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LABORATORY INVESTIGATION

Influence of irrigation dynamic pressure-assisted hydrodissection on intraocular pressure and the posterior chamber-anterior hyaloid membrane barrier during cataract surgery

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Abstract

Purpose To evaluate the effects of irrigation dynamic pressure-assisted hydrodissection (irrigation-hydro: iH) on intraocular pressure (IOP) and the posterior chamber-anterior hyaloid membrane (PC-AHM) barrier in porcine eyes.

Study design Experimental.

Methods In Experiment 1, IOP was recorded while irrigating the anterior chamber (AC), during iH, and during phacoemulsification and aspiration in 20 porcine eyes using bottle heights of 50, 70, and 90 cm. Under the same conditions, IOP was recorded during conventional manual cortical cleaving hydrodissection (manual hydro: mH) in 20 porcine eyes. In Experiment 2, after iH, ACs were perfused for 5 seconds with balanced salt solution containing 1.0-μm fluorescein beads in 20 porcine eyes using bottle heights of 70, 118, and 169 cm. PC-AHM barrier staining grade was evaluated by the Miyake-Apple view.

Results iH proved successful in all cases. In Experiment 1, IOP during iH was relatively stable and peak IOP was below the baseline bottle height-dependent pressure. No eyes showed a peak IOP > 75 mmHg during iH, but 8 eyes showed a peak IOP > 75 mmHg during mH. In Experiment 2, neither AHT nor ruptured capsules were observed at any bottle height.

Conclusion Unlike mH, IOP during iH was relatively stable without any high peak IOP. Thus, iH offers a simple technique for reducing peak IOP and avoiding disturbance of the PC-AHM barrier.

Keywords Low-invasive cataract surgery · Hydrodissection-related complication · Capsular block syndrome · Anterior hyaloid membrane tear · Infusion misdirection syndrome

Introduction

The conventional manual cortical cleaving hydrodissection technique using a syringe and cannula (manual-hydro, mH) is commonly used in modern phacoemulsification cataract surgery. This technique requires manual pressurization of the syringe to achieve adequate dynamic pressure of injected fluid for cortical-capsular cleavage [1–3]. Although this procedure is useful for cleavage of the cortical-capsular connection, significant increases in intraocular pressure (IOP) are reported during mH [4–6]. IOP during this procedure depends on several factors, including the volume of injected fluid, the volume and type of the injected ophthalmic viscosurgical device (OVD), the volume of the extracted OVD, incision size, strength of added manual pressure, and surgical technique. Because of these factors, excessively high pressure can arise within the endocapsular space and posterior chamber, resulting in the possibility of severe complications in the capsule-zonule complex and posterior chamber-anterior hyaloid membrane (PC-AHM) barrier area [4, 5]. Complications associated with pressurization during mH include capsular block syndrome (CBS), extension of anterior capsule tear through the posterior capsule, tears in the anterior hyaloid membrane, and acute aqueous misdirection

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syndrome [5, 7–14]. Kawasaki et al. identified rapid elevation of IOP due to mH as a risk factor for anterior hyaloid membrane tear (AHT) and state that the subsequent collapse of the PC-AHM barrier might relate to the development of endophthalmitis [5]. Although the incidence is low, such occurrences can lead to severe complications such as endophthalmitis, retinal break, and retinal detachment. Surgeons need to be careful to avoid these complications.

To avoid these complications, various methods to replace mH have been investigated [15, 16, 19, 20]. We propose a method for utilizing the irrigation dynamic pressure derived from the phacoemulsification tip (phaco tip) sleeve hole. We refer to this replacement method as "irrigation dynamic pressure-assisted hydrodissection" (irrigation-hydro: iH) [15, 16]. Induction of iH is achieved either by intentionally initiating a vacuum through of irrigation fluid or by depressing the side port with a hook to leak intraocular fluid, leading to irrigation jet from the sleeve hole. The advantage of the irrigation pressure derived from the phaco tip sleeve hole is that it is limited by the height of the irrigation fluid bottle, which might lead to avoidance of excessively high IOP during iH. To confirm the advantages of the iH, we compared the effects of iH and mH on IOP, and the integrity of the PC-AHM barrier in isolated porcine eyes.

