A DISSERTATION
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Effect of Bottle Height and Vacuum Level on Fluid Dynamics during Phacoemulsification in Normal Canine Eyes Ex Vivo

정상 개의 적출 안구에서 수정체초음파유화술 시 관류액 높이와 진공 흡입력이 유체역학에 미치는 영향

by

Seonmi Kang

MAJOR IN VETERINARY CLINICAL SCIENCES
DEPARTMENT OF VETERINARY MEDICINE
GRADUATE SCHOOL
SEOUL NATIONAL UNIVERSITY

February, 2015

Effect of Bottle Height and Vacuum Level on Fluid Dynamics during Phacoemulsification in Normal Canine Eyes Ex Vivo

by
Seonmi Kang

Supervised by
Professor Kangmoon Seo

Thesis
Submitted to the Faculty of the Graduate School
of Seoul National University
in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy in Veterinary Medicine

October, 2014

Major in Veterinary Clinical Sciences
Department of Veterinary Medicine
Graduate School
Seoul National University

December, 2014

Effect of Bottle Height and Vacuum Level on Fluid Dynamics during Phacoemulsification in Normal Canine Eyes Ex Vivo

Advisor : Professor Kangmoon Seo

Submitting a doctoral thesis of
veterinary clinical sciences
October 2014

Graduate School of Seoul National University
Veterinary Clinical Sciences
Department of Veterinary Medicine

Seonmi Kang

Confirming the doctoral thesis written by Seonmi Kang
December 2014

Chair ________________________

Vice Chair ________________________

Examiner ________________________

Examiner ________________________

Examiner ________________________

Effect of Bottle Height and Vacuum Level on Fluid Dynamics during Phacoemulsification in Normal Canine Eyes Ex Vivo

Supervised by

Professor Kangmoon Seo

Seonmi Kang

Major in Veterinary Clinical Sciences, Department of Veterinary Medicine
Graduate School, Seoul National University

ABSTRACT

The purpose of the present study was to evaluate the effects of phacoemulsification with different fluidic parameters on the intraocular tissues and intraocular pressure (IOP) in dogs. Phacoemulsification is the most commonly performed cataract surgery. Fluid dynamics and phacodynamics have been reported as one of the important contributing factors to postoperative complications following phacoemulsification. Fluidic parameters consist of bottle height (BH), ultrasound energy, vacuum, and aspiration and irrigation flow rate. To improve the success rate of phacoemulsification, the surgeon must understand these parameters which maintain anterior chamber stability during phacoemulsification by the balance between the influx of irrigating fluid and both the efflux of aspirating fluid and incisional fluid loss. Advances in phacoemulsification technology and fluidics have enabled the operator to control these parameters, making the procedure safer and more effective.

This study was performed to evaluate the effects of phacoemulsification using different BHs and vacuum levels on fluid dynamics inducing IOP and intraocular structural changes in normal canine eyes ex vivo. This study consists of two chapters.

Chapter I demonstrated the effects of phacoemulsification with different fluidic parameters on the intraocular tissues using contrast-enhanced magnetic resonance imaging (CE-MRI). Phacoemulsification with the BH / the vacuum pressure set at 50 cm / 80 mmHg for one eye and at 120 cm / 150 mmHg for the opposite eye was performed on 10 pairs of enucleated canine eyes using irrigation fluid containing diluted MRI contrast agent. CE-MRI was carried out immediately after phacoemulsification. Low fluidic parameters led to decreased fluid passage through the zonules, reducing fluid passage into the vitreous. These also resulted in decreased amount of irrigation solution used during phacoemulsification in the dog.

Chapter II optimized fluid dynamics to define the fluidic parameters for preventing surge and IOP elevation through measuring IOP in a venturi phacoemulsification machine in dogs. Flow and IOP were measured using a pressure transducer at various settings of BH and vacuum and with two different sized clear corneal incisions (CCI). Flow was directly proportional to the BH and vacuum, whereas IOP was directly proportional to the BH and inversely to the vacuum. Flow with an irrigation/aspiration (I/A) handpiece was significantly less than with a phaco handpiece, explaining why IOP with an I/A handpiece was significantly higher than with a phaco handpiece. With the I/A handpiece, vacuum parameters less than 450 mmHg did not result in surge. Although phacoemulsification with a 3.2 mm CCI could induce lower IOP, a 3.0 mm CCI might lessen the irrigation flow stress on the eye.

Based on the results of the present studies, low fluidic parameters led to reduced surgical stress on the intraocular tissues by decreasing the amount of irrigation solution used and by decreasing IOP during phacoemulsification in the dog. In particular, BH during the I/A stage should be reduced to avoid unnecessary stress on the canine eye when using a venturi system.

Keywords: Cataract, Phacoemulsification, Anterior chamber stability, Fluidic parameters, Dog

Student number: 2005-31155

List of Abbreviations

AC	Anterior Chamber
AHD	Anterior Hyaloid Membrane Detachment
AHM	Anterior Hyaloid Membrane
BH	Bottle Height
BSS	Balanced Salt Solution
CCI	Clear Corneal Incision
CE-MRI	Contrast-Enhanced Magnetic Resonance Imaging
I/A	Irrigation/Aspiration
IOL	IntraOcular Lens
IOP	IntraOcular Pressure
LIU	Lens-Induced Uveitis
LV	Leakage Volume
LV/VV%	Leakage Volume-to-Vitreous Volume ratio
PC	Posterior Chamber
PLC	Posterior Lens Capsule
ROI	Region Of Interest
SI	Signal Intensity
VV	Vitreous Volume

CONTENTS

CHAPTER I.

Evaluation of Fluid Leakage into the Canine Vitreous Humour during Phacoemulsification Using Contrast-Enhanced Magnetic Resonance Imaging

CHAPTER II.

Fluid Dynamics and Intraocular Pressure Using Venturi Phacoemulsification Machine in Dogs Ex Vivo

Materials and Methods

Step I: in vitro experiments

Step II: ex vivo experiments

Results

GENERAL INTRODUCTION

Cataracts are the most frequent cause of blindness and cataract removal is the most common intraocular surgery performed in veterinary ophthalmology. Among the various methods of cataract removal, phacoemulsification is the most commonly performed surgical operation (Biros *et al.*, 2000; Cook, 2008; Klein *et al.*, 2011). Phacoemulsification lead to decreased surgical time and trauma by a smaller corneal incision and more effective removal of lens material (Sigle and Nasisse, 2006). Consequently, complications after phacoemulsification has been minimized, with the potential to restore or preserve vision after the surgery increasing (Klein *et al.*, 2011).

Many efforts have been made to improve the success rate of phacoemulsification. Especially, enhanced phacoemulsifier fluidics management system have enabled the operator to control many parameters, such as the aspiration and irrigation flow rate and the vacuum level, making phacoemulsification surgery safer and more effective (Fine *et al.*, 2002; Bellucci, 2006; Vasavada *et al.*, 2010). Although there have been significant advances in phacoemulsification techniques and equipment, complications persist (Klein *et al.*, 2011). Fluid dynamics and phacodynamics have been reported as one of the important contributing factors to postoperative complications following phacoemulsification (Vasavada and Raj, 2003; Suzuki *et al.*, 2009; Vasavada *et al.*, 2010; Kawasaki *et al.*, 2011). Therefore, the surgeon must understand the fluidic parameters to improve the success rate of phacoemulsification.

Anterior chamber pressure during phacoemulsification is directly proportional to the bottle height (BH). The flow attracts lenticular fragments, the vacuum holds them, and ultrasound energy is used to emulsify the crystalline lens (Seibel, 2005; Wilkie and Colitz, 2007). The flow and vacuum also maintain an adequate anterior chamber depth, while the emulsate is aspirated. Anterior chamber stability is maintained by the balance between the influx of irrigating fluid and both the efflux of aspirating fluid and incisional fluid loss (Liyanage *et al*., 2009; Sharma *et al*., 2012). Postocclusion surge inducing an unstable anterior chamber decreases with increasing BH and decreasing aspiration rate (Georgescu *et al*., 2007). Intraocular pressure (IOP) during phacoemulsification is determined by the irrigating pressure originating from the BH, vacuum pressure, aspiration rate, and incisional fluid leakage (Suzuki *et al*., 2009).

This study was designed to investigate changes in the structural integrity of the eye according to different fluidic parameters and to explain why intraocular structural changes could be different between high and low fluidic parameters. First, the effects of phacoemulsification with different fluidic parameters on the intraocular tissues were evaluated and compared using contrast-enhanced magnetic resonance imaging (Chapter I). Second, the real time IOP and flow were directly measured at different fluidic parameters and with two different sized corneal incisions and the fluidic parameters of a venturi phacoemulsification machine for preventing surge and IOP elevation were defined in dogs (Chapter II).

CHAPTER I.

Evaluation of Fluid Leakage into the Canine Vitreous Humour during Phacoemulsification Using Contrast-Enhanced Magnetic Resonance Imaging

Abstract

The purpose of this study was to evaluate the effects of phacoemulsification with different fluidic parameters on the intraocular tissues using contrast-enhanced magnetic resonance imaging (CE-MRI). Phacoemulsification with intraocular lens (IOL) implantation was performed on 10 pairs of enucleated canine eyes. Irrigation fluid containing diluted MRI contrast agent was used, with the bottle height / the vacuum pressure set at 50 cm / 80 mmHg for one eye (Group L) and at 120 cm / 150 mmHg for the opposite eye (Group H). CE-MRI was carried out immediately after phacoemulsification to evaluate the presence of anterior hyaloid membrane detachment (AHD) and the leakage volume-to-vitreous volume ratio (LV/VV%). The ultrasound time, the volume of irrigation solution used, and the total irrigation time were recorded. AHD was seen in seven of the 10 eyes in Group L and in nine of the 10 eyes in Group H. Fluid leakage into the vitreous humour (LV/VV%) was significantly greater in Group H than in Group L ($P < 0.01$). The LV/VV% was also correlated with the total irrigation time in both groups ($P < 0.05$). The volume of irrigation solution used in Group H was significantly greater than that used in Group L ($P < 0.001$). There was no statistically significant difference in the ultrasound time between the two groups. Low fluidic parameters led to decreased fluid passage through the zonules, reducing fluid passage into the vitreous. These may also lead to reduced surgical stress on the intraocular tissues by decreasing the amount of irrigation solution used during phacoemulsification in the dog.

Introduction

Cataract extraction is a widely performed surgery in veterinary ophthalmology. Among the various methods of cataract removal, phacoemulsification with intracapsular IOL implantation is the most commonly performed (Biros *et al*., 2000; Sigle and Nasisse, 2006; McLean *et al*., 2012). Many efforts have been made to improve the success rate of phacoemulsification. In particular, advances in phacoemulsification technology and fluidics have enabled the operator to control many parameters, such as the aspiration rate, the vacuum level, and the irrigation flow rate, making the procedure safer and more effective (Fine *et al*., 2002; Bellucci, 2006; Vasavada *et al*., 2010). Despite marked improvements in phacoemulsification techniques and equipment, complications still occur after surgery.

Reported complications of phacoemulsification include uveitis, postoperative ocular hypertension, glaucoma, retinal detachment, endophthalmitis, posterior capsule opacification, fibropupillary membrane formation, and corneal edema (Taylor *et al*., 1995; Biros *et al*., 2000; Moore *et al*., 2003; Wilkie and Colitz, 2009; Klein *et al*., 2011). Studies of factors that contribute to the postoperative complications of phacoemulsification have shown that lens-induced uveitis (LIU), microbial contamination during surgery, surgical trauma, the surgical technique, the use of certain chemical or physical agents, and phacodynamics play a role (Apple *et al*., 1984; Beyer *et al*., 1984; Beyer *et al*., 1985; Paulson *et al*., 1986; Taylor *et al*., 1995; Moore *et al*., 2003; Vasavada and Raj, 2003; Ledbetter *et al*., 2004; Bellucci, 2006; Kawasaki *et al*., 2009; Suzuki *et al*., 2009; Vasavada *et al*., 2010).

