FULL PAPER *Surgery*

Real-time intraocular pressure measurement during phacoemulsification in dogs *ex vivo*

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ABSTRACT. This study was performed to evaluate changes in intraocular pressure (IOP) during standard coaxial phacoemulsification using 4 different bottle heights (BHs) and 2 different incision sizes. Coaxial phacoemulsification was performed with a venturi-based machine in 8 enucleated canine eyes through 3.0 and 3.2 mm clear corneal incisions (CCIs). A pressure transducer inserted in the peripheral cornea monitored the IOP in real-time. The surgery was subdivided into 4 stages: sculpt-segment removal, irrigation/aspiration, capsular polishing and viscoelastic removal. The mean IOP and the difference between the maximum and minimum IOPs were calculated at each stage and compared. The ultrasound time and volume of irrigation fluid used were recorded. The mean IOP increased with an elevation in the BH. The mean IOP in the irrigation/aspiration stage was significantly higher than that in the sculpt-segment removal stage at the same BH. The difference between the maximum and minimum IOP at each stage was greater in the 3.2 mm than the 3.0 mm CCIs, although the mean IOP was lower with the 3.2 mm than the 3.0 mm CCIs. The ultrasound time and irrigation fluid volume were greater with the 3.2 mm than the 3.0 mm CCIs. Therefore, fluidic parameters during each stage could be reassessed and adjusted to reduce complications arising from an elevated IOP. Phacoemulsification with 3.0 mm CCIs at a lower BH might lead to less stress on the eye from IOP fluctuations, ultrasound energy and irrigation fluid.

KEY WORDS: canine, fluidic parameter, hydrodynamic stress, intraocular pressure, phacoemulsification

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Phacoemulsification is the most frequently performed ophthalmic surgical procedure in human and veterinary ophthalmology [4, 5, 13]. Technological advancements in phacoemulsification equipment have enabled surgeons to alter specific parameters, such as the vacuum level, bottle height (BH), flow rate and ultrasound power. In addition, improved fluidics, decreased postocclusion surges and the ability to select a maximum vacuum level in recent phacoemulsification machines make it possible to perform the surgery rapidly [23, 28]. However, a higher vacuum inevitably necessitates more infusion to maintain the stability of the anterior chamber. The resulting higher fluidic settings have been reported to increase hydrodynamic stress during phacoemulsification, although they reduce the duration and the amount of ultrasound energy [21, 23]. Previous studies emphasized that higher fluidics resulted in more complications than ultrasound energy in surgery [9, 21, 23].

Phacodynamics play an important role in complications that occur during and after phacoemulsification [9, 21–23]. To minimize the risk of such complications, anterior chamber depth should be maintained adequately to prevent surge or intraocular pressure (IOP) elevation [5, 10]. Studies have reported that the influx of irrigation fluid into the eye and the efflux of the fluid through the aspiration port and corneal incision site influence the IOP [2, 21, 26]. Uncontrolled surges can induce posterior capsular rupture and vitreous prolapse during phacoemulsification [24]. Increasing the BH can help to reduce postocclusion surges, but this increases the infusion of irrigation fluid, resulting in elevations and fluctuations in the IOP [21, 28]. A temporary high IOP has been reported to damage ocular tissues, such as the optic nerve, retina and choroid [28].

Standard coaxial phacoemulsification has been performed through a 2.8–3.5 mm clear corneal incision (CCI) in veterinary ophthalmology [3, 4, 14, 16]. The size of the CCI and the amount of fluid leaked through the incision were reported to influence the stability of the anterior chamber and the IOP [13]. Some human studies of real-time IOP during phacoemulsification objectively evaluated the importance of the CCI size and adverse effects of elevations in IOP during the surgery on the eye [2, 11, 21, 26, 28]. They found that the IOP fluctuated during the surgery due to imbalances between the inflow and outflow of the irrigation fluid and that fluidic parameters and the size of the CCI influenced the range of IOP fluctuations during phacoemulsification [11, 21, 26]. Direct intraoperative continuous monitoring of IOP throughout phacoemulsification surgery in the canine eye is limited, and there is little information on the range of IOPs during the surgery in dogs. Therefore, this study was performed to directly measure real-time IOP during phacoemulsification in canine eyes and to investigate changes in IOP at 4 different BHs and 2 different CCI sizes.