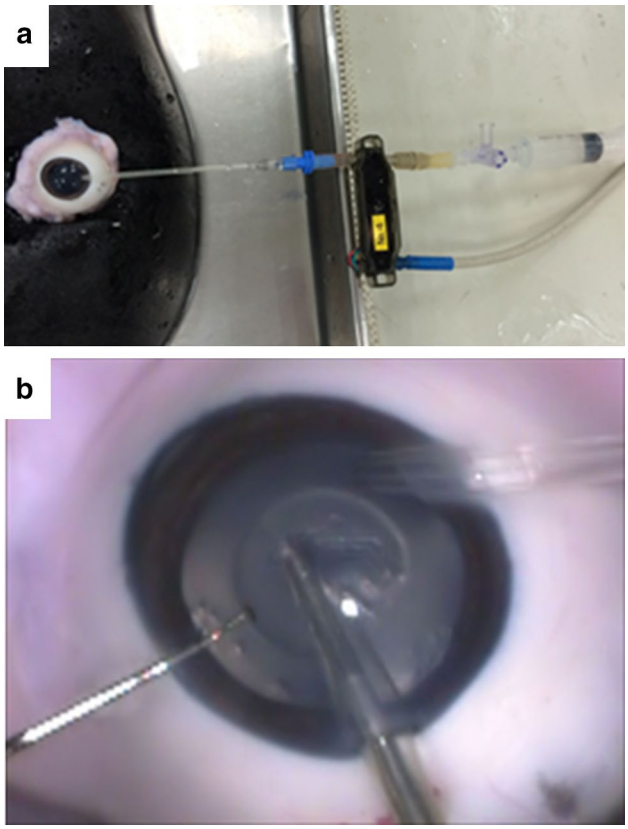

Fig. 1 Evaluation of intraocular pressure (IOP) modulation. **a** A 16-gauge needle was attached to a pressure sensor used to monitor IOP in porcine eyes. **b** The phaco tip was inserted into the anterior chamber with irrigation flow without use of conventional manual cortical cleaving hydrodissection (manual hydro: mH), and irrigation dynamic pressure-assisted hydrodissection (irrigation-hydro: iH) was performed

Materials and methods

This study was conducted in accordance with the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research. The ethics committee ruled that approval was not required for the study.

Porcine eyes were stored at 4°C and used within 12 h after enucleation. Eyes with corneal trauma or other obvious abnormalities were not used. Advance preparations for Experiments 1 and 2 included infusion of 0.4 mL of an OVD, (molecular weight, 1,900,000–3,900,000 Da; 10 mg/mL) into the anterior chamber (AC) via a 1.0-mm corneal incision at the 2 o'clock position. Subsequently, continuous curvilinear capsulorhexis with a diameter of 5.5 mm was performed.

Experiment 1

Evaluation of IOP during cataract surgery using iH

A 16-gauge needle attached to a pressure sensor (DI-151RS; DATAQ Instruments, Akron, OH; Fig. 1a) was introduced into the AC at the 7 o'clock position of the limbus and used for IOP monitoring.

After making a 3.0-mm corneal incision at the 11 o'clock position, the phaco tip was inserted into the AC using irrigation flow. A Shinkawabashi hook (Inami & Co.) was then inserted into the AC via a 1.0-mm incision side port made at the 2 o'clock position (Fig. 1b, Video 1).

We recorded IOP during irrigation of the AC from the phaco tip sleeve, which we refer to here as "$IOP_{irrigAC}$".

We subsequently performed iH. After placing the phaco tip under the capsulorhexis edge at the 5 o'clock position, we induced irrigation jet using a hook to depress the side port. We recorded IOP during iH, which we refer to here as "IOP_{iH}".

After iH, we performed phacoemulsification and removed the lens. IOP recorded during this procedure is referred to here as "IOP_{PEA}".

To distinguish the timing between $IOP_{irrigAC}$, IOP_{iH} and IOP_{PEA}, we intentionally set the IOP to zero by adjusting the foot pedal modulation to the zero position.

We examined IOPs with bottle heights of 50, 70, and 90 cm above eye level using 20 porcine eyes for each bottle height. The phaco machine used in this study was a Sovereign Compact® system (Abbott Medical Optics). We used a straight 20-gauge phaco tip with 20-gauge LAMINAR

Flow Infusion Sleeve (Abbott Medical Optics), and BSS Plus (Alcon Laboratories). Phacoemulsification parameters used were: aspiration flow rate, 28 cc/min; vacuum pressure, 200 mmHg; and ultrasound power, 40%.

Comparison of IOP during iH and mH

We recorded IOP during mH in 20 porcine eyes using a same monitoring method, here referred to as "IOP_{mH}". The mH was performed via corneal incision using a blunt 27-gauge cannula on a 5-mL syringe filled with BSS Plus®.