A previous study evaluated disruption of the posterior chamber (PC)-anterior hyaloid membrane (AHM) barrier in enucleated porcine eyes by CE-MRI after phacoemulsification using irrigation fluid containing diluted MRI contrast agent to explain how endophthalmitis occurred in a number of eyes that underwent phacoemulsifiction without any intraoperative complications (Kawasaki *et al*., 2009). Using CE-MRI, it identified the presence of the irrigation fluid beneath the posterior lens capsule, showing that microorganisms could enter the vitreous cavity via the irrigation fluid, particularly if the AHM tear had developed. This finding was supported by another study, which investigated the leakage of lens proteins into the vitreous cavity during phacoemulsification in human eyes and found alterations in the protein composition of the vitreous body following the surgery (Neal *et al*., 2005).

The canine lens is much larger than the human lens (0.5 ml vs. 0.3 ml, respectively), and the hardness of most canine cataracts is similar to that of human brunescent cataracts. The canine lens is also harder than the porcine lens (Williams, 2004; Samuelson, 2007; Cook, 2008). The phacoemulsification surgery time increases in accordance with an increase in the size and the hardness of the lens. Therefore, the present study applied CE-MRI after phacoemulsification using irrigation fluid containing diluted MRI contrast agent to enucleated canine eyes to determine whether a longer surgery time led to abnormalities other than structural changes in the PC-AHM barrier. Furthermore, the effects of the fluidic parameters on the CE-MRI findings were evaluated.

Materials and Methods

1. Preparation of canine eyes

Ten pairs of normal eyes enucleated from 10 adult beagle dogs following euthanasia for an unrelated cause were used for phacoemulsification within 6 hours of euthanasia. One eye was used for Group L (n = 10), and the opposite eye of the same dog was used for Group H (n = 10). This study was approved by the Institutional Animal Care and Use Committee of Seoul National University (SNU-120504-2).

2. Preparation of the irrigation solution

Gadolinium-based MRI contrast agent (Magnevist®; Bayer Schering Pharma AG, Berlin, Germany) diluted in balanced salt solution (BSS; Alcon Laboratories, Inc., Fort Worth, Texas, USA) at a concentration of 2 mM was used for the irrigation fluid during phacoemulsificaton (Kawasaki *et al.*, 2009). The MRI contrast agent was a 0.5 M solution originally and was diluted to 1/250 solution in BSS for use of irrigation fluid, as the concentration of 2 mM was expected to produce maximum contrast enhancement on T1-weighted images. In common with the previous study (Kawasaki *et al.*, 2009), 0.1 ml of this irrigation fluid was injected intracamerally or intravitreally. CE-MRI was then performed according to the protocol described below to assess whether this imaging technique was appropriate for the subsequent experiments (Fig.1-1A-C).

3. Phacoemulsification

Phacoemulsification was performed (Millennium™ Microsurgical System REF CX6100; Bausch & Lomb Inc., Rochester NY, USA) on the enucleated canine eyes. A 3.0 mm clear corneal incision was made superiorly with a clear corneal blade (ClearCut™; Alcon Laboratories Inc., Fort Worth, Texas, USA). After injecting 0.4 ml of ophthalmic viscoelastic material (Hyal 2000®; LG Life Sciences, Daejon, Korea), a capsulorhexis was created with a diameter of 6.0 ± 0.5 mm. Phacoemulsification was performed using two bottle height settings. To minimize any variability within the study, the bottle height was set at 50 cm for one eye (Group L) and at 120 cm for the opposite eye (Group H) of the dog. The vacuum pressure in Group L and Group H was 80 mmHg and 150 mmHg, respectively, and the phacoemulsification power limit was set at 40 % in both groups. Phacoemulsification was undertaken using a phaco handpiece with a 19 G, straight 30-degree needle. After injecting 0.6 ml of ophthalmic viscoelastic material again, a foldable soft acrylic one-piece IOL (Acrivet, Salt Lake City, UT, USA) was implanted into the capsular bag. The ophthalmic viscoelastic material was removed by irrigation and aspiration, and each pair of eyes had the same total irrigation time. The corneal incision was closed with 8-0 polyglactin 910 (Vicryl®; Ethicon, Inc., Somerville, NJ, USA). The ultrasound time and the volume of irrigation solution used for each eye and the total irrigation time for each pair of eyes were recorded.

4. CE-MRI

Immediately after phacoemulsification, CE-MRI was carried out on each eye. One eye at a time, and then the other eye, was performed. Not to be influenced by the elapsed time from euthanasia and enucleation, Group H was done first at this time and Group L was first at next time. All the MRI scans were performed in the dorsal and the sagittal plane using a 0.3-T open-bore MRI with a quadrature knee coil (AIRIS Vento; Hitachi Medical Corporation, Tokyo, Japan). The T1-weighted spin-echo images were obtained. Pulsing parameters were TR = 41 ms and TE = 23 ms and the whole volume coverage of the eyeball was acquired using 20 contiguous 1.8 mm slices with 1.0 mm gap. Each image acquisition required 6.5 min. The eyeball was placed corneal side up with corneal incision site at the same position. The CE-MRI findings were evaluated using a modified version of the method used in a previous study (Kawasaki *et al*., 2009). To calculate the leakage volume (LV) of the MRI contrast agent into the vitreous humor to the total vitreous volume (VV) ratio (LV/VV%), T1-weighted images were analyzed using image analysis software (INFINITT PACS; INFINITT Healthcare, Seoul, Korea). Measurements were carried out on all 20 sagittal planes. The first region of interest (ROI) was manually drawn along the outer margin of the vitreous body, and then the second ROI around the contrast-enhanced vitreous area at the signal intensity (SI) above determined threshold level of 300 SI within the first ROI by an experienced radiologist on each slice. The generated areas of two ROIs, combined with the known slice thickness, were then used to calculate LV, VV, and LV/VV%. Drawing an ROI produced a mean SI of the pixels enclosed by the ROI. The mean SI of the contrast-enhanced vitreous area (the second ROI) was recorded to compare between the two groups.

5. Statistical analyses

The Student's *t*-test was used to compare the ultrasound time, the volume of irrigation solution used, the occurrence of AHD, the LV/VV%, and the mean SI of the contrast-enhanced vitreous area between the two groups. The level of significance was set at $P < 0.05$.

Spearman's correlation analysis was used to analyze the relationship between the LV/VV% and the ultrasound time, between the LV/VV% and the total irrigation time, and between the LV/VV% and the volume of irrigation solution used. A value of $P < 0.05$ was considered statistically significant.

Results

The ultrasound time of Group L (mean 117.1 ± 12.1 sec) was longer than that of Group H (mean 95.9 ± 31.4 sec), but no statistically significant difference was found between both groups (Table 1-1). The volume of irrigation solution used in Group L (mean 165 ± 54 ml) was significantly less ($P < 0.001$) than that used in Group H (mean 255 ± 33 ml).

After phacoemulsification, the CE-MRI findings of the PC type and the AHD type were evaluated by the modified method of the previous study (Kawasaki *et al*., 2009). In the PC type, contrast enhancement was seen in the anterior chamber (AC) and the PC but not beneath the posterior lens capsule (PLC) connected to the AHM via hyaloideocapsular ligament (Samuelson, 2007). In the AHD type, contrast enhancement was observed in the AC, the PC, and the space beneath the PLC, pointing to the detachment of the AHM from the PLC. The PC type was seen in three of 10 eyes in Group L and in one of 10 eyes in Group H (Fig. 1-1D). The AHD type was observed in seven of 10 eyes in Group L and in nine of 10 eyes in Group H (Fig. 1-1E). The occurrence of AHD was not significantly different between the two groups.

Independently of the types, contrast enhancement of the vitreous was observed, revealing irrigation fluid leakage into the vitreous. Irrigation fluid leakage into the vitreous humour occurred in all of the eyes in both groups, with the fluid leaking peripherally through the zonular fibers and the peripheral AHM. In all the experimental eyes, the fluid leakage occurred mainly at the opposite side of the corneal incision in the sagittal plane (Fig. 1-1F) and at the left side in the dorsal plane (Fig. 1-1D and E). In all 10 pairs of eyes, the eye in Group H had more leakage than the opposite eye in Group L. The CE-MRI of the sagittal images after phacoemulsification with IOL implantation showed that the amount of leakage into the vitreous body was greater in the same sagittal planes in Group H than in Group L (Fig. 1-2).

The LV/VV% was significantly greater ($P < 0.01$) in Group H (mean 67 ± 14 %) than in Group L (mean 44 ± 14 %). The mean SI of the contrast-enhanced vitreous area was also significantly greater ($P < 0.001$) in Group H (mean 793.63 ± 79.21) than in Group L (mean 636.47 ± 55.77) (Table 1-2).

The LV/VV% was correlated with the total irrigation time in Group L (0.67; $P < 0.05$) and in Group H (0.68; $P < 0.05$). A longer irrigation time was associated with a higher LV/VV% in both groups (Fig. 1-3). However, the LV/VV% was not correlated with the ultrasound time or with the volume of irrigation solution used in both groups.

Table 1-1. Surgical parameters in this study

Parameters	Group L ($n = 10$)	Group H ($n = 10$)	P value[*]
Ultrasound time (sec)	117.1 ± 12.1	95.9 ± 31.4	0.062
Volume of irrigation solution[†] (ml)	165 ± 54	255 ± 33	0.000

Mean ± SD; [*] Student's *t*-test; [†] Significant difference between the two groups ($P < 0.05$).

Table 1-2. Profile of the data from CE-MRI

Parameters	Group L (n = 10)	Group H (n = 10)	P Value[*]
LV/VV[‡] ratio[†] (%)	44 ± 14	67 ± 14	0.001
Mean signal intensity[†]	636.47 ± 55.77	793.63 ± 79.21	0.000

Mean ± SD; [‡] LV/VV, leakage volume to vitreous volume; [*] Student's *t*-test; [†] Significant difference between the two groups ($P < 0.05$).

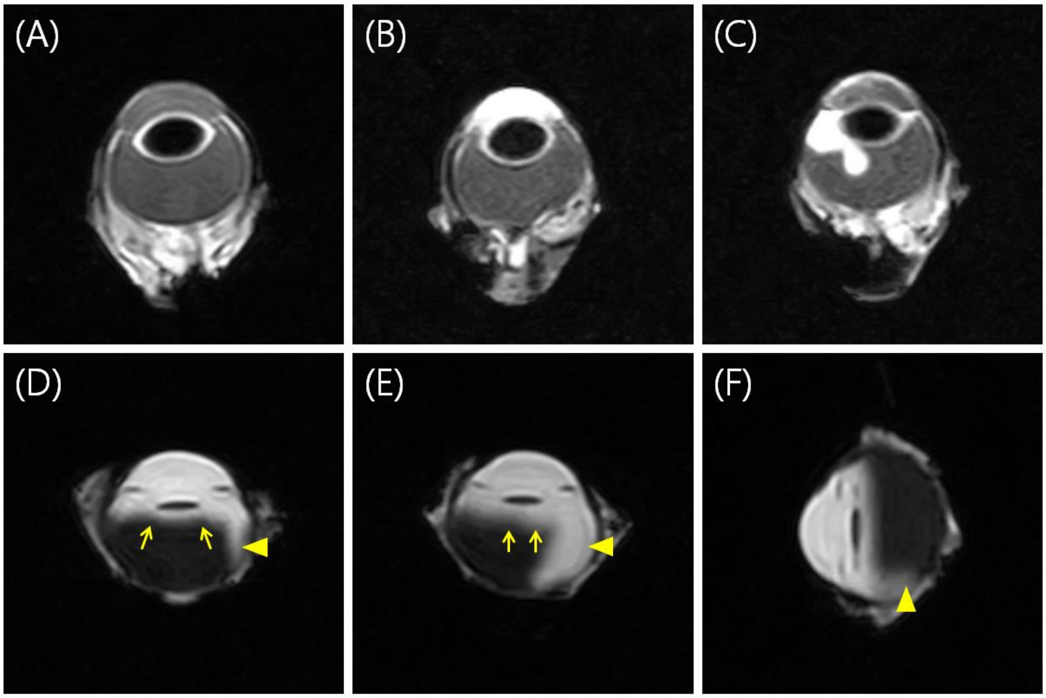


Fig. 1-1. Representative images of CE-MRI findings in the canine eye. (A) CE-MRI dorsal plane image of a normal canine eye; (B) CE-MRI dorsal plane image after intracameral MRI contrast agent injection; (C) CE-MRI dorsal plane image after intravitreal MRI contrast agent injection; (D) the PC type after phacoemulsification with IOL implantation. Note the lack of contrast agent beneath the PLC, the attachment of the AHM (arrows), and the leakage (arrowhead); (E) the AHD type. Note the contrast agent beneath the PLC, the detachment of the AHM (arrows), and the leakage (arrowhead); (F) CE-MRI sagittal image. Note the leakage (arrowhead).