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MATERIALS AND METHODS

Preparation of canine eyes: Four pairs of normal eyes were obtained from 4 adult beagle dogs (5–7 years old, 6–10 kg) without ocular diseases that were euthanized for unrelated causes. All the eyes were immersed in normal saline solution and stored at 4°C. All the eyes were used within 6 hr of euthanasia. The BH was the same for each pair of eyes. A CCI of 3.0 mm was made in one of the eyes and a CCI of 3.2 mm in the opposite eye of the same dog. All eyes were placed at the same height so that the actual distance from the bottle was the same as the BH displayed on the device.

IOP recording: A pressure transducer was connected to the enucleated canine eye to directly measure the IOP. The measuring system consisted of the following four parts: a 26 G needle, a pressure transducer (List No. 42584-05; Hospira, Inc., Lake Forest, IL, U.S.A.), a monitoring cable (List No. 42661-40; Hospira, Inc.) and a monitor (Datex-Ohmeda S/5, Helsinki, Finland). The pressure transducer was calibrated on a mercury manometer (Dwyer Flex-Tube® U-Tube Manometer, Dwyer Instruments, Inc., Michigan, IN, U.S.A.) before the measurements. The pressure on the monitor was set to zero when the 26 G needle, pressure transducer and the enucleated canine eye were located at the same height. The calibrated pressure transducer was inserted through the peripheral cornea. The sharp 26 G needle tip of the pressure transducer was located in the anterior chamber at the six o'clock position of the limbus. The monitor instantly showed real-time IOP. A data acquisition system (Datex-Ohmeda S/5 Collect, Helsinki, Finland) was connected to the measuring system and automatically recorded multipoint IOPs during each stage. A drop of tissue adhesive (Vetbond®, 3M, Saint Paul, MN, U.S.A.) was applied between the needle and the cornea to prevent it from being pulled out of the cornea due to changes in the anterior chamber depth during phacoemulsification (Figs. 1 and 2).

Phacoemulsification including CCIs and fluidic parameters: Four different BHs of 50, 70, 100 and 120 cm were used. Two incisions were made: 3.0 mm and 3.2 mm. To maintain an IOP of 20 mmHg with a phaco handpiece, the BH/vacuum pressure was set at 50/70, 70/100, 100/170 and 120 cm/200 mmHg, respectively, in the eyes with the 3.0 mm CCI and 50/30, 70/50, 100/100 and 120 cm/150 mmHg, respectively, in the eyes with the 3.2 mm CCI.

A 3.0 or 3.2 mm CCI was made using a clear corneal blade (ClearCut®, Alcon Laboratories Inc., Fort Worth, TX, U.S.A.) at the 12 o'clock position of the peripheral cornea in each eye (Fig. 2). After injecting 0.4 m*l* of ophthalmic viscoelastic material (1% sodium hyaluronate; Hyal 2000®, LG Life Sciences, Daejon, Korea) and creating a capsulorhexis with a diameter of 6.0 mm, coaxial phacoemulsification of the enucleated canine eyes was performed with a venturi-based machine (Millennium Microsurgical System REF CX6100, Bausch & Lomb Inc., Rochester, NY, U.S.A.). The phacoemulsification power limit was set at 40%, and a balanced salt solution (BSS Plus®, Alcon Laboratories Inc.) in a 500 m*l* plastic bag was used for the irrigation/aspiration fluid in all the experiments. The surgery was subdivided into

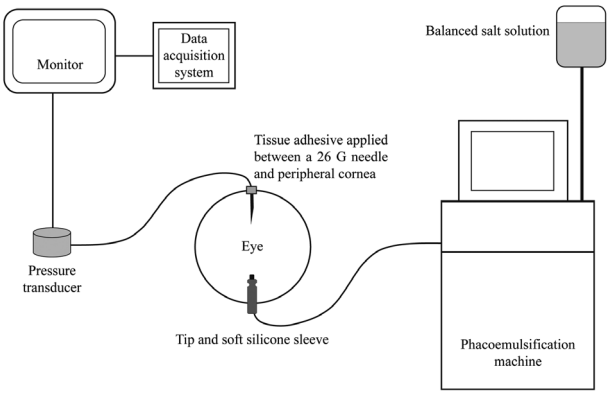

Fig. 1. Schematic diagram of real-time IOP measurement during phacoemulsification.