Experiment 2

Influence of iH on the PC-AHM barrier

Similar to Experiment 1, iH was performed using bottle heights of 70, 118, and 169 cm in 20 eyes for each bottle height. Subsequently, the AC was irrigated for 5 seconds while using perfusion fluid comprising balanced salt solution (BSS Plus®; Alcon Laboratories) and 1.0-μm fluorescein bead solution (Fluoresbrite YG Carboxylate 1.0 μm Microspheres; Polysciences) at a ratio of 100:3.0 mL.

After the procedure, eyes were bisected at a 45° angle to the equatorial plane using a razor blade. Fluorescein staining pattern was observed under an ophthalmic surgical microscope with a Miyake-Apple view [17, 18]. Based on the classification of staining patterns for fluorescein beads reported by Kawasaki et al. [5], we separated eyes into 5 grades as follows: grade 1 (AC type: fluorescein beads remained in the AC); grade 2 (Zinn type: fluorescein beads reached the zonule of Zinn); grade 3 (AHM type: fluorescein beads were situated in the space between the zonule of Zinn and AHM); grade 4 (AHT type: beads reached vitreous cavity through tear formation in the AHM); and grade 5 (Rupture type: posterior lens capsule was ruptured [5]).

Bottle height adjustment

The eye level was adjusted to the lowest height to achieve higher bottle height. In Experiment 1, bottle heights of 50, 70, and 90 cm were selected to investigate the effects of clinical settings on IOP. In Experiment 2, bottle heights of 70, 118, and 169 cm were used to study the effects of high IOP on the PC-AHM barrier.

Statistical analyses

Statistical analyses were performed using SPSS for Windows version 22.0 (IBM Japan). In terms of IOP values, paired or unpaired t-tests were used to compare factors when repeated-measure analysis of variance (ANOVA) detected a significant difference among methods or bottle heights. Fisher's exact test was used to compare the ratio. Spearman rank correlation test was used to investigate whether significant correlations existed between staining grade and bottle height.

Results

The iH successfully cleaved the cortical-capsular connection in all eyes.

Experiment 1

IOP waveforms

Temporal courses for IOP during iH cataract surgery for each bottle height are shown in Fig. 2 (Fig. 2a: 50 cm; Fig. 2b: 70 cm; Fig. 2c: 90 cm).

Although a relatively constant $IOP_{irrigAC}$ waveform was observed, some pressure fluctuations due to eye stress were observed at the time of insertion of the phaco tip and hook. Moderate decrease in the IOP_{iH} and mild fluctuations were observed whenever the side port was depressed by a hook to induce irrigation from the tip sleeve hole. Larger fluctuations in the IOP_{PEA} waveform were also observed.

Variability among porcine eyes was observed in fluctuations in IOP_{mH}; Fig. 3 shows examples of the three waveforms. Positive IOP spikes were observed in many eyes during the mH procedure. In some instances, as shown in Fig. 3a, IOP fluctuations were generally small with no positive spikes. In other instances, positive spikes were large (Fig. 3b, c).

Comparison of IOP among different surgical phases during iH cataract surgery with different bottle heights

A comparison of mean IOP is presented in Table 1. Mean IOP_{iH} was significantly lower at all bottle heights than mean $IOP_{irrigAC}$ (all $p < 0.001$, paired t-test with Bonferroni correction). Furthermore, mean IOP_{iH} was significantly lower for bottle heights of 70 and 90 cm than mean IOP_{PEA} (all $p < 0.001$, paired t-test with Bonferroni correction) and approximately equal for 50 cm.

Peak IOP values are compared in Table 2. No significant differences were detected between peak IOP_{iH} and peak $IOP_{irrigAC}$ for any bottle heights (all $p > 0.05$, paired t-test with Bonferroni correction). Peak IOP_{iH} was lower than peak IOP_{PEA} for bottle heights of 70 and 90 cm (all $p < 0.001$, paired t test with Bonferroni correction).

Both mean and peak IOP of all surgical phases increased as bottle height increased (all $p < 0.001$, unpaired t test). Moreover, the increasing rate of IOP_{iH} in line with higher