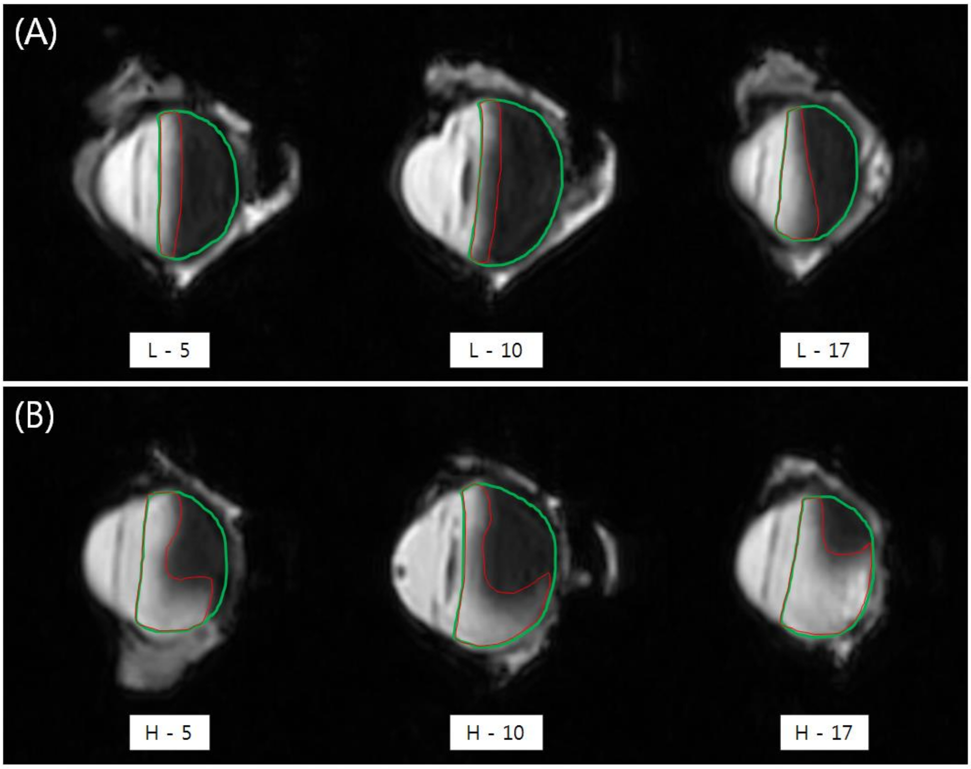


Fig. 1-2. Contrast-enhanced T1-weighted sagittal images of a dog after phacoemulsification with IOL implantation. (A) The 5th, 10th, and 17th sagittal planes among 20 contiguous 1.8 mm slices with 1.0 mm gap of the whole volume coverage of the eyeball in Group L; (B) The same sagittal planes in Group H. The amount of irrigation fluid leakage (red line) into the vitreous body (green line) was greater in Group H than in Group L. In both groups, there was more leakage in the opposite area than the entry site into the AC.

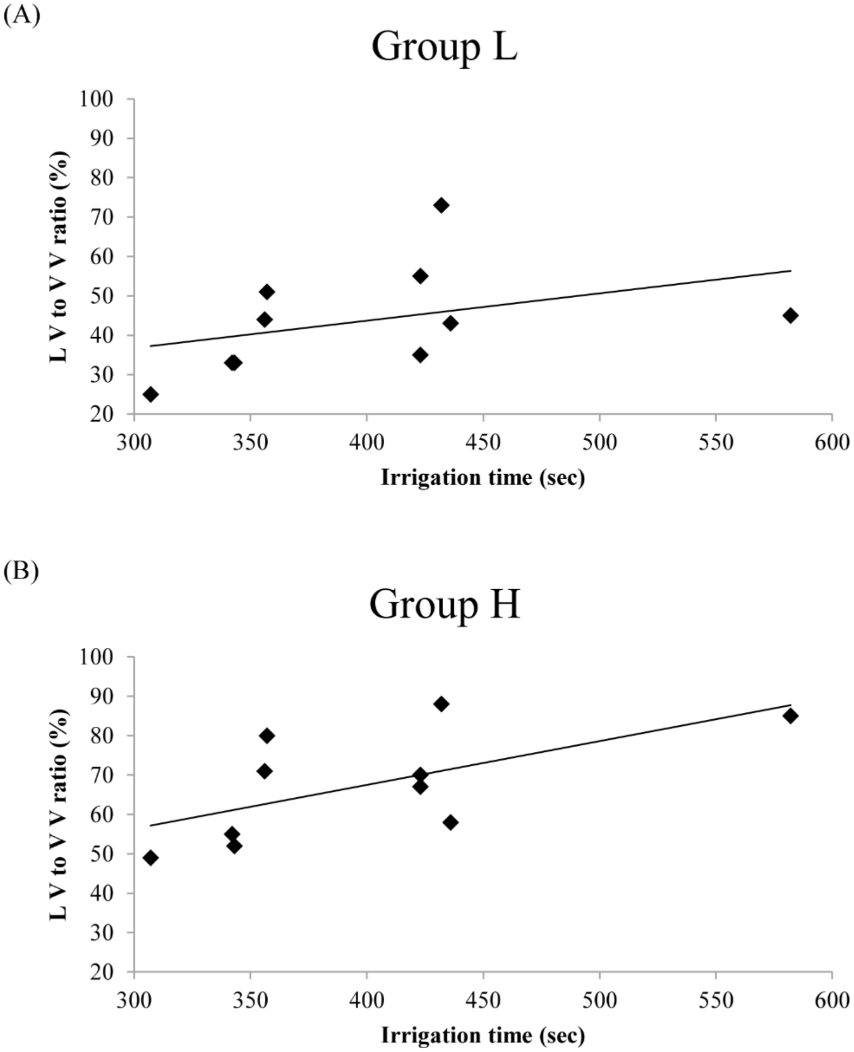


Fig. 1-3. Scatter plots showing the relationship between the LV to VV ratio (%) and the total irrigation time. The LV/VV% was correlated with the total irrigation time in Group L (A, Spearman's coefficient = 0.67; *P* = 0.035) and Group H (B, Spearman's coefficient = 0.68; *P* = 0.030).

Discussion

This study demonstrated that irrigation fluid leakage into the vitreous humour, as well as AHD, occurred during phacoemulsification in canine eyes. A previous porcine study demonstrated that AHD was not observed in the eyes when the whole surgery generally took 4 min but that it had a strong association with prolonged surgeries that involved an additional 5 min with total surgery time being 9 min or above (Kawasaki *et al*., 2009). In this study, it took 21.9 ± 6.4 min (mean ± SD) to perform the phacoemulsification in the canine eyes. The AHD occurred in seven of the 10 eyes in Group L and in nine of the 10 eyes in Group H, showing no significant difference between the groups. Irrigation fluid leakage into the vitreous humor occurred peripherally around the zonule in all the eyes in both groups. Therefore, the longer duration of phacoemulsification surgery in canine eyes compared to the same surgery in the porcine eyes (Kawasaki *et al*., 2009) may adversely affect the intraocular tissues.

Irrigation fluid leakage was most severe at the opposite and left sides of the corneal incision in all eyes of both groups. Relatively large volumes of irrigation fluid could flow into the opposite side of the entrance of the phaco tip into the AC. With right-handed surgeons, including the surgeon in this study, the volume of fluid flow would also be larger in the left side based on the fluid dynamics during phacoemulsification. Therefore, the water pressure of these sites could be higher during phacoemulsification, enabling a larger amount of irrigation fluid to leak through the zonule.

It has been documented that IOP levels and IOP fluctuations with higher bottle heights are greater than with lower bottle heights (Suzuki *et al*., 2009; Vasavada *et al*., 2010). In this study, the eyes in Group H showed significantly wider and greater leakage than those in Group L. The higher intraoperative IOP and excessive fluid turnover with higher fluidic parameters might induce more forceful movement of the irrigation fluid into the PC and the zonule, the route into the vitreous cavity, and allow the fluid to penetrate the peripheral AHM. The AHM which consist of the anterior vitreous face is not a membrane in the ultrastructural sense but condensations of fibrils (Boeve and Stades, 2007). Therefore, forceful movement of the irrigation fluid made the tear or disruption of the AHM and the irrigation fluid leaked into the vitreous humour. If microorganisms are introduced into the AC during surgery, they can also enter the vitreous humour along with the irrigation fluid, despite the intact PLC. It has been demonstrated that microbial contamination of the AC occurs during phacoemulsification in both human and veterinary ophthalmology (Taylor *et al.*, 1995; Ledbetter *et al.*, 2004; Kawasaki *et al.*, 2009) and that the progression from contamination to endophthalmitis may be associated with the integrity of the PLC, which prevents microorganisms from entering the vitreous cavity by confining them to the AC (Beyer *et al.*, 1984; Beyer *et al.*, 1985; Taylor *et al.*, 1995; Ledbetter *et al.*, 2004). Rupture of the PLC during surgery may enable the microorganisms that have entered the AC to migrate into the vitreous cavity without difficulty, thereby increasing the incidence of postoperative endophthalmitis (Beyer *et al.*, 1984; Beyer *et al.*, 1985; Taylor *et al.*, 1995; Ledbetter *et al.*, 2004). However, the present study showed that despite an intact PLC, it is possible for microorganisms to enter the vitreous humor and that higher fluidic settings are associated with significantly broader and greater leakage than lower fluidic settings. This may be one reason why endophthalmitis occurs in eyes that have undergone phacoemulsification without any intraoperative complications (Kawasaki *et al.*, 2009).

A previous experimental primate study demonstrated that AC infections are more easily controlled than vitreous cavity infections (Beyer *et al.*, 1984). If postoperative endophthalmitis develops from a vitreous cavity infection, aggressive treatments, such as vitreous tap or vitrectomy and intravitreal medications, would be needed to prevent any permanent vision loss (Beyer *et al*., 1985).

