The Netherlands) on the upper arm of the patient during the procedure. DOPP was determined as the difference between diastolic blood pressure (DBP) and IOP.9

Results are expressed as the mean ± SD. Differences in IOP and DOPP were assessed by means of repeated-measures analysis of variance (Re-ANOVA). Post hoc paired t-tests were used to determine statistically significant pair-wise differences (P < 0.05). Based on the 1 mm Hg precision of the pressure transducer and the normal IOP of 16 ± 5 mm Hg, the minimum sample size to detect a 10-mm Hg group difference with a 99% statistical power was 7.10 Because the changes in IOP were expected to be more than 10 mm Hg, a sample of 25 cases was more than adequate for this study.

RESULTS

At baseline, the directly measured IOP was 13 ± 4.7 mm Hg (Table 3). The static IOP was very close to the theoretical pressure determined by the height of the infusion bottle. It increased to an average of 96 ± 6.2 mm Hg at setting A, which simulated cortical cleanup and viscoelastic removal. This was within the range of the theoretical value at setting A, 91.9 (125 cm) to 99.3 (135 cm) mm Hg, and significantly more than the baseline value (post hoc, P < 0.001; Table 3, Fig. 2). For setting B, which simulated nuclear disassembly, the static IOP was 76 ± 5.5 mm Hg, significantly greater than the baseline IOP (post hoc, P < 0.001; Table 3, Fig. 2). It was within the range of the theoretical pressure at setting B, 71.1 (95 cm) to 78.6 (105 cm) mm Hg. At setting C, which simulated anterior capsule polishing, the static IOP reached 62 ± 6.0 mm Hg, also significantly greater than the baseline value (post hoc, P < 0.001; Table 3, Fig. 2). The theoretical pressure at setting C was 56.1 (75 cm) to 65.6 (85 cm) mm Hg. Dynamic IOP fluctuated from 74 ± 5.1 mm Hg during simulated cortical cleanup and viscoelastic removal, setting A, to 52 ± 5.0 mm Hg during simulated anterior capsule polishing, setting C (post hoc, P < 0.001 for all pair-wise comparisons of settings A, B, and C, Table 3, Fig. 2).

The mean DBP was 70 ± 8.8 mm Hg (Table 3). When aspiration was not being activated, the mean static DOPP was −26 ± 11.2 mm Hg at setting A, −7 ± 9.6 mm Hg at setting B, and 8 ± 11.3 mm Hg at setting C (post hoc, P < 0.001 for all pair-wise comparisons of settings A, B, and C; Table 3). The static DOPP was lower than 0 mm Hg in all cases at setting A and in most cases (19/25) at setting B, whereas it was above 0 mm Hg in most cases (19/25) at setting C, including four patients in whom DOPP was only slightly above 0. When aspiration was performed, the mean dynamic DOPP was −4 ±

| Table 1. Demographic Characteristics of Patients |
|----------------------|----------------------|----------------------|----------------------|
| Age (y)             | Sex (M/F)           | History of Glaucoma  | Refractive Error (D)* |
| 70.67 ± 12.30       | 15/10               | None                | −3.31 ± 4.22         |

<table>
<thead>
<tr>
<th>Visual Acuity</th>
<th>Axial Length (mm)†</th>
<th>Keratometric Value (K1/K2)</th>
<th>Lens Photography Grading of Cataract</th>
</tr>
</thead>
<tbody>
<tr>
<td>20/200 ± 20/160</td>
<td>24.48 ± 2.92</td>
<td>43.51 ± 1.63/44.44 ± 1.49</td>
<td>I: 2 patients</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>II: 10 patients</td>
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<td></td>
<td></td>
<td></td>
<td>III: 9 patients</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>IV: 4 patients</td>
</tr>
</tbody>
</table>

Data are expressed as the mean ± SD.

* Of the 25 patients, refractive error in 17 could not be obtained because of cataract.
† Determined with the Intraocular Lens Master (IOL-Master, Carl Zeiss Meditec, Oberkochen, Germany) or A scan (Axis II RP, Quantel Medical, Clermont Ferrand, France).
DISCUSSION

With the improvements in phacoemulsification, high vacuum levels are available to complete surgeries quickly. However, high vacuums carry the risk of anterior chamber instability, unless accompanied by increased infusion pressure produced by elevation of the irrigation bottle height or forced infusion. Increased infusion pressure may lead to increased IOP and the potential reduction of the vascular perfusion pressure. To the best of our knowledge, this is the first report of in vivo DOPP fluctuations during simulated steps of phacoemulsification. The measured static IOP in the present study was very close to the theoretical value based on the bottle height, perhaps due to the silicone sleeve that prevented leakage of fluid from the main incision and the minimal outflow through the side port incision at the start of the procedure. Our results were similar to those in a previous study by Khng et al.