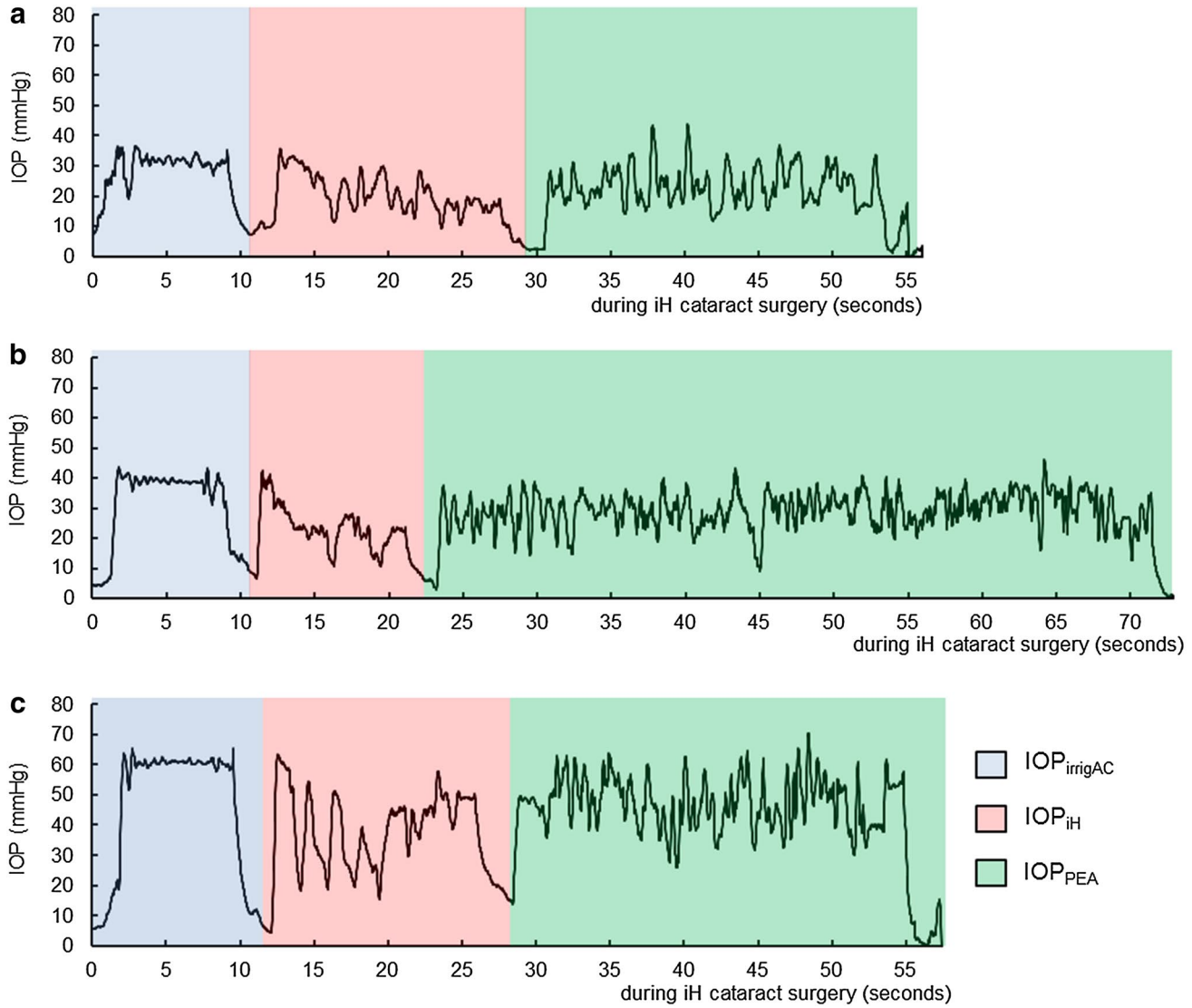

Fig. 2 Temporal course of IOP in iH cataract surgery. Bottle heights above eye level. **a** 50 cm; **b** 70 cm; and **c** 90 cm. $IOP_{irrigAC}$ IOP during irrigation of the AC from the phaco tip sleeve, IOP_{iH} IOP during iH, IOP_{PEA} IOP during PEA

bottle heights can be considered lower than $IOP_{irrigAC}$ and IOP_{PEA} ($p < 0.001$, repeated-measures ANOVA).

Comparison of IOP during iH and mH

Mean (standard deviation: SD) IOP_{mH} was 21.2 (7.7) mmHg. Mean (SD) peak IOP_{mH} was 74.2 (55.9) mmHg; a very large variability was observed among porcine eyes (range, 25.3-248.5 mmHg).

Figure 4a presents a comparison of mean IOP. Mean IOP_{iH} and IOP_{mH} were approximately equal at a bottle height of 50 cm ($p > 0.99$, unpaired t-test with Bonferroni correction), but mean IOP_{iH} was significantly higher than mean IOP_{mH} at 70 and 90 cm (all $p < 0.001$, unpaired t-test with Bonferroni correction).