The leakage of lens proteins into the vitreous humour during phacoemulsification suggested by this study might exacerbate LIU, leading to the sequelae of chronic persistent uveitis, including cyclitic membranes, synechiae, retinal detachment, phthisis bulbi, and glaucoma (Apple *et al*., 1984; van der Woerdt, 2000). More recently, lens fragments seen behind the PLC during phacoemulsification were suggested to indicate the passage of fluid through the zonules into the anterior vitreous, which was a potential complication of all surgeries, even those with good surgical outcomes (Bellucci, 2006). A previous study also reported that dislocation of lens fragments into the vitreous cavity during phacoemulsification due to zonular dehiscence or rupture of the PLC induces secondary glaucoma, uveitis, retinal detachment, and cystoid macular edema in human eyes (Moisseiev *et al*., 2011).

In the present study, a longer total irrigation time was associated with a higher LV/VV% in both groups, suggesting that longer irrigation times during phacoemulsification surgery result in more severe leakage of lens proteins into the vitreous cavity. As the canine lens is much larger and harder than the human lens, phacoemulsification would require a longer irrigation time compared to surgery of the human lens, resulting in more severe leakage of lens proteins into the vitreous humor (Cook, 2008). This may explain why the incidence of retinal detachment following phacoemulsification, which is believed to be due to surgery-induced structural changes within the vitreous, is higher in canine eyes than in human eyes (2–8% vs. 1–3%, respectively), without consideration of surgical experience (Moore *et al*., 2003). Moreover, the possible leakage of lens fragments into the peripheral vitreous as shown in this study can cause chorioretinitis, which may contribute to retinal detachment, especially at higher fluidic settings. Studies have shown that the vitreous body gradually liquefies and that zonules become permeable to fluid with age (Harocopos *et al*., 2004; Bellucci, 2006). A canine ultrasonographic study documented that the prevalence of vitreous degeneration had a tendency to increase with the maturity of the cataract, although not significantly so (van der Woerdt *et al*., 1993). Mature or hypermature cataractous or older eyes may be at risk for more severe leakage of lens proteins into the vitreous humour. In such cases, phacoemulsification parameters, such as the ultrasound energy, the vacuum level, and the irrigation fluid rate, would need to be carefully controlled to avoid unnecessary damage to the eye and to prevent postoperative complications.

The introduction of low-power phacoemulsification has reduced the duration and the amount of ultrasound energy, but higher fluidic settings are needed with low-level ultrasound. Studies have shown that this creates additional complications besides those related to ultrasound energy (Vasavada and Raj, 2003; Bellucci, 2006). Similarly, in the current study, the LV/VV% was significantly greater at higher fluidic settings (Group H) than at lower fluidic settings (Group L), and the LV/VV% was not correlated with the ultrasound time. Studies have documented that lower fluidic parameters can improve postoperative outcomes compared to higher parameters, with decreased anterior uveitis and corneal endothelial damage reported in human clinical trials (Suzuki *et al*., 2009; Vasavada *et al*., 2010). In particular, these studies suggested that large increases and fluctuations in intraoperative IOP at higher fluidic settings increase surgical trauma to the eye. In the present study, the volume of irrigation solution used in Group L was significantly less than that used in Group H. Thus, the lower fluidic settings, with the ultrasound energy tailored to the grade of the cataract, could reduce damage to the anterior segment of the eye by decreasing the hydrodynamic stress arising from turbulence of the irrigation solution, as well as minimizing damage to the posterior segment of the eye by helping to prevent irrigation fluid leakage into the vitreous humour.

A limitation of this study was that enucleated canine eyes do not exhibit physiological aqueous flow. Therefore, the structural integrity of the eye might have been weakened. However, as the phacoemulsification was performed on all the eyes within 6 hours after euthanasia and enucleation, the changes in the ocular integrity were minimized. This study showed that irrigation fluid leakage into the vitreous humour occurred in eyes undergoing phacoemulsification cataract surgery, with the leakage significantly greater at higher fluidic settings. The leakage may lead to structural changes within the vitreous and contribute to postoperative complications. A further study using ultrasonography would be needed to determine whether the vitreous body of the eye shows structural changes after phacoemulsification compared to that of the nonoperated fellow eye.

Conclusions

Lower fluidic parameters led to significantly less irrigation fluid leakage into the vitreous humour than higher fluidic parameters. This might decrease the possibility of microorganisms or lens particles passing into the vitreous humour with the irrigation fluid. In addition, the lower fluidic parameters significantly decreased the amount of irrigation solution used, thereby potentially reducing the stress on the intraocular tissues during phacoemulsification surgery in the dog.

CHAPTER II.

Fluid Dynamics and Intraocular Pressure Using Venturi Phacoemulsification Machine in Dogs Ex Vivo

Abstract

The purpose of this study was to optimize fluid dynamics through measuring IOP in a venturi phacoemulsification machine in dogs. In step I, flow and IOP of the test chamber were measured using a pressure transducer with the bottle height (BH) set at 50, 70, 100, and 120 cm and the vacuum from 30 to 450 mmHg. A 19 G phaco and a 0.3 mm irrigation/aspiration (I/A) handpiece were used. In step II, flow and IOP were measured in an enucleated canine eye with a 3.0 and a 3.2 mm clear corneal incision (CCI), respectively. IOP was measured using the pressure transducer at a 30 mmHg vacuum to allow corneal deformation, in order to define the fluidic parameters for preventing surge. Flow was directly proportional to the BH and vacuum, whereas IOP was directly proportional to the BH and inversely to the vacuum. Flow with an I/A handpiece was significantly less than with a phaco handpiece, explaining why IOP with an I/A handpiece was significantly higher than with a phaco handpiece. With the I/A handpiece, vacuum parameters less than 450 mmHg did not result in corneal deformation. IOP with a 3.2 mm CCI was significantly lower than with a 3.0 mm CCI, with the 3.2 mm flow being greater than the 3.0 mm flow. BH during the I/A stage could be reduced to avoid unnecessary stress on the canine eye when using a venturi system. Although phacoemulsification with a 3.2 mm CCI could induce lower IOP, a 3.0 mm CCI might lessen the irrigation flow stress on the eye.

Introduction

Phacoemulsification with IOL implantation has been the most commonly performed cataract surgery in veterinary ophthalmology for the past three decades (Biros *et al.*, 2000; Sigle and Nasisse, 2006). Even though many efforts have been made to improve the success rate of phacoemulsification, complications still occur after surgery.

Phacodynamics has been reported as one of the important contributing factors to postoperative complications following phacoemulsification (Vasavada and Raj, 2003; Suzuki *et al.*, 2009; Vasavada *et al.*, 2010; Kawasaki *et al.*, 2011). To improve the success rate of phacoemulsification, the surgeon must understand the parameters of BH, ultrasound energy, vacuum, and flow. Anterior chamber pressure is directly proportional to the BH. The flow attracts lenticular fragments, the vacuum holds them, and ultrasound energy is used to emulsify the crystalline lens (Seibel, 2005; Wilkie and Colitz, 2007). The flow and vacuum also maintain an adequate anterior chamber depth, while the emulsate is aspirated. Anterior chamber stability is maintained by the balance between the influx of irrigating fluid and both the efflux of aspirating fluid and incisional fluid loss (Liyanage *et al.*, 2009; Sharma *et al.*, 2012).

Postocclusion surge is thought to be created by decompression of the elastic aspiration system following occlusion break, overwhelming the inflow and inducing an unstable anterior chamber (Georgescu *et al.*, 2007; Ward *et al.*, 2008). The BH and aspiration rate can be adjusted to overcome the surge as it can induce intraoperative and postoperative complications (Ward *et al.*, 2008). Surge decreases with increasing BH and decreasing aspiration rate (Georgescu *et al.*, 2007).

Even though a higher BH prevents surge, this also elevates IOP during phacoemulsification (Seibel, 2005; Suzuki *et al*., 2009). IOP during phacoemulsification is determined by the irrigating pressure originating from the BH, vacuum pressure, aspiration rate, and incisional fluid leakage (Suzuki *et al*., 2009). Direct measurement of IOP using a pressure transducer has been reported to provide adequate information about the dynamic changes of IOP according to these parameters (Blumenthal *et al*., 1992; Grinbaum *et al*., 2003; Khng *et al*., 2006; Zhao *et al*., 2009). In this study, the real time IOP and flow were directly measured at various settings of BH and vacuum and with two different sized corneal incisions. The measurements of flow and IOP were performed through in vitro and ex vivo experiments. The purpose of this study was to define the fluidic parameters of a venturi phacoemulsification machine for preventing surge and IOP elevation in dogs.

Materials and Methods

Step I: in vitro experiments

1. Measurement of flow with a simulated anterior chamber

A phacoemulsification machine (Millennium^{TM} Microsurgical System REF CX6100; Bausch & Lomb Inc., Rochester NY, USA) using a venturi pump was equipped with a phacoemulsification handpiece with a 19 G, straight 30-degree needle. The handpiece was inserted into a BSS-filled silicone test chamber to simulate the closed system of an anterior chamber to identify the actual flow (Adams *et al*., 2006). The I/A tubing set and the handpiece, except for the cassette, were filled with BSS. The handpiece was placed so that the actual distance from this to the bottle was the same as the BH displayed on the device. BSS in a 500 mL plastic bag was used for the irrigation/aspiration fluid in all experiments. The BH was set at 50, 70, 100, and 120 cm. The vacuum was set from 30 to 450 mmHg for each BH in all experiments. The flow of BSS was collected for one minute (mL/min) in the I/A mode, and the aspirate was measured using a graduated cylinder. An I/A handpiece with a 0.3 mm aspiration port attached to the test chamber was installed subsequent to the phaco handpiece. Three measurements were performed at each setting, with the foot controller of the phacoemulsification machine fully depressed.

2. Measurement of simulated IOP using a test chamber

A pressure transducer was connected to the BSS-filled silicone test chamber to measure the simulated IOP, or pressure of the test chamber. The measuring system consisted of four parts: 26 G needle, pressure transducer (List No. 42584-05; Hospira, Inc., Lake Forest, IL, USA), monitoring cable (List No. 42661-40; Hospira, Inc.), and monitor (Datex-Ohemada S/5, Helsinki, Finland). After zeroing the pressure transducer, the needle connected to the pressure transducer was inserted through the apex of the BSS-filled silicone test chamber (Fig. 2-1A). The monitor instantly showed the simulated IOP. The transducer was multipoint calibrated on a mercury manometer before the measurement. No leakage was observed around the 26 G needle or between the handpiece and test chamber, thus allowing accurate measurement of the simulated IOP and maintaining a closed system.

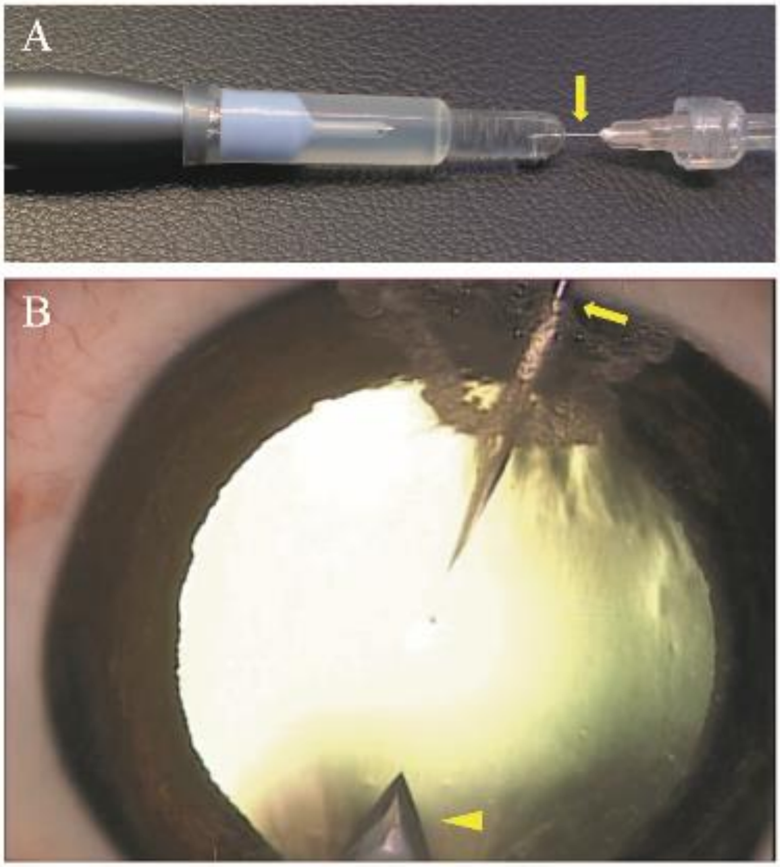


Fig. 2-1. Measuring methods of the flow and IOP. (A) Step I – The phacoemulsification handpiece inserted into the BSS-filled silicone test chamber connected to the needle of the pressure transducer (arrow); (B) Step II – The pressure transducer (arrow), being secured with a drop of tissue adhesive, was inserted into the eye, and corneal incision was performed on the opposite site (arrowhead).