Phacoemulsification surgery can induce substantial fluctuations in IOP. Grinbaum et al. measured IOP continuously during in vivo phacoemulsification operations with a column height of 65 cm above eye level. They did not change the settings during the different parts of the operation and found that IOP varied from 38 to 2-3 mm Hg during phacoemulsification. Khng et al. conducted IOP measurement across eight stages of phacoemulsification in cadaveric eyes. They documented that IOP exceeded 60 mm Hg during 48% to 85% of the standard coaxial or bimanual microincision phacoemulsification procedure time. In the present report, IOP fluctuated from 13 mm Hg at baseline to 96 mm Hg during the static conditions of setting A, which simulated the cortical cleanup and viscoelastic removal stages. The reported variations may be due to different aspiration flow and vacuum settings during the course of each operation. It is worth noting that in our study, the IOP was greater than 60 mm Hg, which is the retinal artery perfusion pressure, during the three simulated steps of phacoemulsification. The simulated cortical cleanup and viscoelastic removal stages generated higher transient pressures. Even the pressures during simulated anterior capsular polishing were close to the retinal perfusion pressure. These results may correlate with the clinical experience of pain and intermittent visual phenomena reported by some patients when the I/A tip or phaco tip is inserted into the anterior chamber.

A postocclusion surge during the occlusion break from the phacoemulsification tip is a common phenomenon in phacoemulsification procedures. Theoretically, IOP decreases to the lowest level when the postocclusion surge occurs. Khng et al. simulated the postocclusion surge by placing a kink in the aspiration tubing of the phacoemulsification handpiece to completely occlude it during coaxial phacoemulsification in cadaveric eyes, causing the lowest IOP. Although we could not simulate an occlusion in vivo, we hypothesize that IOP would drop to about the baseline level if the decrease IOP was similar to that in Khng’s study, which ranged from 40.7 to 59.6 mm Hg.

Rapid fluctuations in IOP above a 30-mm Hg range could lead to compromised posterior segment blood flow. Geijer and Bill found that high elevations in IOP reduced the perfusion pressures and caused marked reductions in optic nerve blood flow in monkeys. In healthy volunteers, optic nerve head blood flow decreased more than 80% due to rapid and large decreases in the mean ocular perfusion pressure of 100% or more. In the present report, the IOP at all static and dynamic points was more than 59 mm Hg above baseline IOP. During a modern cataract procedure, nuclear disassembly, cortical cleanup, capsular polishing, and viscoelastic removal may take a few minutes, during which the IOP might be significantly elevated. Although increases of IOP are typically transient, the cumulative effects of elevated IOP could exceed perfusion pressure and reduce ocular blood flow, resulting in damage to the optic nerve head. Riva et al. suggested that the recovery of optic nerve head blood flow to baseline was affected by the duration of IOP elevation. Although it is the common clinical experience that most eyes do well after phacoemulsification surgery, previous studies have suggested that cataract extraction increased the incidence of NAION. The onset of NAION may result from the transient elevations of IOP that occur immediately after cataract surgery. There is also another report of a cataract extraction and closed vitrectomy with complications of retinal and choroidal ischemic infarctions. The authors indicated that transiently increased IOP could be one important factor contributing to the changes in ocular blood perfusion.

Table 2. Different Infusion Column Heights, Vacuums, and Flow Rates Simulated as Three Steps of Phacoemulsification

<table>
<thead>
<tr>
<th>Setting</th>
<th>Column Height (cm)²</th>
<th>Vacuum (mm Hg)</th>
<th>Flow Rate (mL/min)</th>
<th>Simulated Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>130 ± 5</td>
<td>650</td>
<td>38</td>
<td>Cortical cleanup and viscoelastic removal</td>
</tr>
<tr>
<td>B</td>
<td>100 ± 5</td>
<td>350</td>
<td>32</td>
<td>Nuclear disassembly</td>
</tr>
<tr>
<td>C</td>
<td>80 ± 5</td>
<td>150</td>
<td>18</td>
<td>Anterior capsular polishing</td>
</tr>
</tbody>
</table>

* Each column height was set by a combination of machine adjustments ± 5 cm with a 30-cm pole extension. Without the I/A tip occlusion, the actual vacuums achieved were 325 mm Hg on setting A, 253 mm Hg on setting B, and 75 mm Hg on setting C.