Figure 4b presents a comparison of peak IOP. Peak IOP_{iH} tended to be lower at all bottle heights than peak IOP_{mH}. The difference was significant for 50 cm ($p = 0.01$, unpaired t-test with Bonferroni correction), whereas no significant differences were identified for 70 cm and 90 cm ($p = 0.184$ and $p > 0.99$, unpaired t-test with Bonferroni correction).

The ratios of porcine eyes with peak IOP ≥ 75 mmHg are shown in Table 3. For IOP_{iH}, no porcine eyes exhibited peak IOP ≥ 75 mmHg for all bottle heights. However, 8 eyes subject to IOP_{mH} recorded a peak IOP ≥ 75 mmHg, and this higher frequency was statistically significant (all $p = 0.003$, Fisher's exact test).

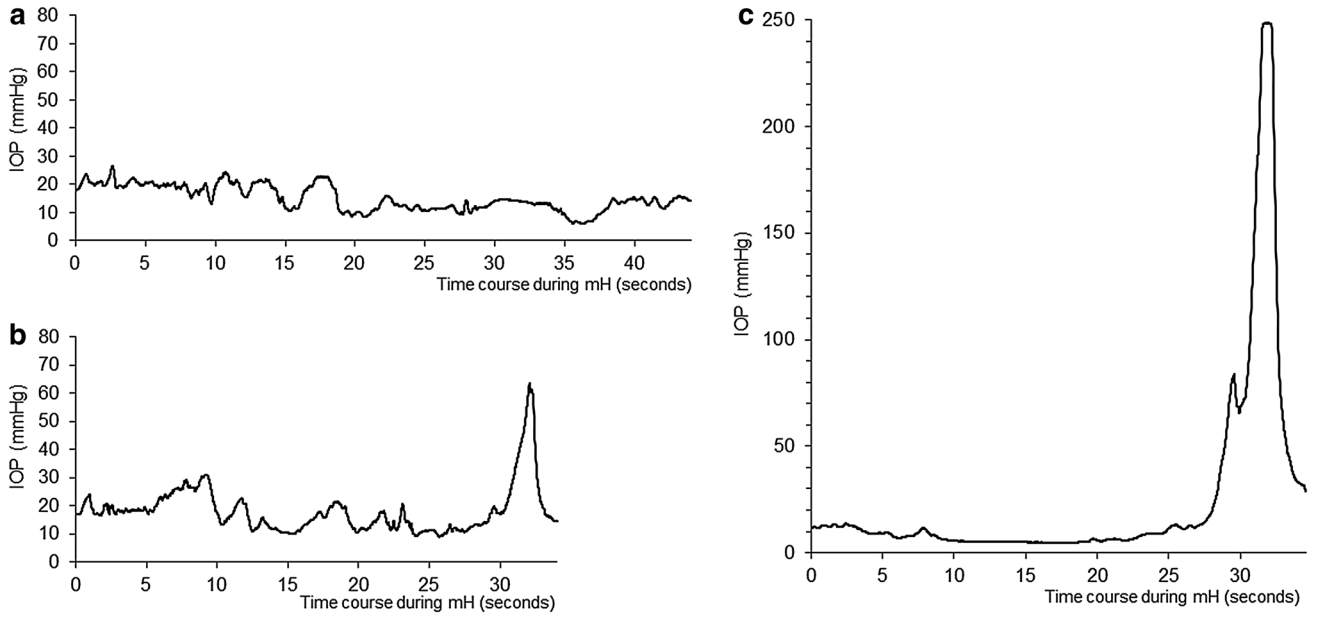

Fig. 3 Temporal course of IOP_{mH}. **a** No positive spikes are apparent during mH, and IOP during mH remains stable near the baseline. **b**, **c** Positive spikes are seen during mH, reaching a peak of 63.5 mmHg in case **b**, and 248 mmHg in case **c**

Table 1 Comparison of mean IOP among three methods for iH cataract surgery

	$IOP_{irrigAC}$	IOP_{iH}	IOP_{PEA}	P values		
				$IOP_{irrigAC}$ vs. IOP_{iH}	$IOP_{irrigAC}$ vs. IOP_{PEA}	IOP_{iH} vs. IOP_{PEA}
Bottle height						
50 cm	30.0 (2.0)	20.1 (4.8)	20.8 (4.9)	< 0.001*	< 0.001*	> 0.999
70 cm	44.5 (4.4)	30.4 (6.5)	35.4 (5.7)	< 0.001*	< 0.001*	0.006*
90 cm	57.9 (2.3)	39.9 (6.5)	45.7 (5.6)	< 0.001*	< 0.001*	0.002*