4 stages: sculpt-segment removal (SS), irrigation/aspiration (IA), capsular polishing (CP) and viscoelastic removal (VR). A phaco handpiece with a 19 G, straight 30-degree needle (Storz® DP8130, Bausch and Lomb) and a soft silicone sleeve was used in the SS stage under the conditions of the above-determined BH/vacuum. At all 4 bottle heights, an irrigation/aspiration handpiece with a 20 G, 0.3 mm aspiration port tip (Storz® DP9745, Bausch and Lomb) and a soft silicone sleeve was used for the IA, CP and VR stages, with the vacuum pressure set at 450, 10 and 450 mmHg, respectively. A foldable soft acrylic one-piece intraocular lens (Acrivet 30V-12 41D®, Acrivet, Salt Lake City, UT, U.S.A.) was implanted after injecting 0.6 m*l* of ophthalmic viscoelastic material again. The CP and VR stages were performed for 20 and 50 sec in all the eyes, respectively. All phacoemulsification procedures were performed by one skilled surgeon using the same method. Throughout the surgery, the leakage around the needle was checked using microsurgical sponge spears.

The ultrasound time, volume of irrigation fluid used and total irrigation time for each eye were recorded.

Statistical analyses: The mean IOP at each stage was calculated using IOP values recorded digitally on the data acquisition system. The difference between the maximum and minimum IOP and the amount (sec) and proportion (%) of time in which the IOP was greater than 60 mmHg at each stage were also calculated and compared. The Student's *t*-test was used to compare the mean IOP between the SS and IA stages and between the 3.0 mm and 3.2 mm CCIs. The difference was judged to be statistically significant at $P<0.05$.

RESULTS

No leakage was identified around the needle of the pressure transducer throughout the IOP measurements, and the static IOP was very close to the theoretical pressure according to the BH described by Wilbrandt and Wilbrandt [26], confirming that the measured IOPs were reliable. Phacoemulsification was successfully performed using the determined fluidic parameters, and the stability of the anterior

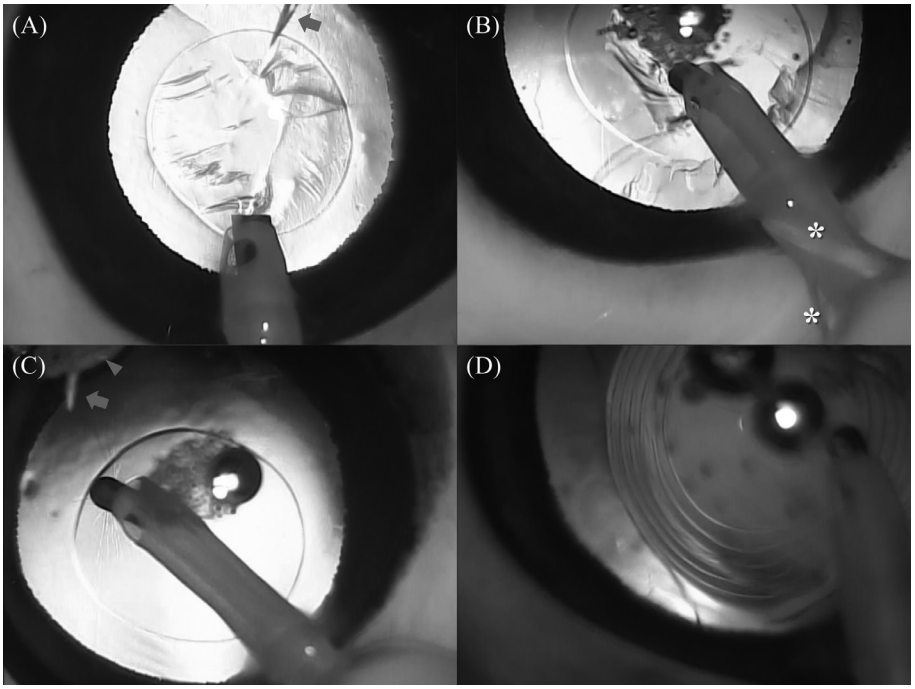

Fig. 2. Representative images of measuring real-time IOP during phacoemulsification in canine eyes. (A) Sculpt-segment removal stage. Apressure transducer (arrow) was inserted into the eye; (B) Irrigation/aspiration stage. The irrigation fluid was leaking through the clear corneal incision (asterisk); (C) Capsular polishing stage. Wrinkled posterior capsule around the tip was observed with the pressure transducer (arrow) secured with a drop of tissue adhesive (arrowhead); (D) Viscoelastic removal stage. An acrylic intraocular lens was implanted after injecting of ophthalmic viscoelastic material.

chamber was maintained in 7 enucleated eyes, except in one eye with a 3.2 mm CCI where the BH and vacuum pressure were 50 cm and 30 mmHg, respectively. The vacuum pressure of 30 mmHg was not enough to aspirate lens fragments, and a higher vacuum with the BH set at 50 cm caused anterior chamber collapse, with large incisional leakage in the 3.2 mm CCIs.