Table 3. IOP, DOPP, and DBP during Three Simulated Steps of Phacoemulsification

<table>
<thead>
<tr>
<th>Setting</th>
<th>Static IOP</th>
<th>Dynamic IOP</th>
<th>Static DOPP</th>
<th>Dynamic DOPP</th>
<th>Baseline IOP</th>
<th>DBP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Setting A</td>
<td>96 ± 6.2</td>
<td>74 ± 5.1</td>
<td>-26 ± 11.2</td>
<td>-4 ± 10.4</td>
<td>15 ± 4.7</td>
<td>70 ± 8.8</td>
</tr>
<tr>
<td>Setting B</td>
<td>76 ± 5.3</td>
<td>58 ± 5.4</td>
<td>-7 ± 9.6</td>
<td>12 ± 10.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Setting C</td>
<td>62 ± 6.0</td>
<td>52 ± 5.0</td>
<td>8 ± 11.3</td>
<td>18 ± 10.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values are expressed as mean ± SD. Setting A: column height, 130 ± 5 cm, simulating cortical cleanup and viscoelastic removal stage; setting B: column height, 100 ± 5 cm, simulating nuclear disassembly stage; setting C: column height, 80 ± 5 cm, simulating anterior capsular polishing stage. P < 0.001 for all pair-wise comparisons of Settings A, B, and C.
Previous studies have speculated that autoregulatory responses in ocular arteries occur within certain limits. Garhofer et al. reported that a short-term increase of IOP up to 43 mm Hg does not alter retina or optic nerve head regulation. However, large fluctuations in IOP overwhelm the ocular autoregulatory capacity and cause the reduction of ocular perfusion. There may be a difference between the effects of chronically elevated IOP and those caused by intermittent, acute IOP spikes. The association between long-term, low DOPP (< 55 mm Hg) and an increased prevalence and incidence of primary open-angle glaucoma (POAG) has been demonstrated from large-scale clinical data analysis. These findings suggest that low diastolic blood pressure and abnormal autoregulatory responses in ocular arteries occur within certain limits. The authors suggested that low diastolic blood pressure and abnormal autoregulation play important roles in the genesis and progression of POAG. However, the relationship between short-term reduced ocular blood flow, as occurs during cataract surgery, and the damage of visual function remains unclear. Trible and Anderson suggested that the degree of acute visual field depression during acute periods of elevated IOP depends on ocular perfusion pressure. Bui et al. demonstrated that a gradient of retinal functional deficits can be caused by acutely elevated IOP. In the current research, during simulation of cortical cleanup and viscoelastic removal, DOPP was less than zero in all cases, and during simulation of nuclear disassembly, DOPP was usually less than zero. Even when aspiration was performed, DOPP was still less than zero in more than half of the cases. Retinal ischemia occurs when retinal perfusion pressure is reduced to less than approximately 20 mm Hg. Logically, vascular perfusion of the retina and choroid was blocked when DOPP was less than zero. Thus, ocular perfusion is likely blocked intermittently during phacoemulsification procedures, especially in patients with diastolic blood pressure lower than 70 mm Hg.

There are many cataract patients with compromised optic nerves, such as occur in glaucoma and atrophic optic nerve. They are more prone to have optic nerve damage during phacoemulsification. Nguyen et al. evaluated seven patients with nonarteritic anterior and posterior ischemic optic neuropathy after cataract extraction and found that all patients had vascular risk factors. A history of NAION in the fellow eye had been suggested as an additional risk factor for the incidence of NAION after cataract extraction. Thus, it seems that column height should be set lower for these patients; however, the suitable height and vacuum during phacoemulsification remains unclear until further studies are undertaken.

A main limitation of the present study was that the measurement of IOP was not performed continuously. For the safety of the cataract eyes, the pressure transducer was not present in the anterior chamber continuously during the procedure to prevent trauma to the corneal endothelium, iris, or lens capsule. However, the results of static IOP measurements in the present study were very close to the theoretical values. The irrigation and aspiration phase produced mean pressure readings that were similar to those during nuclear disassembly in both bimanual and coaxial eyes. The discontinuous measurement of IOP in the present study may limit us from determining the full range of IOP and DOPP magnitudes. However, this limitation does not affect our conclusions because we focused on the fluctuations of IOP and DOPP at selected time points during simulated steps of phacoemulsification.

In conclusion, IOP and DOPP fluctuated widely in this study during three simulated steps of phacoemulsification. The transient changes have the potential to adversely affect blood flow to the optic nerve, retina, and choroid.

Acknowledgments

The authors thank Brit Bromberg, PhD, Xenofile Editing, for providing editing services for the manuscript, and the operating theater nurses for coordinating the study.

References