Values: mean (SD)

$IOP_{irrigAC}$ IOP during irrigation of the AC from the phaco tip sleeve, *IOP_{iH}* IOP during iH, *IOP_{PEA}* IOP during PEA

* $p < 0.05$, paired t test (with Bonferroni correction)

Table 2 Comparison of peak IOP among three methods for iH cataract surgery

	$IOP_{irrigAC}$	IOP_{iH}	IOP_{PEA}	P values		
				$IOP_{irrigAC}$ vs. IOP_{iH}	$IOP_{irrigAC}$ vs. IOP_{PEA}	IOP_{iH} vs. IOP_{PEA}
Bottle height						
50 cm	35.2 (2.4)	34.7 (4.9)	37.1 (6.2)	> 0.999	0.419	0.154
70 cm	48.2 (3.5)	49.9 (7.8)	55.4 (6.7)	0.583	< 0.001*	0.007*
90 cm	65.5 (3.7)	63.6 (4.5)	73.6 (6.6)	0.433	< 0.001*	< 0.001*

Values: mean (SD)

* $p < 0.05$, paired t test (with Bonferroni correction)

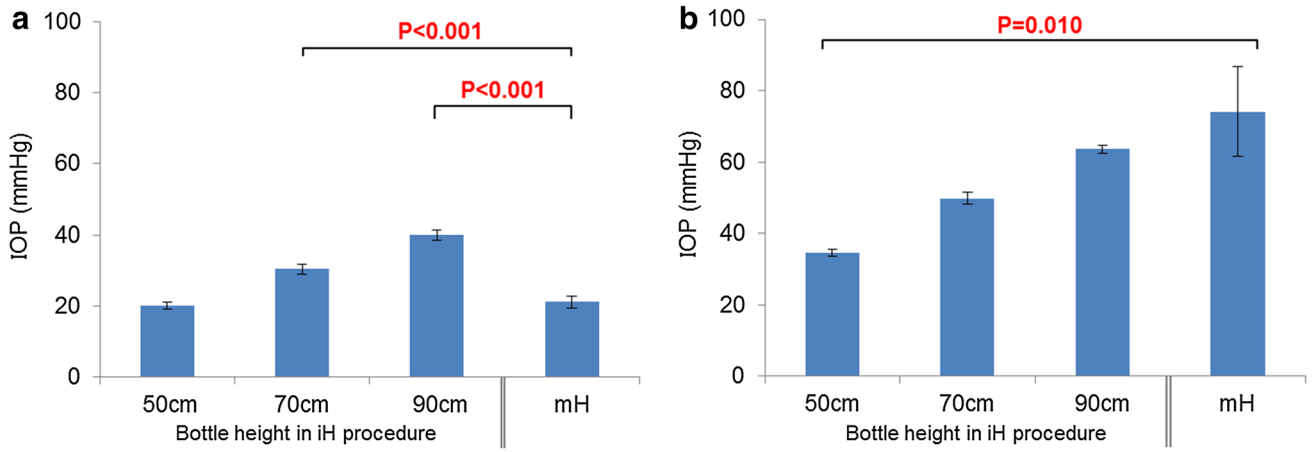

Fig. 4 Comparison of IOP_{iH} and IOP_{mH}. **a** Comparison of mean IOP; **b** Comparison of peak IOP. Data represent mean ± standard error of the mean. P value: unpaired t test with Bonferroni correction (vs. mH). IOP_{mH} IOP during mH

Table 3 Comparison of count data for eyes recording an IOP ≥ 75 mmHg during IOP_{iH} and IOP_{mH}

	IOP_{iH}	IOP_{mH}	P value
Bottle height			
50, 70, 90 cm	0, 0, 0	8	0.003*

Values: n

IOP_{mH} IOP during mH

* $p < 0.05$, Fisher's exact test

Experiment 2

Observed were staining grades 1–3 (Fig. 5a–c). Grades 4 and 5 were not observed at any bottle height. Table 4 shows the relationship between staining grades and each bottle height. Mean (SD) theoretical hydrostatic IOPs in which AC, Zinn, and AHM occurred were 69.2 (22.6) mmHg, 92.4 (29.4) mmHg, and 123.5 (0) mmHg, respectively. Although staining grade tended to be higher as IOP increased, no significant correlation was found between staining grade and bottle height (Spearman rank correlation). Theoretical hydrostatic IOP was calculated using the following equation:

$$\text{Theoretical hydrostatic IOP (mmHg)} = \text{bottle height (cm)} \times 10/13.6$$

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

Discussion

The iH method utilizes the kinetic energy (dynamic pressure) of the irrigation jet derived from the phaco tip sleeve hole [15, 16]. When the dynamic pressure is stronger than the adhesive force of the cortical-capsular layers, the cortical-capsular connection will be separated. Although irrigation flow and dynamic pressure do not occur in a closed space, we were able to induce irrigation jet and generate dynamic pressure by intentionally reducing the intraocular fluid via extraocular leakage from the side port and/or vacuuming the intraocular fluid.