The intraoperative IOP fluctuated in a sawtooth wave pattern (Fig. 3). The mean IOP increased in accordance with an increase in the BH (Table 1). With respect to the different stages, the mean IOP in the IA stage (performed with an irrigation/aspiration handpiece) was significantly higher than that in the SS stage (performed with a phaco handpiece) in all 7 eyes undergoing phacoemulsification ($P<0.001$).

With regard to the different CCI sizes, the mean IOP was significantly lower with the 3.2 mm than the 3.0 mm CCI in most stages at all BHs (Table 1). The mean IOP was significantly lower with the 3.2 mm CCI than with the 3.0 mm CCI in the IA and VR stages at all BHs ($P<0.001$) and in the CP stage with the BH of 70 cm ($P<0.001$). However, it was significantly higher with the 3.2 mm CCI than with the 3.0 mm CCI in the SS stages with the BHs set at 100 and 120 cm ($P<0.001$ and $P=0.001$, respectively). In the CP stage with the BH set at 100 cm, the mean IOP was also significantly higher with the 3.2 mm CCI ($P<0.001$).

The difference between the maximum and minimum IOPs was greater in the 3.2 mm CCI eye than the 3.0 mm CCI eye at all stages with all BHs, except in the SS and CP stages when the BH was set at 100 cm (Table 1). The maximum IOP was similar in the 2 CCIs, but the minimum IOP was lower with 3.2 mm CCI. The difference between the maximum and minimum IOPs showed a tendency to increase with an elevation in the BH, with the maximum IOP increasing with higher BH (Table 1).

In the 3.0 mm CCI eye at a BH of 50 cm, the IOPs were always less than 60 mmHg in all 4 stages (Table 2). The amount and proportion of time that the IOP was greater than 60 mmHg increased in accordance with a rise in the BH, particularly at the BHs of 100 and 120 cm. Total amount and proportion of time that the IOP was greater than 60 mmHg throughout phacoemulsification decreased in the 3.2 mm CCIs at the BHs of 70 and 120 cm, and were similar in the 2 CCIs at the BH of 100 cm.

On the other hand, the ultrasound time and irrigation fluid volume used increased in the 3.2 mm CCIs compared to the 3.0 mm CCIs at the same BH. The total irrigation time was also greater in the 3.2 mm CCIs at the BHs of 70 and 100 cm, and similar at the BH of 120 cm (Table 3).

