

Fluid Dynamics of small Diameter Tubes Used in Membrane-tube Type Glaucoma Shunt Devices

소구경 튜브를 사용하는 막-튜브형 녹내장 셉트 장치의 유체역학

문헌 핵심요약

1. 연구 목적:

- ◆ 녹내장 임플란트에서 소구경 실리콘 튜브와 내강 스텐트(intraluminal stents)를 사용한 유체 역학 특성을 조사.
- ◆ 안전하고 효과적인 안압 조절 및 단계적 감소 가능성을 검증.

2. 방법:

- ◆ MicroMT (내경 100 μm) 및 Finetube MT (내경 200 μm) 튜브를 사용.
- ◆ 다양한 유속(2~25 $\mu\text{L}/\text{min}$)에서 튜브 내 압력 및 저항 측정.
- ◆ 내강 스텐트가 풀 길이, 절반 길이, 스텐트 제거 상태에서 각각 테스트.

3. 주요 결과:

- ◆ 내강 스텐트 길이에 따라 압력과 저항이 점진적으로 감소.
- ◆ 스텐트 제거 후 안구 저혈증 위험이 크게 감소하며, 안정적 압력 유지 가능.
- ◆ MicroMT와 Finetube MT 모두 임상적으로 안전한 안압 범위(13.2~6.2 mmHg) 제공.

4. 의의:

- ◆ **안전성:** 초기 수술 후 과도한 안압 감소(안구 저혈증) 예방.
- ◆ **효율성:** 스텐트를 단계적으로 제거하며 점진적 안압 감소 가능.
- ◆ **비교 우위:** 기존 튜브 대비 개선된 안압 조절 능력.

A-stream 강점

1. 혁신적인 기술

- ◆ 기존 녹내장 임플란트 대비 소구경 튜브 설계를 통한 더 나은 안압 조절.
- ◆ 내강 스텐트 기술로 수술 후 합병증 예방.

2. 안전성 보장

- ◆ 스텐트 단계적 제거를 통한 안구 저혈증 방지.
- ◆ 임상 시험에서 1년 후 안정적 안압 유지 확인.

3. 환자 맞춤형 솔루션

- ◆ 단계적 안압 감소로 다양한 환자 상태에 적응 가능.
- ◆ 최소한의 개입으로 효과적인 안압 관리 가능.

*MicorMT는 Astream®의 prototype device입니다.

Fluid Dynamics of Small Diameter Tubes Used in Membrane-tube Type Glaucoma Shunt Devices

Jong Chul Han¹, Young Hoon Hwang², Byung Heon Ahn²

¹Department of Ophthalmology, Samsung Medical Center, Sungkyunkwan University School of Medicine, Seoul, Korea

²Department of Ophthalmology, Myung-Gok Eye Research Institute, Kim's Eye Hospital, Konyang University College of Medicine, Seoul, Korea

Purpose: To investigate the outflow characteristics of silicone tubes with intraluminal stents used in membrane-tube (MT) type glaucoma shunt devices.

Methods: The silicone tubes used in MicroMT (internal diameter of 100 μ m with a 7-0 nylon intraluminal stent) and Finetube MT (internal diameter of 200 μ m with a 5-0 nylon intraluminal stent) were connected to a syringe-pump that delivered a continuous flow of distilled water at flow rates of 2, 5, 10, and 25 μ L/min. The pressures and resistances of tubes were measured at a steady flow rate with full-length, half-length, and absence of intraluminal stents.

Results: The mean outflow resistance of the two types of tubes ranged from 3.0 ± 1.9 to 3.8 ± 1.7 mmHg/ μ L/min with a full-length intraluminal stent, 1.8 ± 1.1 to 2.2 ± 1.1 mmHg/ μ L/min with a half-length intraluminal stent, and 0.1 ± 0.0 to 0.2 ± 0.0 mmHg/ μ L/min without an intraluminal stent. Theoretically, for a physiologic state with a flow rate of 2 μ L/min and episcleral venous pressure of 6 mmHg, the mean pressures of tubes were expected to be 13.2 ± 3.0 , 10.5 ± 2.4 , and 6.4 ± 0.2 mmHg in MicroMT with full-length, half-length, and absence of intraluminal stents, respectively, and 12.5 ± 3.9 , 9.6 ± 2.4 , and 6.2 ± 0.2 mmHg in Finetube MT with full-length, half-length, and absence of intraluminal stents, respectively. The pressure variance also decreased with intraluminal stent retraction ($p < 0.01$).

Conclusions: The small diameter tubes of 100 and 200 μ m internal diameters, with 7-0 and 5-0 nylon intraluminal stents, respectively, used in the MT-type glaucoma shunt device showed safe and effective outflow characteristics.