In all cases in both Experiments, iH was successfully performed after depressing the side port by a hook in the porcine eye. A slow decrease in IOP_{iH} was observed, consistent with leakage from the side ports, thereby allowing cleavage of the cortical-capsular layers using the induced irrigation jet.

In Experiment 1, mean and peak IOP_{iH} increased as bottle height increased. In addition, peak IOP_{iH} pressure did not surpass that of $IOP_{irrigAC}$, which was close to the bottle height-dependent hydrostatic pressure. Thus, we proved that IOP during iH depends on bottle height and never surpasses peak bottle height-dependent hydrostatic pressure. With a phaco machine that actively controls the perfusion pressure according to the aspiration flow rate, the IOP during iH is presumed to be constant.

Several studies report finding significant increases in IOP during mH [4–6]. Khng et al. report that IOP during mH was highest among the overall cataract surgeries, with possible peak pressures exceeding 400 mmHg [4]. Kawasaki et al. report that IOP measured during mH in porcine eyes ranged from 15.49 to 115.33 mmHg, with the pressure depending upon the type of injected OVD [5]. Ohnuma et al. report that the type of injected OVD and incision size affected IOP during mH, with the measured IOP ranging from 23.96 to 318.7 mmHg [6]. Such findings indicate that IOP increases in porcine eyes will vary depending on conditions such as the volume and type of injected OVD and incision size.

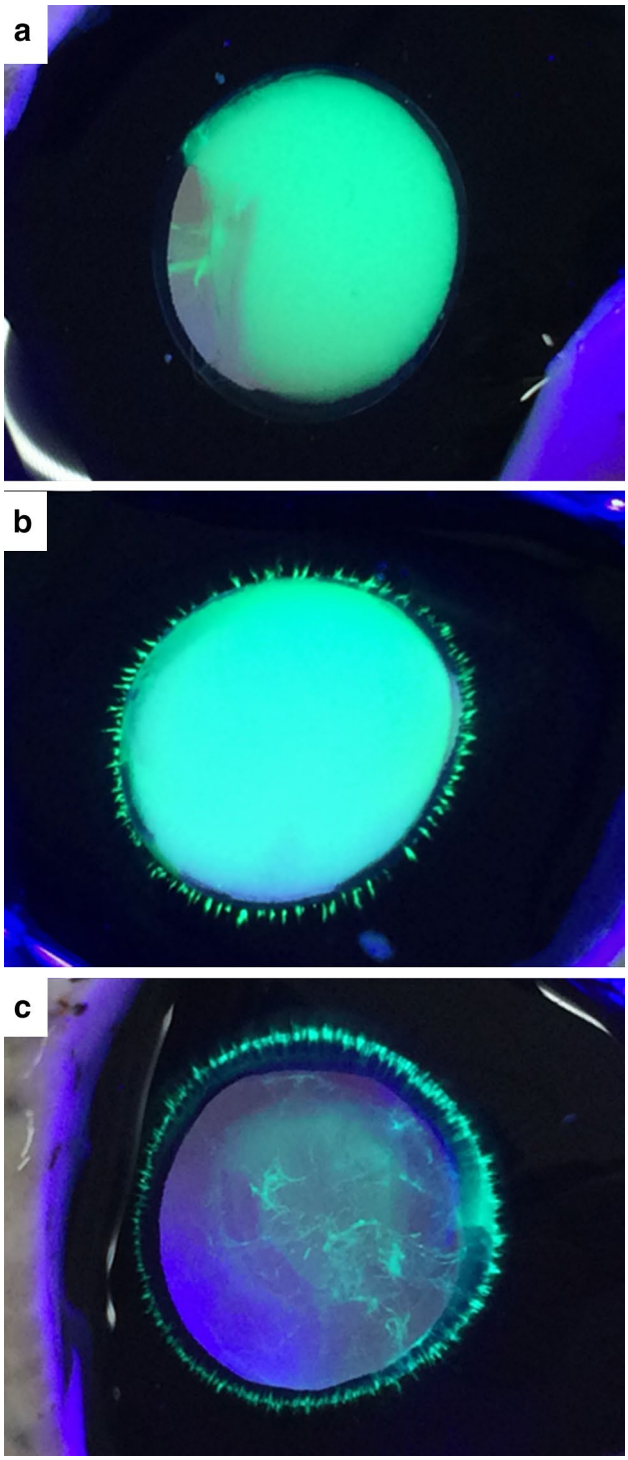

Fig. 5 Staining grades determined using the Miyake-Apple view after iH. **a** Grade 1; **b** Grade 2; and **c** Grade 3