Step II: ex vivo experiments

3. Preparation of canine eyes

Two pairs of normal eyes without ocular diseases were obtained from two adult beagle dogs that were euthanized for an unrelated cause. All experimental procedures were performed within six hours of euthanasia. One eye was used for a 3.0 mm CCI, and the opposite eye of the same dog was used for a 3.2 mm CCI. One pair of eyes was used for the measurement of flow and the other pair for the measurement of IOP. This study was approved by the Institutional Animal Care and Use Committee of Seoul National University (SNU-140219-5).

4. Measurement of flow in canine ex vivo eyes

One eye was placed at the same height where the simulated flow and IOP were measured. A 3.0 mm CCI was made using a clear corneal blade (ClearCut^{TM}; Alcon Laboratories Inc., Fort Worth, Texas, USA). The original weight (g) of BSS in a 500 mL plastic bag (A) was measured in advance and hung up on the phacoemulsification machine with the I/A tubing set and the handpiece filled with BSS. The handpiece was inserted through a 3.0 mm CCI. The vacuum was set at 100 mmHg on each setting for the four BHs. After fully depressing the foot controller for a minute, the weight of BSS in the plastic bag (B) was measured. To obtain the total flow including the aspirated volume in the cassette and the volume of the corneal incisional leakage, the difference between the two weights (A minus B) was converted into the volume (mL) using the calculated specific gravity (= 1.03). The same procedure was then performed on the opposite eye with a 3.2 mm CCI as outlined above.

5. Measurement of IOP in canine ex vivo eyes

The needle connected to 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 needle was secured with a drop of tissue adhesive (Vetbond® ; 3M, Saint Paul, Minnesota, USA) to prevent it from being pulled out during several IOP measurements. A 3.0 mm CCI was made at the 12 o'clock position of the peripheral cornea (Fig. 2-1B). The handpiece was inserted through the CCI. Pressure measurement was performed from the vacuum of 30 mmHg to that showing corneal deformation at each BH. Throughout the measurements, the leakage around the needle was checked using microsurgical sponge spears. On the other eye, a 3.2 mm CCI was performed. The procedures outlined above were repeated.

6. I/A tubing set

The above measurements were performed using a disposable (Premium Venturi Phaco Pack single use; Bausch & Lomb Inc., Rochester NY, USA) and a reusable (Venturi Phaco Pack reusable; Bausch & Lomb Inc., Rochester NY, USA) I/A tubing set one after the other, except for the flow in step II, which was measured using only disposables because of deterioration of the eye condition. The reusable tubing set was more flexible than the disposable, providing a higher compliance for the I/A system of the phacoemulsification machine.

7. Statistical analyses

The mean flow (mL/min) of three measurements with a simulated anterior chamber was obtained. The Student's *t*-test was used to compare flows and simulated IOPs in vitro and the 3.0 and 3.2 mm IOPs between the phaco and I/A handpieces and between the disposable and reusable tubing sets. The Mann–Whitney *U* test was used to compare flows between the 3.0 and 3.2 mm CCIs. The one-sample t-test was used to compare the 3.0 and 3.2 mm IOPs. A multiple linear regression model was used to analyze the flow and simulated IOP in vitro and 3.0 and 3.2 mm IOP, dependent on the vacuum and bottle height. The coefficient of determination (r^2) was obtained from each regression model. Statistical significances were assessed at the 5% level for all analyses used.

Results

1. Step I: in vitro experiments

Flow was directly proportional to the BH and vacuum (Tables 2-1 and 2-2). Both the intercept and slope of the I/A handpiece were larger than those of the phaco handpiece (Fig. 2-2). Flow with the I/A handpiece was significantly less than that with the phaco handpiece ($P < 0.001$). The data from the Student's *t*-test are shown in Table 2-3.

Measured IOP was close to the theoretical pressure determined by the following formula (Wilbrandt and Wilbrandt, 1993):

Pressure = BH (cm) x 10/13.59 (the specific gravity of water/mercury)

Simulated IOP was directly proportional to the BH and inversely proportional to the vacuum (Tables 2-1 and 2-2). Simulated IOP with the I/A handpiece was significantly higher than that with the phaco handpiece ($P < 0.001$).

Table 2-1. Variables of multiple linear regression model in disposable tubing set

Dependent variables (Y)		Intercept (α)	Vacuum (X_1) Slope (β_1)	Bottle height (X_2) Slope (β_2)	P Value	r^{2*}
Phaco handpiece	Flow	9.277	0.157	0.158	2.2×10^{-16}	0.994
	Simulated IOP	11.651	-0.232	0.564	2.2×10^{-16}	0.991
	3.0 mm IOP	14.764	-0.226	0.473	2.2×10^{-16}	0.988
	3.2 mm IOP	6.409	-0.162	0.331	4.3×10^{-13}	0.978
I/A handpiece	Flow	9.001	0.045	0.034	2.2×10^{-16}	0.987
	Simulated IOP	3.345	-0.036	0.742	2.2×10^{-16}	0.997
	3.0 mm IOP	11.038	-0.037	0.667	6.2×10^{-15}	0.997
	3.2 mm IOP	1.796	-0.038	0.657	8.5×10^{-12}	0.994

[*] r^2, coefficient of determination; All regression models were significant ($P < 0.001$); $Y = \alpha + \beta_1 X_1$ (mmHg) $+ \beta_2 X_2$ (cm).

Table 2-2. Variables of multiple linear regression model in reusable tubing set

Dependent variables (Y)		Intercept (α)	Vacuum (X_1)	Bottle height (X_2)	P Value	r^{2*}
			Slope (β_1)	Slope (β_2)		
Phaco handpiece	Flow	14.224	0.156	0.151	2.2×10^{-16}	0.990
	Simulated IOP	11.691	-0.272	0.496	2.2×10^{-16}	0.997
	3.0 mm IOP	12.291	-0.262	0.436	2.2×10^{-16}	0.994
	3.2 mm IOP	4.972	-0.185	0.296	9.3×10^{-12}	0.990
I/A handpiece	Flow	8.717	0.045	0.045	2.2×10^{-16}	0.983
	Simulated IOP	5.315	-0.037	0.719	2.2×10^{-16}	0.998
	3.0 mm IOP	8.423	-0.037	0.649	1.1×10^{-14}	0.999
	3.2 mm IOP	-0.560	-0.041	0.579	7.3×10^{-7}	0.957

[*] r^2, coefficient of determination; All regression models were significant ($P < 0.001$); $Y = \alpha + \beta_1 X_1$ (mmHg) + $\beta_2 X_2$ (cm).

Table 2-3. Profile of the data from the Student's *t*-test

	Disposable tubing set			Reusable tubing set		
	Phaco handpiece	I/A handpiece	*P* Value*	Phaco handpiece	I/A handpiece	*P* Value*
Flow (mL/min)†	55.1 ± 21.2	21.2 ± 6.1	<0.001	59.2 ± 21.0	21.8 ± 6.1	<0.001
Simulated IOP (mmHg)†	34.6 ± 19.3	58.9 ± 20.8	<0.001	29.7 ± 17.2	58.6 ± 20.2	<0.001
3.0-mm IOP (mmHg)†	28.8 ± 18.4	56.2 ± 20.0	<0.001	26.1 ± 15.9	55.2 ± 19.5	<0.001
3.2-mm IOP (mmHg)†	19.7 ± 11.0	51.2 ± 20.4	<0.001	16.9 ± 9.5	39.3 ± 18.3	<0.001

Mean ± SD; * Student's *t*-test; † Significant difference between the two groups ($P < 0.05$).

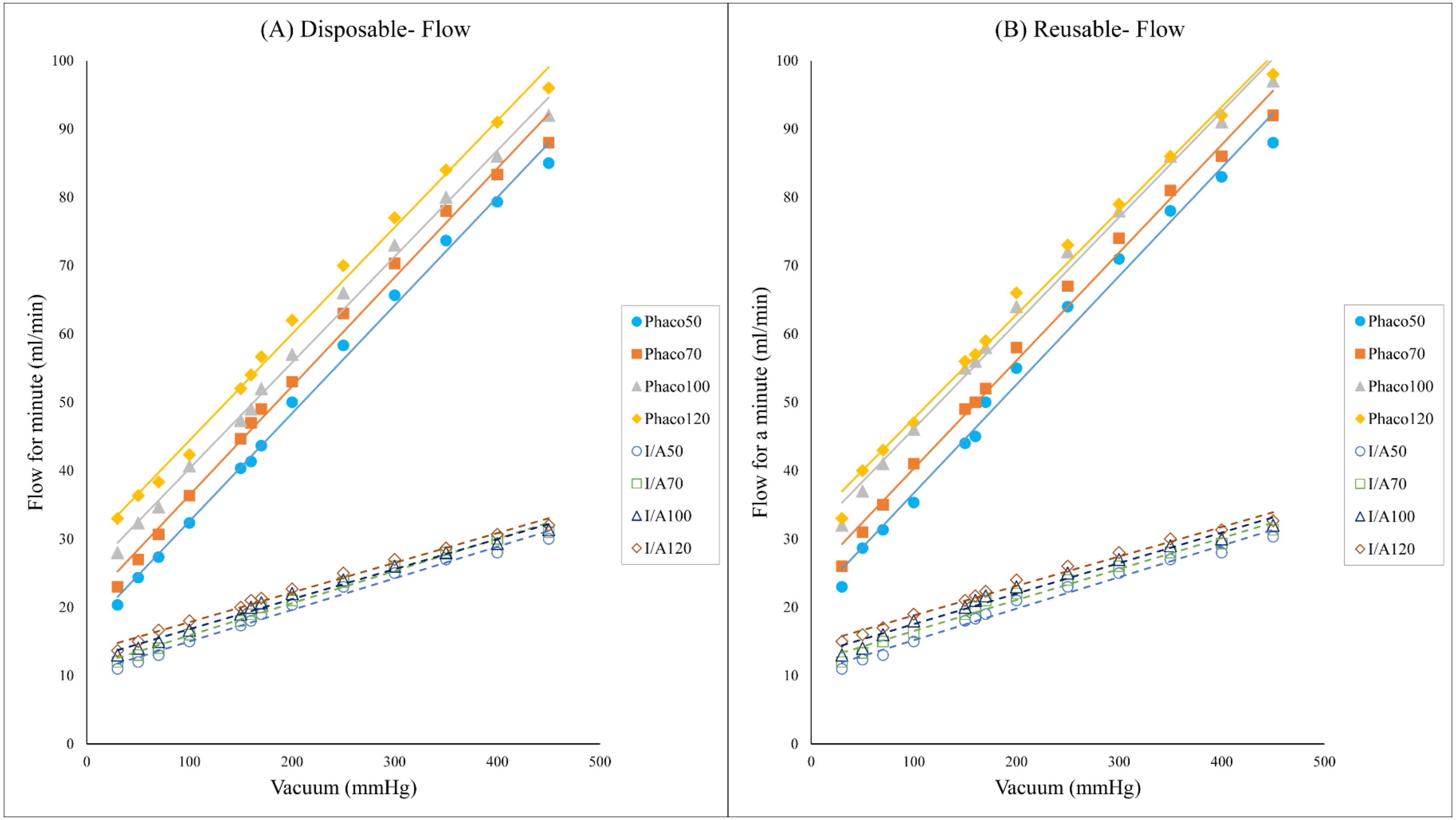


Fig. 2-2. Flow with phacoemulsification and I/A handpiece. The bottle height was set at 50, 70, 100, and 120 cm in disposable (A) and reusable (B) tubing set of Step I. The flow was directly proportional to the vacuum and bottle height. Both intercept and slope of I/A handpiece were larger than those of phaco handpiece.