Key Words: Glaucoma, Glaucoma drainage device, Glaucoma surgery, Intraocular pressure

Glaucoma drainage devices (GDDs) have been introduced to control intraocular pressure (IOP), especially in

eyes with refractory glaucoma such as neovascular glaucoma and uveitic glaucoma, and in eyes that have failed glaucoma surgery. Theoretically, the amount of aqueous drainage through the GDD is determined based on its fluid dynamics profile. Thus, GDDs have to offer standardized and predictable control of IOP. However, despite the use of temporal ligation of the tube, staged operations, and valve-type GDDs, postoperative ocular hypotony due to excessive aqueous drainage still occurs [1-7].

Received: February 19, 2019 Final revision: April 20, 2019
Accepted: April 29, 2019

Corresponding Author: Young Hoon Hwang, MD. Department of Ophthalmology, Kim's Eye Hospital, 136 Yeongsin-ro, Yeongdeungpo-gu, Seoul 07301, Korea. Tel: 82-2-2639-7777, Fax: 82-2-2633-3976, E-mail: brainh@kimeye.com

© 2019 The Korean Ophthalmological Society

This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/3.0/>) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

To overcome this limitation, we introduced two types of membrane-tube (MT) type glaucoma shunt devices (MT-device; MicroMT, using a 100 μm internal diameter tube with a 7-0 nylon intraluminal stent and Finetube MT, using a 200 μm internal diameter tube with a 5-0 nylon intraluminal stent) [8,9]. MT-devices consist of 0.1-mm-thick expanded polytetrafluoroethylene membranes and small diameter silicone tubes with intraluminal stents. These devices prevent postoperative ocular hypotony and provide stepwise reduction in IOP after surgery by retracting the stent [8,9]. During development of the MT-device, various *in vivo* and *in vitro* experiments were performed to determine the proper fluid dynamics profiles of tubes with safe (minimal risk of postoperative ocular hypotony) and effective (sufficient for IOP control) outflow characteristics [10-15]. For instance, when tubes of conventional GDDs (external diameter, 630 μm ; internal diameter, 300 μm) were replaced with smaller tubes (external diameter, 300 μm ; internal diameter, 200 μm), the replacements showed effective IOP control [10-12]. In animal studies, the materials used in MT-devices had good biocompatibility [13,14], and in an experiment using a constant flow setting, the pressure levels of tubes with various diameters and materials were investigated [15]. In the present study, we report the pressure and resistance of silicone tubes with intraluminal stents used in MT-devices at various steady-state flow rates.

Materials and Methods

Preparation of the tubes

Two types of silicone tubes, used in MicroMT [8] and Finetube MT [9] respectively, were investigated. These devices are still investigational and not yet commercially available. The tube used in MicroMT has a 200 μm external diameter and 100 μm internal diameter (Silicone no. 1; ARAM Micro Tubing, Japan) with a 7-0 nylon thread intraluminal stent. The tube used in Finetube MT has a 300- μm external diameter and a 200- μm internal diameter (Silicone no. 2, ARAM Micro Tubing), with a 5-0 nylon thread intraluminal stent (Fig. 1). The MT-devices were designed to induce aqueous drainage from the anterior chamber to the post-limbal (MicroMT) and post-equatorial (Finetube MT) subconjunctival spaces, respectively. There-

fore, the tube lengths used for MicroMT and Finetube MT were set at 5 and 10 mm, respectively. In this experiment, a total of 60 tubes (30 MicroMT and 30 Finetube MT) were used.

Devices for measuring pressure and resistance

Experiments were performed based on the experimental design described in the previous studies [15,16]. The instrument consisted of three components: a perfusion pump and syringe, a pressure transducer and detector, and a housing

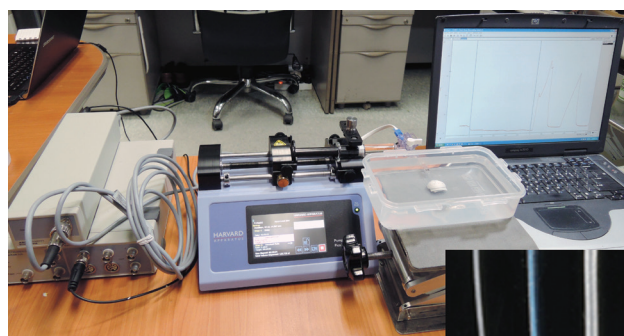


Fig. 1. A photograph of the perfusion apparatus and tubes (a black-colored box in the right inferior corner). To compare the tube diameters, a tube with a 200- μm external diameter and 100 μm internal diameter with a 7-0 nylon intraluminal stent (left in the box) and a tube with a 300- μm external diameter and 200- μm internal diameter with a 5-0 nylon intraluminal stent (middle in the box) were placed together with a tube with a 630- μm external diameter and 300- μm internal diameter used for the conventional glaucoma drainage devices (right in the box).