In Experiment 1, positive IOP spikes were consistently observed in many porcine eyes during mH. On the other hand, moderate decreases in IOP were constantly observed during iH. The resulting waveforms clearly illustrate the contrasting nature of the two mechanisms. Mean IOP_{iH} was either equal to or higher than mean IOP_{mH}, but peak IOP_{iH} was lower. However, we think that high peak IOP induced by mH poses a higher risk of complications, such as AHT and posterior capsule rupture. Our observations, thus, focused on increased IOP, because Kawasaki et al. indicate that eyes subjected to pressure > 75 mm Hg during mH are at increased risk of AHT [5]. For iH, no porcine eyes recorded an IOP ≥ 75 mmHg. On the other hand, eight eyes subject to mH recorded an IOP > 75 mmHg. These findings suggest that rapid pressure rises during mH increase the risk of AHT. While many parameters can induce a high IOP during mH, bottle height is the only factor involved during the iH technique. The ability to adjust the bottle height-dependent hydrostatic pressure is an advantage for the iH technique.

Experiment 2 evaluated the effects of IOP on the PC-AHM barrier during iH using the same method reported by Kawasaki et al. [5]. Using the same OVD as the present study Kawasaki et al. examined the relationship between staining type and mean IOP after mH, and report the following grades: grade 1 at 32.28 (SD 8.88) mmHg, grade 2 at 63.39 (36.23) mmHg, grade 3 at 117.0 (67.47) mmHg, and grade 4 at 185.35 (71.50) mmHg . Although each theoretical mean IOP classified as grade 1, 2, or 3 in our study was higher than the results reported by Kawasaki, we did not find any cases of grade 4 or 5. Use of the iH technique can reduce the influence of the PC-AHM barrier compared to the mH procedure.

The mH can induce posterior capsule rupture in cases with preexisting capsule tear, posterior polar cataract, posterior lenticonus, or continuous curvilinear capsulorhexis tear by increasing pressure within the endocapsular space, reported as CBS [7–10]. CBS during femtosecond laser-assisted cataract surgery has also recently been reported caused of expansion of the endocapsular volume by laser-induced intracapsular gas and cortical changes [11]. Acute aqueous misdirection syndrome, which results from PC-AHM barrier disturbance, can be induced by the mH procedure [12, 13]. Our findings infer that the use of iH can help prevent these complications induced by a high IOP. During our daily iH surgery we have not encountered any induction of complications due to high IOP, such as CBS or any post-surgical endophthalmitis..

In conclusion, the IOPs found during the iH procedure are limited to pressures below baseline and depend on the actual bottle heights used during surgery. Compared to the mH, iH is a simple technique that can be used to reduce the IOP during hydrodissection, thereby helping to avoid

Table 4 Relationship between staining grade and each of the bottle heights

Bottle height (theoretical static IOP)	Staining type (grade)				
	1 (AC)	2 (Zinn)	3 (AHM)	4 (AHT)	5 (rupture)
70 cm (51.5 mmHg)	9	11	0	0	0
118 cm (86.8 mmHg)	6	14	0	0	0
169 cm (123.5 mmHg)	1	17	2	0	0
Mean theoretical IOP (SD) mmHg	69.2 (22.6)	92.4 (29.4)	123.5 (0)		

Although staining grade tended to be higher as IOP increased, no significant correlation was found between staining grade and bottle height (Spearman rank correlation)

disturbing the PC-AHM barrier. These results suggest that the iH technique can be useful for avoiding any hydrodissection-induced complications.

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Conflicts of interest N. Kato, None; Y. Masuda, None; K. Oki, None; H. Iwaki, None; H. Tsuneoka, Grant (Abbott Medical Optics, Alcon, Daiichi Sankyo, Kowa, MSD, Nidek, Otsuka, Santen, Senju), Lecture fees (Abbott Medical Optics, Alcon, Bausch + Lomb, HOYA, Kowa, Nidek, Otsuka, Pfizer, Santen, Senju).

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