2. Step II: ex vivo experiments

Both the 3.0 and 3.2 mm IOPs were directly proportional to the BH and inversely proportional to the vacuum (Tables 2-1 and 2-2). IOP with the I/A handpiece showed fewer changes according to vacuum increase than that with the phaco handpiece. IOP with the I/A handpiece was significantly higher than with the phaco handpiece for both the 3.0 and 3.2 mm CCIs (both $P < 0.001$). There was no corneal deformation with the I/A handpiece for all four BHs and the two CCIs. The lowest IOPs with the I/A handpiece were 12 and 20 mmHg in the reusable and disposable tubing sets, respectively, under the condition of the BH/vacuum set at 50 cm/450 mmHg in the 3.2 mm CCI eye. The fluidic parameters inducing corneal deformation with the phaco handpiece are shown in Fig. 2-3.

Flow and simulated IOP in vitro and the 3.0 and 3.2 mm IOPs of the phaco and I/A handpiece (dependent variable; Y), according to the vacuum and BH (explanatory variables; X_1 and X_2, respectively), were predictable using the multiple linear regression model. All regression models were significant ($P < 0.001$). Dependent and explanatory variables, regression coefficients, and the coefficient of determination (r^2) obtained from each regression model are listed in Tables 2-1 and 2-2. The multiple regression equation including the regression coefficients (intercept; α, slope of vacuum; β_1, slope of BH; β_2) was as follows:

$$Y = \alpha + \beta_1 X_1 \text{ (mmHg)} + \beta_2 X_2 \text{ (cm)}$$

Table 2-4 shows the flows in step II. The flow with the I/A handpiece was significantly less than with the phaco handpiece in both the 3.0 and 3.2 mm CCIs (both $P = 0.029$, Mann–Whitney U test). The 3.2 mm flow was greater than the 3.0 mm flow in the phaco handpiece, but the difference was not significant ($P = 0.114$). With the I/A handpiece, the 3.2 mm flow was significantly greater than the 3.0 mm flow ($P = 0.029$).

3. I/A tubing set

The reusable tubing set was greater in flow and lower in IOP than the disposable one, but the differences were not significant.

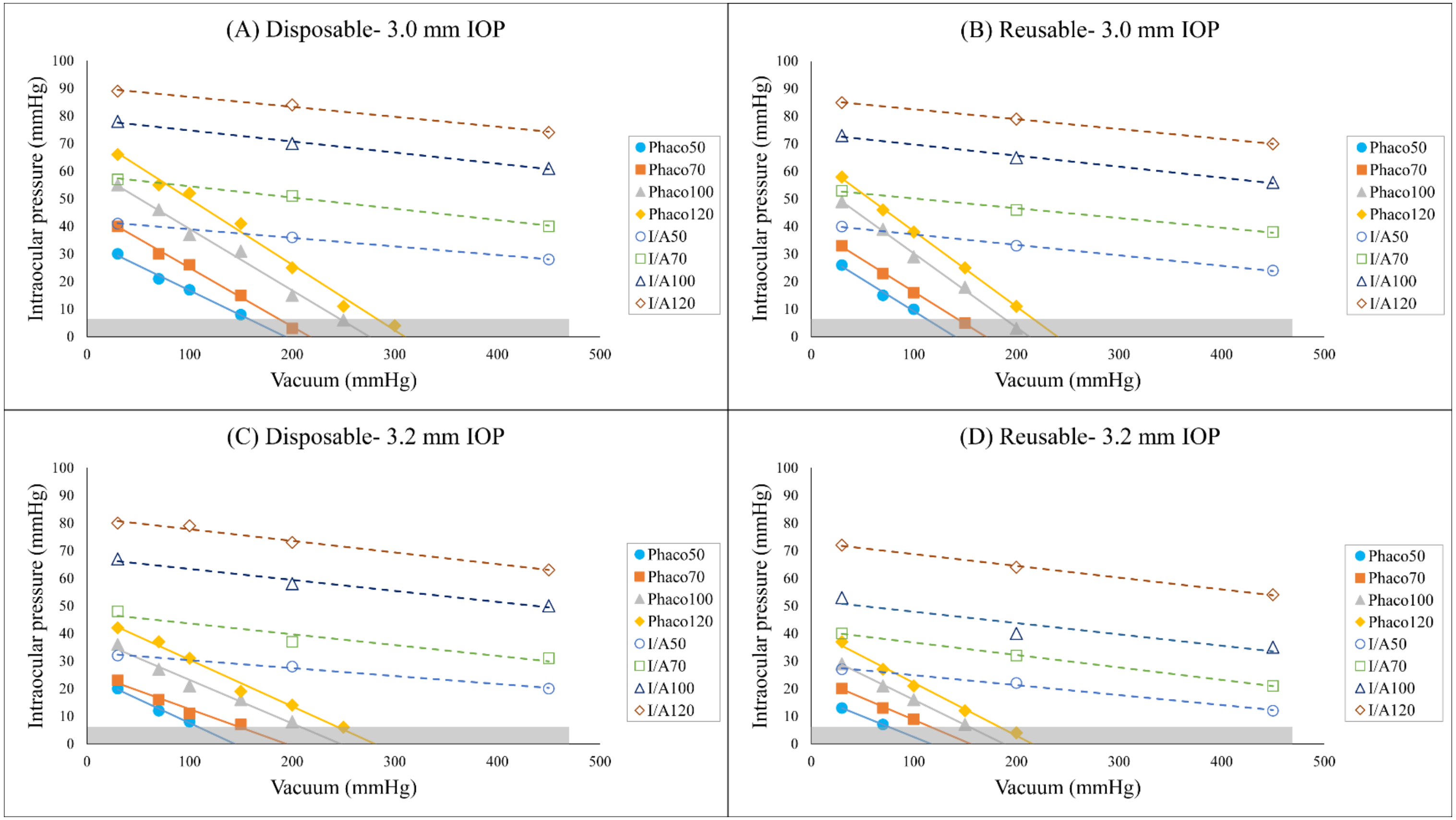
With both the disposable and reusable tubing set, the 3.0 mm IOP was significantly higher than the 3.2 mm IOP (*P* < 0.001, one-sample t-test). The IOP difference between 3.0 and 3.2 mm was 12.7 and 14.6 with the disposable and reusable tubing sets, respectively (Fig. 2-4).

The difference between the simulated and the 3.0 mm IOP was 2.4 and 3.7 and between the simulated and the 3.2 mm IOP was 15.3 and 18.7 in the disposable and reusable tubing sets, respectively. IOP differences were always larger with the reusable tubing set than the disposable one.

Table 2-4. Flow of canine ex vivo eyes with disposable I/A tubing set

	Flow with 3.0 mm CCI [*] (mL)		Flow with 3.2 mm CCI (mL)	
Bottle height (cm)	Phaco handpiece	I/A handpiece	Phaco handpiece	I/A handpiece
50	39	16	45	27
70	40	21	46	26
100	43	25	53	32
120	49	25	56	38

[*] CCI, clear corneal incision.



(A) Disposable- 3.0 mm IOP

(B) Reusable- 3.0 mm IOP

(C) Disposable- 3.2 mm IOP

(D) Reusable- 3.2 mm IOP

Fig. 2-3. IOP with phacoemulsification and I/A handpiece of 4 bottle heights in disposable and reusable tubing set of Step II. IOP with 3.0 mm CCI (A) and 3.2 mm CCI (B) in disposable tubing set and IOP with 3.0 mm CCI (C) and 3.2 mm CCI (D) in reusable one. IOP with the I/A handpiece experienced fewer changes according to vacuum increase than that with the phaco handpiece. The shaded area indicates the bottle height/vacuum showing corneal deformation. Corneal deformation occurred around IOP of 5 mmHg. In IOP with I/A handpiece of both tubing sets, every vacuum less than 450 mmHg showed no corneal deformation at all four bottle heights.

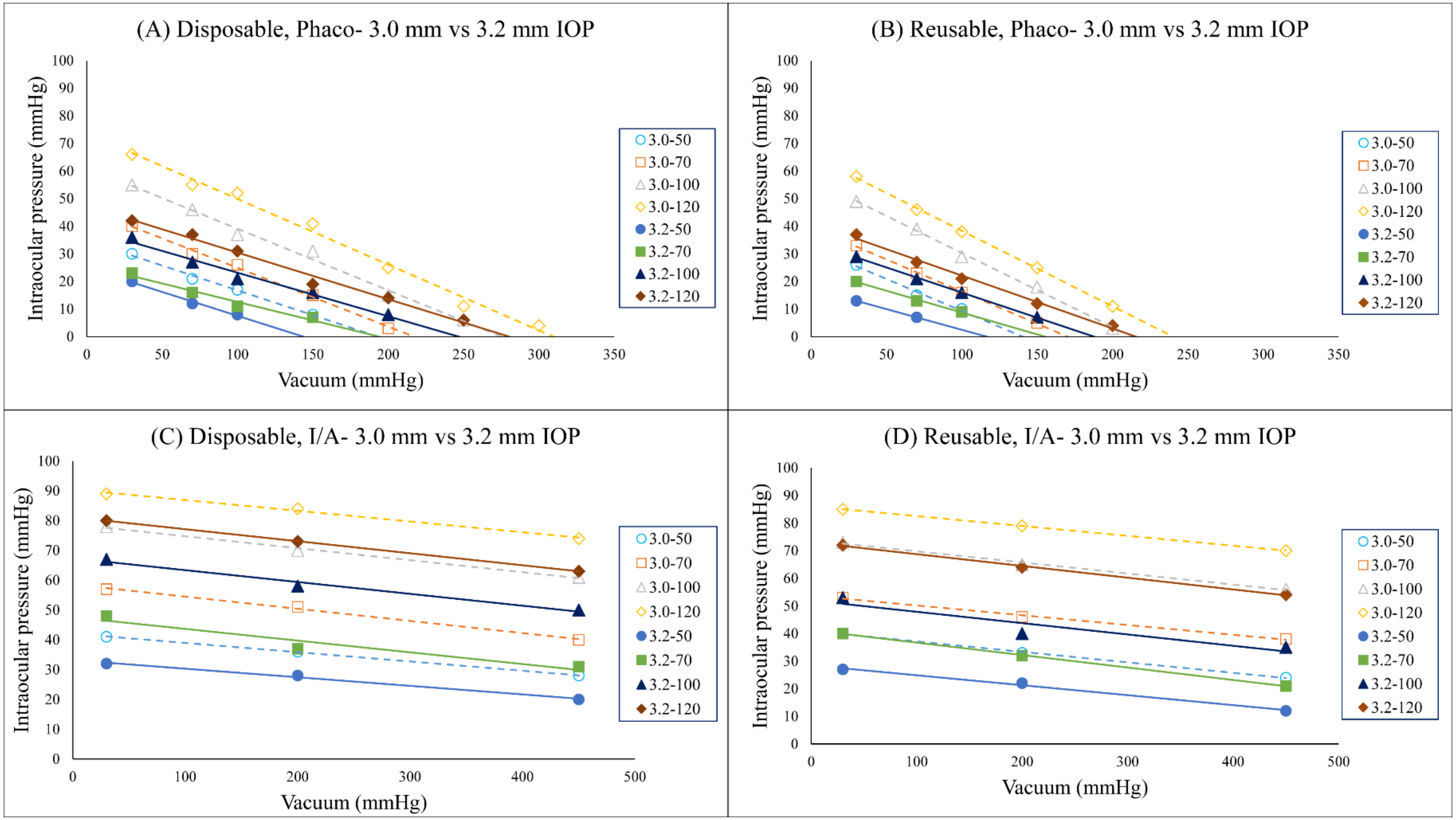


Fig. 2-4. IOP with 3.0 and 3.2 mm CCI of 4 bottle heights in disposable and reusable tubing set of Step II. IOP with phaco (A) and I/A (B) handpiece in disposable tubing set and IOP with phaco (C) and I/A (D) handpiece in reusable one.