DISCUSSION

The intraoperative IOP of the canine eyes fluctuated

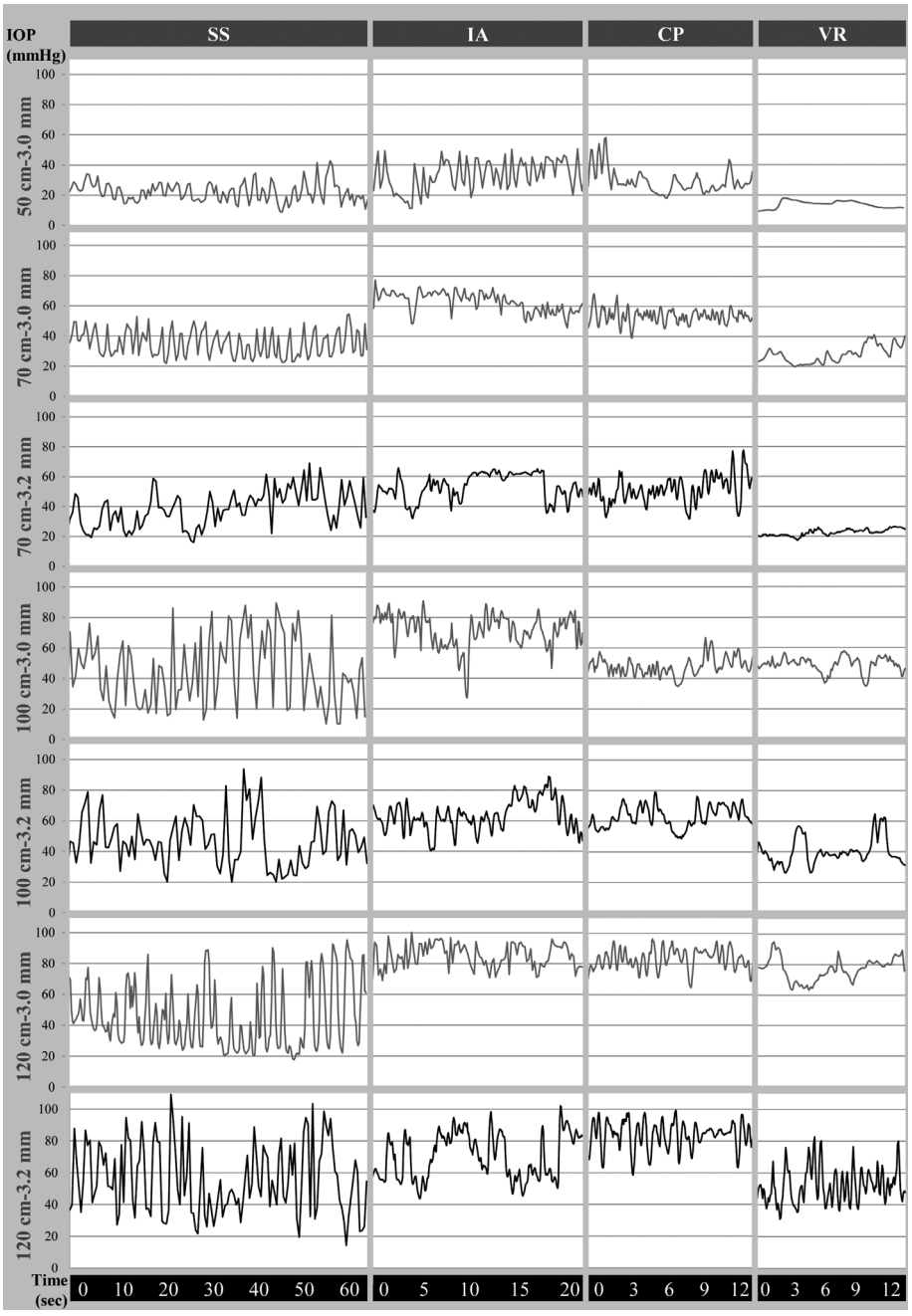

Fig. 3. Intraoperative IOP in 4 consecutive stages including sculpt-segment removal (SS), irrigation/aspiration (IA), capsular polishing (CP) and viscoelastic removal (VR) in all 7 eyes. The difference between the maximum and minimum IOP showed a tendency to increase with an elevation in the BH and with the 3.2 mm CCI.

dynamically in a wave pattern during phacoemulsification, with the peak IOP and wave height being different between various stages of the surgery in this study. Our results are similar to those of previous studies, which demonstrated IOP fluctuations by monitoring the actual IOP during surgery [6, 11, 12, 28]. The results of the real-time measurements of IOP during phacoemulsification in the present study provide insight into the marked variations that occur in the IOP in response to 4 different fluidic parameters and 2 different incision sizes. This information can help surgeons choose surgical modifications in canine eyes.

The mean IOP in the IA stage when an irrigation/aspiration handpiece was used was significantly higher than that during the SS stage when a phaco handpiece was employed.

Table 1. Profile of the mean IOPs, the data from the Student's *t*-test, and the maximum and minimum IOPs during phacoemulsification in dogs *ex vivo*

	BH 50 cm	BH 70 cm			BH 100 cm			BH 120 cm		
	3.0-mm CCI	3.0-mm CCI	3.2-mm CCI	*P* Value	3.0-mm CCI	3.2-mm CCI	*P* Value	3.0-mm CCI	3.2-mm CCI	*P* Value
SS	21.2 ± 7.8 [a]	34.7 ± 10.3	34.9 ± 11.2	$P=0.781$	40.1 ± 22.4	47.7 ± 16.5	$P<0.001$	48.8 ± 22.2	53.5 ± 20.5	$P=0.001$
	46.7–1.4 [45.3] [b]	73.0–12.4 [60.6]	69.1–5.9 [63.2]		92.4–6.8 [85.6]	93.7–17.4 [76.3]		101.1–16.1 [85.0]	109.2–12.2 [97.0]	
IA	29.2 ± 9.9	55.9 ± 7.7	44.9 ± 13.5	$P<0.001$	71.5 ± 10.6	61.0 ± 11.3	$P<0.001$	87.0 ± 9.2	70.4 ± 14.2	$P<0.001$
	55.2–4.1 [51.1]	77.4–32.7 [44.7]	65.7–18.6 [47.1]		90.7–27.3 [63.4]	88.9–22.9 [66.0]		102.8–63.7 [39.1]	102.2–43.7 [58.5]	
CP	30.9 ± 8.4	54.5 ± 5.4	51.2 ± 8.8	$P<0.001$	50.9 ± 23.4	62.5 ± 6.8	$P<0.001$	83.8 ± 7.3	83.8 ± 8.4	$P=0.898$
	58.9–17.9 [41.0]	69.4–38.9 [30.5]	77.8–30.6 [47.2]		99.8–48.2 [51.6]	68.4–31.6 [36.8]		104.6–64.9 [39.7]	99.3–58.6 [40.7]	
VR	14.0 ± 2.3	29.2 ± 9.5	23.3 ± 6.9	$P<0.001$	47.1 ± 9.6	40.1 ± 10.2	$P<0.001$	82.7 ± 8.0	48.4 ± 9.3	$P<0.001$
	17.9–11.4 [6.5]	61.3–20.1 [41.2]	56.1–11.2 [44.9]		63.7–22.8 [40.9]	78.2–22.2 [56.0]		97.4–64.3 [33.1]	82.6–24.5 [58.1]	

a) Mean ± SD (mmHg); b) Maximum-Minimum (mmHg) [the difference between them]. BH, bottle height; SS, sculpt-segment removal; IA, irrigation/aspiration; CP, capsular polishing; VR, viscoelastic removal.

Table 2. The amount and the proportion of time that the IOP was greater than 60 mmHg in each stage during phacoemulsification in dogs *ex vivo*

	BH 50 cm	BH 70 cm		BH 100 cm		BH 120 cm	
	3.0-mm CCI	3.0-mm CCI	3.2-mm CCI	3.0-mm CCI	3.2-mm CCI	3.0-mm CCI	3.2-mm CCI
SS	0.0 [0%] [a]	4.0 [0.02%]	2.8 [0.01%]	64.2 [22%]	68.4 [19%]	40.0 [35%]	85.2 [36%]
IA	0.0 [0%]	16.6 [24%]	8.0 [15%]	20.9 [90%]	19.3 [37%]	140.7 [97%]	13.3 [67%]
CP	0.0 [0%]	3.0 [15%]	2.5 [13%]	7.9 [40%]	10.8 [54%]	20.0 [100%]	20.0 [100%]
VR	0.0 [0%]	0.0 [0%]	0.0 [0%]	4.5 [0.09%]	1.7 [0.03%]	50.0 [100%]	6.4 [13%]
Total	0.0 [0%]	23.6 [7%]	13.3 [3%]	97.5 [25%]	100.2 [21%]	250.7 [76%]	124.9 [38%]

a) Seconds [proportion (%)]. BH, bottle height; SS, sculpt-segment removal; IA, irrigation/aspiration; CP, capsular polishing; VR, viscoelastic removal; Total, total time that IOP was greater than 60 mmHg throughout phacoemulsification.

Table 3. Profile of the total irrigation time, ultrasound time and irrigation fluid volume used during phacoemulsification in dogs *ex vivo*

	BH 50 cm	BH 70 cm		BH 100 cm		BH 120 cm	
	3.0-mm CCI	3.0-mm CCI	3.2-mm CCI	3.0-mm CCI	3.2-mm CCI	3.0-mm CCI	3.2-mm CCI
Total irrigation time (sec)	439.0 [a]	337.5	390.8	384.5	488.0	331.3	325.5
SS (sec)	207.3	199.6	268.9	291.2	365.3	115.7	235.5
IA (sec)	161.7	67.9	51.9	23.3	52.7	145.6	20.0
US time (sec)	169.0	149.0	197.0	212.0	219.0	105.0	174.0
Irrigation fluid volume used (m*l*)	264	209	266	346	448	185	275

a) Total irrigation time of SS+IA+CP+VR (seconds); BH, bottle height; US, ultrasound.