Discussion

During each stage of the phacoemulsification procedure, IOP has been reported to fluctuate (Grinbaum *et al*., 2003, Khng *et al*., 2006; Zhao *et al*., 2009). Either hypotony or IOP elevation may lead to complications during and after phacoemulsification (Blumenthal *et al*., 1992). It has been suggested that surge with IOP decreasing to the lowest level may induce posterior capsule rupture, dropped lens material, and vitreous prolapse, increasing the risk of endophthalmitis and cystoid macular edema in human studies (Georgescu *et al*., 2007; Ward *et al*., 2008). IOP elevation has been associated with pain or intermittent visual phenomena of some human patients during surgery, nonarteritic anterior ischemic optic neuropathy (Khng *et al*., 2006; Zhao *et al*., 2009), corneal endothelial damage (Suzuki *et al*., 2009), and glaucoma progression (Vasavada *et al*., 2010). Therefore, anterior chamber stability accompanied by appropriate IOP is essential for minimizing complications through maintaining the microenvironment for intraoperative control (Liyanage *et al*., 2009; Sharma *et al*., 2012).

This study reports multiple regression equations for the prediction of flow and IOP according to the vacuum and BH in a venturi phacoemulsification machine. Using these equations, the fluidic parameters could be adjusted to prevent surge, and intraoperative IOP could be predicted during phacoemulsification surgery in the dog.

In the venturi system, only the level of vacuum, not the flow rate, can be controlled, and the aspiration flow rate was known to be directly dependent on and proportional to the vacuum (Seibel, 2005). In the present study, the actual flow according to each vacuum at various BHs was measured, and it was verified that the flow was directly proportional to the vacuum and BH. The values obtained for flow over one minute in this study would provide the aspiration flow rate (mL/min) for the venturi pump, which could be a helpful reference for phacodynamic studies of the venturi pump machine. Such studies are relatively rare compared to those for the peristaltic pump machine (Adams *et al*., 2006; Zhao *et al*., 2009).

In this study, it was demonstrated that flow with the phaco handpiece was more than twice that with the I/A handpiece. IOP with the I/A handpiece was expected to be even higher than that with the phaco handpiece. In both the simulated IOP and IOP with canine ex vivo eyes, IOP with the I/A handpiece was significantly higher than with the phaco handpiece, suggesting that the BH could be reduced during the I/A stage to avoid unnecessary stress on the eye. Higher IOP has been reported as hazardous to glaucoma or other vascular compromise (Vasavada *et al*., 2010) and corneal endothelial damage (Suzuki *et al*., 2009). It is also important to define the fluidic parameters preventing surge as well as IOP elevation for performance effectiveness during the phaco procedure. This study suggested a fluidic parameter guideline for preventing surge on the basis of showing corneal deformation. These parameters might also be adjusted by observing the trampolining of the posterior capsule or cornea during surgery.

In this study, the difference was small in the simulated vs the 3.0 mm IOP, meaning that the 3.0 mm CCI phacoemulsification approached a closed system. The incisional fluid loss could adversely affect anterior chamber stability (Liyanage *et al*., 2009) or, in other words, force the surgeon to choose a higher bottle height to prevent surge during phacoemulsification with the 3.2 mm CCI rather than the 3.0 mm CCI. This study also demonstrated that the 3.2 mm flow was greater than 3.0 mm flow, meaning that hydrodynamic stress on the eye from the irrigation solution might increase in the 3.2 mm CCI (Suzuki *et al*., 2009; Vasavada *et al*., 2010). The reusable tubing set was greater in flow, though not significantly so, meaning more hydrodynamic stress. Because the reusable tubing set has a higher compliance than the disposable one, higher parameters would be needed, leading to IOP elevation and correspondingly more flow. This was verified when calculations were made using multiple regression equations for this study.

Even though some surgeons prefer higher fluidic settings to decrease ultrasound energy and surgical time, many chose lower settings to increase safety through reducing IOP and the volume of irrigation solution used (Suzuki *et al*., 2009; Vasavada *et al*., 2010; Kawasaki *et al*., 2011; Kang *et al*., 2014). Vasavada and Raj (2003) suggested a step-down technique meaning a graded reduction in parameters during the phacoemulsification procedure. As the vacuum is controlled linearly, in response to the level of the foot controller, and the irrigation fluid was not aspirated when the handpiece tip was blocked by lens fragments, baseline IOP determined by BH in theoretical pressure is important. For this reason, a BH of 65–75 cm as suggested by Wilkie and Colitz (2007) might be beneficial. To use lower fluidic parameters along with preventing surge through minimizing unnecessary incisional leakage, it is also important to create a precise incision and to have the smallest incision length match the instrumentation size, decreasing the volume of fluid turnover (Liyanage *et al*., 2009). The incision size generally is dictated by the IOL type to be inserted, but enlarging the incision for IOL implantation after I/A and capsular polishing can be performed (Cook, 2008). Furthermore, this study demonstrated that a low-compliance disposable tubing set was useful for surge and IOP control.

This study has some limitations. First, the enucleated canine eyes may not precisely reflect the actual IOP of the in vivo eye. IOPs of different eyes are known to vary (Khng *et al*., 2006), meaning that there may be no significant rigidity variation between in vivo and ex vivo eyes. Although our experiments were all performed within six hours after enucleation, the IOP of the eye within the orbit might be also different from that of an enucleated eye (Wilkie and Colitz, 2007). Second, ultrasound power was not considered in this study. Sharma *et al*. (2012) documented that a vibrating phaco tip induced incisional fluid leakage as well as emulsifying and aspirating lens materials with BSS, which caused unwanted instability of the anterior chamber and surge. Further study using canine eyes will be needed to investigate the real-time IOP fluctuation throughout phacoemulsification surgery.

Conclusions

IOP was directly proportional to the BH and inversely proportional to the vacuum. To maintain anterior chamber stability, fluidic parameters for preventing IOP elevation and surge were needed and could be adjusted using the multiple regression equations of this study. IOP with an I/A handpiece was even higher than with a phaco handpiece, so the BH should be reduced during the I/A procedure. Although phacoemulsification with a 3.2 mm CCI could induce lower IOP, a 3.0 mm CCI might lessen the irrigation flow stress on the eye.

GENERAL CONCLUSIONS

Intraocular structural changes following phacoemulsification were different between high and low fluidic parameters. The lower fluidic settings significantly decreased the amount of irrigation solution used, and thereby could reduce damage to the anterior segment of the eye by decreasing the hydrodynamic stress arising from turbulence of the irrigation solution, as well as minimizing damage to the posterior segment of the eye by helping to prevent irrigation fluid leakage into the vitreous humour in chapter I. Therefore, the lower fluidic parameters might decrease the possibility of microorganisms or lens particles passing into the vitreous humour with the irrigation fluid during phacoemulsification surgery in the dog.

Multiple regression equations for the prediction of flow and IOP according to the vacuum, BH, and CCI size in a venturi phacoemulsification machine were reported in chapter II. The aspiration flow rate was directly proportional to the BH and vacuum, whereas IOP was directly proportional to the BH and inversely to the vacuum. Flow with an I/A handpiece was significantly less than with a phaco handpiece, explaining why IOP with an I/A handpiece was significantly higher than with a phaco handpiece. Although phacoemulsification with a 3.2 mm CCI could induce lower IOP, a 3.0 mm CCI might lessen the irrigation flow stress on the eye.

Based on these studies, it is demonstrated that fluidic parameters for preventing IOP elevation and surge were needed and could be adjusted to maintain anterior chamber stability using the multiple regression equations. IOP with an I/A handpiece was even higher than with a phaco handpiece, so the BH should be reduced during the I/A procedure of phacoemulsification surgery in the dog.

REFERENCES

Adams W, Brinton J, Floyd M, Olson RJ, 2006. Phacodynamics: An aspiration flow vs vacuum comparison. American Journal of Ophthalmology 142, 320-322.

Apple DJ, Mamalis N, Steinmetz RL, Loftfield K, Crandall AS, Olson RJ, 1984. Phacoanaphylactic endophthalmitis associated with extracapsular cataract extraction and posterior chamber intraocular lens. Archives of Ophthalmology 102, 1528-1532.

Beyer TL, Vogler G, Sharma D, O'Donnell FE Jr, 1984. Protective barrier effect of the posterior lens capsule in exogenous bacterial endophthalmitis—an experimental primate study. Investigative Ophthalmology and Visual Science 25, 108-112.

Beyer TL, O’Donnell FE, Goncalves V, Singh R, 1985. Role of the posterior capsule in the prevention of postoperative bacterial endophthalmitis: experimental primate studies and clinical implications. British Journal of Ophthalmology 69, 841-846.

Bellucci R, 2006. Vitreous hydration: often a hidden complication of cataract surgery. Cataract & Refractive Surgery Today, 26-28. Available from: http://crstoday.com/PDF%20Articles/0806/CRST0806_01.pdf

Biros DJ, Gelatt KN, Brooks DE, Kubilis PS, Andrew SE, Strubbe DT, Whigham HM, 2000. Development of glaucoma after cataract surgery in dogs: 220 cases (1987-1998). Journal of the American Veterinary Medical Association 216, 1780–1786.

Blumenthal M, Cahane M, Ashkenazi I, 1992. Direct intraoperative continuous monitoring of intraocular pressure. Ophthalmic Surgery 23, 132-134.

Boeve MH, Stades FC, 2007. Diseases and surgery of the canine vitreous. In: Veterinary Ophthalmology, Fourth Ed. (ed. Gelatt KN) Blackwell Publishing, Ames, IA, USA, pp. 932-943.

Cook C, 2008. Canine cataract surgery. Cataract & Refractive Surgery Today, 32–34. Available from: http://veterinaryvision.com/wp-content/uploads/2012/06/caninecatsurg.pdf

Fine IH, Packer M, Hoffman RS, 2002. New phacoemulsification technologies. Journal of Cataract and Refractive Surgery 28, 1054-1060.

Georgescu D, Payne M, Olson RJ, 2007. Objective measurement of postocclusion surge during phacoemulsification in human eye-bank eyes. American Journal of Ophthalmology 143, 437-440.

Grinbaum A, Blumenthal M, Assia E, 2003. Comparison of intraocular pressure profiles during cataract surgery by phacoemulsification and extracapsular cataract extraction. Ophthalmic Surgery, Lasers and Imaging 34, 182–186.

Harocopos GJ, Shui YB, McKinnon M, Holekamp NM, Gordon MO, Beebe DC, 2004. Importance of vitreous liquefaction in age-related cataract. Investigative Ophthalmology and Visual Science 45, 77-85.