However, the maximum IOPs were similar between the two stages. This can be explained by the vacuum pressure not being activated or the handpiece tip being blocked with lens fragments [6]. The minimum IOPs were always lower in the SS stages compared to the IA stages due to aspiration of the emulsate through the larger aspiration port. A postocclusion surge following occlusion break from the tips was responsible for the minimum IOP [5, 11, 24, 28].

In the present study, the mean IOP was lower with the 3.2 mm than the 3.0 mm CCI during most stages at the same BH, verifying that larger incisional leakage with the 3.2 mm CCI reduced the IOP. However, the mean IOP in the SS stage was similar between the two CCIs or was rather higher with the 3.2 mm than the 3.0 mm CCI. This was probably due to the thickness of the phaco tip with the silicone sleeve. It was thicker than the irrigation/aspiration tip with the silicone sleeve and likely decreased incisional leakage of the irrigation fluid from both CCIs [28]. On the other hand, the use of the thinner irrigation/aspiration tip in the IA, CP and VR stages allowed more irrigation fluid to leak through the 3.2 mm CCI than through the 3.0 mm CCI, thereby resulting in lower mean IOPs overall with the former.

The difference between the maximum and minimum IOPs, meaning the range of IOP fluctuation, increased with the 3.2 mm CCI compared with the 3.0 mm CCI in this study. The increase was due to the greater amount of incisional leakage with the 3.2 mm CCI lowering the minimum IOP, while the similar maximum IOP between the 2 CCIs. Incisional leakage was known to be necessary for cooling the phaco tip, which is heated by the ultrasonic vibrations, thereby preventing thermal damage to the surrounding cornea [25]. However, excessive leakage had an adverse effect on the stability of the anterior chamber [13]. Thus, it may be necessary to increase the BH to prevent surges [5]. In this study, the 3.0 mm CCI, one of a number of previously verified CCI sizes for coaxial phacoemulsification [15], showed significant incisional leakage. The fluid flow between the tip and the silicone sleeve was sufficient to provide adequate cooling of the phaco tip. Reducing the size of the incision was reported to produce a stable wound architecture [12]. Additionally, a smaller incision size was reported to significantly reduce surgically induced astigmatism [15].

In addition to having larger IOP fluctuations and a lower mean IOP, the ultrasound time and irrigation fluid volume used were greater with the 3.2 mm CCIs than with the 3.0 mm CCIs. The lower mean IOP with the 3.2 mm CCIs was due to excessive leakage. The ultrasound time and the turbulent flow with a greater volume of irrigation fluid were reported to contribute to corneal endothelial damage [21]. In the present study, the greater irrigation fluid volume used and total irrigation time with the 3.2 mm CCI might be correlated with increased fluid turnover and turbulence in the anterior chamber [23]. These had an adverse effect on the retention of viscoelastic material in the anterior chamber, contributing to increased corneal endothelial damage [21].

The difference between the maximum and minimum IOPs also increased with higher BHs in this study. Higher fluidics induced higher IOPs and larger IOP fluctuations, severely altering the fluid flow in the anterior chamber [21]. A higher IOP and increased fluid turbulence, together with elevations in fluidic parameters, might worsen the collapse of the ciliary cleft which was regarded as the mechanism for postoperative hypertension following phacoemulsification in dogs [16]. Previous canine studies also suggested that excessive IOP and hydrodynamic stress arising from higher fluidics might cause microstructural damage, such as disruption of the posterior chamber–anterior hyaloid membrane barrier and irrigation fluid leakage into the vitreous humor during phacoemulsification [9, 10].

Many studies have described the ocular damage caused by a high IOP [11, 18, 21, 28]. A previous human study reported that IOP reaching a central retinal perfusion pressure of around 60 mmHg during phacoemulsification might be correlated with intermittent visual phenomena described by some patients undergoing phacoemulsification with topical anesthesia [11]. Another human study reported that these occurred when the phaco or irrigation/aspiration tip was inserted into the anterior chamber [28], suggesting that the duration of no vacuum pressure with the footswitch position 1 of the irrigation position should be minimized [6]. Despite changes in perfusion pressure, a constant blood flow was known to be maintained by autoregulation. However, autoregulation operates only within a certain range of perfusion pressure and breaks down out of the range [8]. Large fluctuations of IOP during phacoemulsification could overwhelm the ocular autoregulatory capacity, potentially reducing ocular perfusion and resulting in nonarteritic anterior ischemic optic neuropathy (NAION) following the surgery [19]. Ocular perfusion during phacoemulsification was likely blocked intermittently, because of fluctuating patterns in the IOP [28]. In this study, the amount and the proportion of time when the IOP was greater than 60 mmHg increased with higher BHs, particularly in the CP and VR stages at the BH of 120 cm. In these stages, the IOP was greater than 60 mmHg 100% of the time, potentially continuously blocking ocular perfusion, something that is even more dangerous than intermittent blockages [11]. It might take a longer time to perform phacoemulsification in canine eyes compared with human eyes, as the canine lens is larger and harder than the human lens [7, 9]. Therefore, fluidic parameters, particularly during the IA stage, should be adjusted carefully to reduce complications associated with the longer duration of IOP elevation. In this study, a lower BH and a 3.0 mm CCI induced small fluctuations in the IOP during phacoemulsification, and these might lead to less compromised posterior segment blood flow in dogs. Many dog breeds predisposed to cataracts are known to also be predisposed to inherited, primary angle-closure glaucoma [27]. In these breeds, the benefit of a lower intraoperative IOP associated with a lower BH might help to prevent the progression of glaucoma [23]. Although higher fluidic parameters could be used for effective performance during phacoemulsification, a graded reduction in fluidic parameters during and between stages might help to decrease the prevalence of perioperative complications [22].

Incisional fluid loss is inversely proportional to anterior

chamber stability, preventing an increase in vacuum pressure [13]. In the determined fluidic parameters of this study, the vacuum pressure required to maintain the IOP at 20 mmHg in the 3.2 mm CCIs was lower than that needed to maintain the same IOP in the 3.0 mm CCIs at the same BH. The lower vacuum pressure decreased the aspiration flow rate and the followability of lens fragments, inducing insufficient effectiveness [1, 20]. Thus, the ultrasound time and total irrigation time might be longer with the 3.2 mm CCIs than with the 3.0 mm CCIs in this study. Additionally, excessive leakage and fluid flow might transport lens fragments outside the eye before the vacuum pressure held them, also inducing insufficient effectiveness. In the present study, phacoemulsification was successfully performed with the 3.0 mm CCI, even at the BH of 50 cm. In contrast, it could not be performed with the 3.2 mm CCI at the same BH. A lower BH decreases the influx of irrigating fluid and may induce hypotony or a postocclusion surge under conditions of excessive incisional leakage, potentially leading to complications, such as posterior capsular rupture [2]. Hypotony was reported as one of the putative causative factors of NAION, together with IOP elevations and increased intraorbital pressure [17]. Therefore, minimizing incisional fluid loss through correctly creating a smaller incision for matching tip size [13] was required to perform phacoemulsification using lower fluidic parameters for smaller IOP elevation with improving chamber stability. Excessive vertical or horizontal tension on the incision site should also be avoided during the surgery to prevent wound deformation and excessive leakage [13]. The aforementioned might explain why the results with the BH of 100 cm were sometimes inconsistent with those of other BHs in this study. Although the incision size depends on the intraocular lens, extending the incision could follow the IA and CP stages before implanting the intraocular lens [4].

This study had some limitations. First, we used enucleated canine eyes out of the orbit. Second, the most appropriate BH and optimum vacuum pressure in canine eyes remained unclear. Further studies are needed on canine *in vivo* ocular perfusion pressure during phacoemulsification.

In conclusion, direct measurement of IOP using a pressure transducer provided adequate information about dynamic changes in the IOP according to fluidic parameters and corneal incision sizes during phacoemulsification in canine eyes. This study demonstrated that higher fluidic parameters induced higher IOPs and greater IOP fluctuations. It also showed that the 3.2 mm CCI induced lower IOPs and greater IOP fluctuations than the 3.0 mm CCI and resulted in worse anterior chamber stability, necessitating higher BH compared to the 3.0 mm CCI. Fluidic parameters could be reassessed and lowered to avoid elevations in IOP, while maintaining the effectiveness of the surgery. Phacoemulsification with the 3.0 mm CCI at a lower BH might place less stress on the eye from IOP fluctuations, ultrasound energy and irrigation fluid rather than phacoemulsification with the 3.2 mm CCI.

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