Kang S, Jeong M, Ahn J, Lee E, Kim S, Park S, Yi K, Choi M, Seo K, 2014. Evaluation of fluid leakage into the canine vitreous humor during phacoemulsification using contrast-enhanced magnetic resonance imaging. Veterinary Ophthalmology. Feb 18. DOI:10.1111/vop.12156

Kawasaki S, Suzuki T, Yamaguchi M, Tasaka Y, Shiraishi A, Uno T, Sadamoto M, Minami N, Naganobu K, Ohashi Y, 2009. Disruption of the posterior chamber-anterior hyaloid membrane barrier during phacoemulsification and aspiration as revealed by contrast-enhanced magnetic resonance imaging. Archives of Ophthalmology 127, 465-470.

Kawasaki S, Tasaka Y, Suzuki T, Zheng X, Shiraishi A, Uno T, Ohashi Y, 2011. Influence of elevated intraocular pressure on the posterior chamber–anterior hyaloid membrane barrier during cataract operations. Archives of Ophthalmology 129, 751-757.

Khng C, Packer M, Fine H, Hoffman RS, Moreira FB, 2006. Intraocular pressure during phacoemulsification. Journal of Cataract and Refractive Surgery 32, 301-308.

Klein HE, Krohne SG, Moore GE, Stiles J, 2011. Postoperative complications and visual outcomes of phacoemulsification in 103 dogs (179 eyes): 2006-2008. Veterinary Ophthalmology 14, 114-120.

Ledbetter EC, Millichamp NJ, Dziezyc J, 2004. Microbial contamination of the anterior chamber during cataract phacoemulsification and intraocular lens implantation in dogs. Veterinary Ophthalmology 7, 327-334.

Liyanage SE, Angunawela RI, Wong SC, Little BC, 2009. Anterior chamber instability caused by incisional leakage in coaxial phacoemulsification. Journal of Cataract and Refractive Surgery 35, 1003-1005.

McLean NJ, Ward DA, Hendrix DV, Vaughn RK, 2012. Effects of one-week versus one-day preoperative treatment with topical 1% prednisolone acetate in dogs undergoing phacoemulsification. Journal of the American Veterinary Medical Association 240, 563-569.

Moisseiev E, Kinori M, Glovinsky Y, Loewenstein A, Moisseiev J, Barak A, 2011. Retained lens fragments: nucleus fragments are associated with worse prognosis than cortex or epinucleus fragments. European Journal of Ophthalmology 21, 741-747.

Moore DL, McLellan GJ, Dubielzig RR, 2003. A study of the morphology of canine eyes enucleated or eviscerated due to complications following phacoemulsification. Veterinary Ophthalmology 6, 219-226.

Neal RE, Bettelheim FA, Lin C, Winn KC, Garland DL, Zigler JS Jr, 2005. Alterations in human vitreous humour following cataract extraction. Experimental Eye Research 80, 337-347.

Paulson ME, Lavach JD, Severin GA, Eichenbaum JD, 1986. The effect of lens-induced uveitis on success of extracapsular cataract extraction: a retrospective study of 65 lens removals in the dog. Journal of the American Animal Hospital Association 22, 49-56.

Samuelson DA, 2007. Ophthalmic anatomy. In: Veterinary Ophthalmology, Fourth Ed. (ed. Gelatt KN) Blackwell Publishing, Ames, IA, USA, pp. 37-148.

Seibel BS, 2005. Phacodynamics: Mastering the tools and techniques of phacoemulsification surgery, Fourth Ed. Slack Incorporated, Thorofare, NJ, USA, pp. 1-151.

Sharma D, Desai D, Solanki K, 2012. To compare incisional fluid loss during different stages of phacoemulsification and its effect on anterior chamber stability in micro coaxial and bimanual phacoemulsification. Delhi Journal of Ophthalmology 23, 175-181.

Sigle KJ, Nasisse MP, 2006. Long-term complications after phacoemulsification for cataract removal in dogs: 172 cases (1995-2002). Journal of the American Veterinary Medical Association 228, 74-79.

Suzuki H, Oki K, Shiwa T, Oharazawa H, Takahashi H, 2009. Effect of bottle height on the corneal endothelium during phacoemulsification. Journal of Cataract and Refractive Surgery 35, 2014-2017.

Taylor MM, Kern TJ, Riis RC, McDonough PL, Erb HN, 1995. Intraocular bacterial contamination during cataract surgery in dogs. Journal of the American Veterinary Medical Association 206, 1716-1720.

van der Woerdt A, Wilkie DA, Myer CW, 1993. Ultrasonographic abnormalities in the eyes of dogs with cataracts: 147 cases (1986-1992). Journal of the American Veterinary Medical Association 203, 838-841.

van der Woerdt A, 2000. Lens-induced uveitis. Veterinary Ophthalmology 3, 227-234.

Vasavada AR, Raj S, 2003. Step-down technique. Journal of Cataract and Refractive Surgery 29, 1077–1079.

Vasavada AR, Praveen MR, Vasavada VA, Vasavada VA, Raj SM, Asnani PK, Garg VS, 2010. Impact of high and low aspiration parameters on postoperative outcomes of phacoemulsification: randomized clinical trial. Journal of Cataract and Refractive Surgery 36, 588-593.

Ward MS, Georgescu D, Olson RJ, 2008. Effect of bottle height and aspiration rate on postocclusion surge in Infiniti and Millennium peristaltic phacoemulsification machines. Journal of Cataract and Refractive Surgery 34, 1400-1402.

Wilbrandt HR, Wilbrandt TH, 1993. Evaluation of intraocular pressure fluctuations with differing phacoemulsification approaches. Journal of Cataract and Refractive Surgery 19, 223-231.

Wilkie DA, Colitz CMH, 2007. Surgery of the canine lens. In: Veterinary Ophthalmology, Fourth Ed. (ed. Gelatt KN) Blackwell Publishing, Ames, IA, USA, pp. 888-931.

Wilkie DA, Colitz CMH, 2009. Update on veterinary cataract surgery. Current Opinion in

Ophthalmology 20, 61-68.

Williams DL, 2004. Lens morphometry determined by B-mode ultrasonography of the normal and cataractous canine lens. Veterinary Ophthalmology 7, 91-95.

Zhao Y, Li X, Tao A, Wang J, Lu F, 2009. Intraocular pressure and calculated diastolic ocular perfusion pressure during three simulated steps of phacoemulsification in vivo. Investigative Ophthalmology and Visual Science 50, 2927-2931.

국문초록

정상 개의 적출 안구에서 수정체초음파유화술 시 관류액 높이와 진공 흡입력이 유체역학에 미치는 영향

지도교수: 서 강 문

강 선 미

서울대학교 대학원
수의학과 임상수의학 전공

본 연구에서는 개의 수정체초음파유화술 시 관류조건의 변화에 따른 안구 내 구조의 변화 및 안압의 변화를 알아보고자 하였다. 수정체초음파유화술은 가장 널리 시행되는 백내장 수술 방법으로써, 유체역학 및 초음파동역학(phacodynamics)은 수정체초음파유화술 후 발생할 수 있는 합병증에 영향을 미치는 주요 인자 중 하나로 보고되어 왔다. 수정체초음파유화술 장비의 관류조건은 관류액 높이, 초음파 에너지, 진공 흡입력, 흡인 및 관류 유속 등으로 구성되어 있다. 수정체초음파유화술의 수술 성공률을 높이기 위해서 수술자는 이와

같은 관류조건을 숙지해야만 하는데, 이는 관류조건의 조절을 통해 안구 내로의 관류액의 유입량과 안구 외로의 흡입량 및 각막 절개부 누수량을 포함하는 관류액의 유출량 사이에 균형을 이루어 줌으로써 수정체초음파유화술이 진행되는 동안 전안방안정성을 유지할 수 있어야 하기 때문이다. 수정체초음파유화술 장비의 유체공학 및 기술의 발달은 수술자로 하여금 각각의 관류조건들을 따로 조절할 수 있게 함으로써, 더욱 안전하고 효율적인 수정체초음파유화술을 가능하게 하였다.

본 연구는 정상 개의 적출 안구에서 서로 다른 조건의 관류액 높이와 진공 흡입력을 이용한 수정체초음파유화술이 유체역학에 미치는 영향을 알아보기 위해 안압 및 안구의 구조 변화를 조사하였다. 본 논문은 총 2개의 장으로 구성되어 있다.

제1장에서는 서로 다른 관류조건을 이용하여 수정체초음파유화술을 실시한 후 개의 안구 내 구조 변화를 조영증강 자기공명영상을 이용하여 평가하여 관류조건의 변화가 안구에 미치는 영향을 비교하였다. 적출한 10쌍의 개의 안구 중 한쪽 안구는 50 cm 관류액 높이와 80 mmHg 진공 흡입력으로, 반대쪽 안구는 120 cm 관류액 높이와 150 mmHg 진공 흡입력 조건 하에서, 자기공명영상 조영제가 포함된 관류액을 이용하여 수정체초음파유화술을 실시하였다. 수술 직후 조영증강 자기공명영상을 촬영하였다. 낮은 관류조건을 이용해

수술한 군에서 수술 중 수정체 소대를 통과하여 초자체 내로 유입되는 관류액의 양이 감소함을 확인하였다. 또한 낮은 관류조건을 사용할 때 수술 시 사용되는 관류액의 양이 감소하였고, 이로 인해 안구 내 관류액의 와류에 의해 안구 조직이 받는 수술 자극이 감소하였다.

제2장에서는 관류조건의 변화에 따른 개의 눈의 안압을 직접 측정하여, 안구허탈 현상 및 안압 상승을 방지하는 관류조건을 설정함으로써, 벤투리 타입(venturi type) 수정체초음파유화술 장비의 사용 시 개의 눈에서의 유체역학을 최적화하였다. 압력계가 삽입된 개의 적출 안구에서 다양한 관류액 높이와 진공 흡입력에서의 관류량 및 안압을 측정하였고, 이에 더하여 2 종류 길이의 각막 절개에 따른 관류량 및 안압을 측정하였다. 관류량은 관류액 높이와 진공 흡입력에 정비례하였고, 안압은 관류액 높이에는 정비례하지만 진공 흡입력에는 반비례하였다. 또한 관류량은 초음파유화흡입기(phacoemulsification handpiece)를 장착했을 때보다 관류흡입기(I/A handpiece)를 장착했을 때 유의적으로 적은 양을 나타냈으며, 이로 인해 안압이 유의적으로 높아지는 결과를 보였다. 특히 관류흡입기 장착 시에는 450 mmHg의 진공 흡입력에 도달할 때까지도 안구허탈 현상이 발생하지 않는 것을 확인하였다. 각막 절개 길이가 3.2 mm인 경우는 3.0 mm인 경우에 비해 상대적으로 안압 상승을 유발하진 않았지만, 3.0 mm의 각막 절개

시 관류량이 감소함으로써 안구 내 관류 스트레스가 감소하였다.

본 연구의 결과에 따르면 벤투리 타입 수정체초음파유화술 장비를 이용한 개의 수정체초음파유화술 시 낮은 수준의 관류조건을 사용함으로써 관류액의 사용량을 줄이고 수술 도중의 안압을 낮춰줌으로써 안구 내 조직에 대한 수술 자극을 감소하는 효과를 얻을 수 있을 것으로 판단된다. 특히 관류흡입기를 이용하는 수술 과정 동안에는 초음파유화흡입기를 이용하는 수술 과정 시보다 관류액의 높이를 더욱 낮춰주어야 하며, 이는 수술 도중에 발생하는 안압의 증가로 인해 안구가 겪을 수 있는 조직 자극을 최소화함으로써 개의 수정체초음파유화술의 성공률 향상에 기여할 수 있을 것으로 판단된다.

주요어: 백내장, 수정체초음파유화술, 전안방안정성, 관류조건, 개

학번: 2005-31155