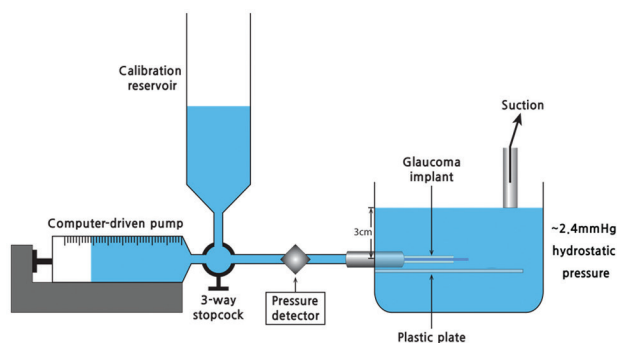


Fig. 2. Schematic diagram of the perfusion apparatus used in the present experiment. The instrument consisted of a perfusion pump, syringe, pressure transducer, pressure detector, and a housing unit where the glaucoma implant was submerged in fluid. The height of the fluid was fixed at 3 cm (approximately 2.4 mmHg) from the plastic plate. The three-way stopcock was used to remove the fluid to maintain the baseline pressure during the experiments.

unit where the glaucoma implant was submerged in distilled water (Fig. 1, 2). A perfusion pump with a stepper motor (Model 11; Harvard Apparatus, Holliston, MA, USA) was used. The perfusion pump was connected to a 1 mL glass syringe (Hamilton, Reno, NV, USA). A three-way stopcock was connected to the end of the glass syringe and calibration reservoir. A pressure transducer (PX260; Edwards Lifesciences, Irvine, CA, USA) and detector (8SP; ADInstruments, Colorado Springs, CO, USA) were connected to a personal computer, which monitored the pressure change in units of 0.01 mmHg using the Chart v5.1 (ADInstruments) software. We verified the pressure gauges whenever they were calibrated. A hole 1.5 cm from the base was made in the housing unit, and a 26-gauge needle sleeve was attached to the hole using silicone glue. The plastic cylinder, made from half of the plastic syringe used to fix the silicone tubes, was attached beneath the hole. The silicone tubes were submerged and connected to the pump and pressure transducer through the needle sleeve in the housing unit. The zero reference line was marked beyond the level of the hole (approximately 3 cm height from the base), and the pressure was measured as approximately 2.4 mmHg at that level. The height of this fluid was maintained by suction to define a zero reference line. This height was selected because the level was easy to control in our housing unit (6 cm height for the plastic box) and the glaucoma implant could be submerged completely at that level. Resistance was calculated using Poiseuille's equation at flow rates of 0, 2, 5, 10, and 25 $\mu\text{L}/\text{min}$. Assuming ideal fluid flow in a noncollapsible tube, the equation can be simplified to resistance = $(P_{\text{in}} - P_{\text{out}}) / \text{rate of steady flow}$. P_{in} was measured using the pressure transducer and P_{out} was set constantly submerging the apparatus under a fluid column at a given height as described above.

Measurement of pressure and resistance of the tubes

In the experiments, the perfusion rate was increased in a stepwise manner from 0 to 2, to 10, and to 25 $\mu\text{L}/\text{min}$. Each pressure at each flow rate was recorded (Fig. 3). Since we assumed the episcleral venous pressure in the human eye to be 6 mmHg, we corrected the baseline pressure to 6 mmHg. Then, the pressure at each flow rate was corrected by adjusting the baseline pressure. For example, if the baseline pressure was 2.5 mmHg, we added 3.5 mmHg and set the baseline pressure as 6.0 mmHg. After that, we add-

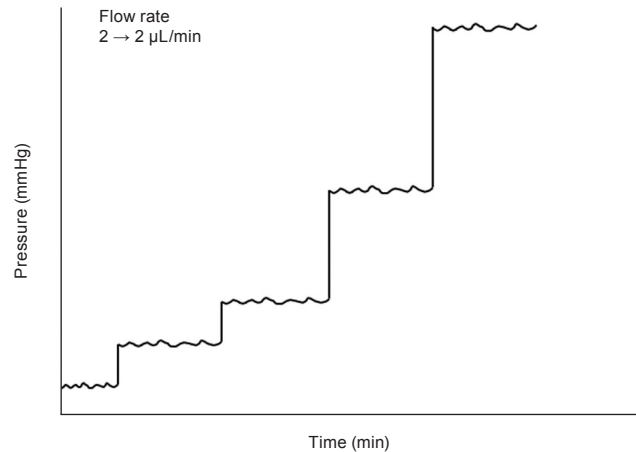


Fig. 3. Step function tests performed to measure the pressure according to each flow rate (2, 5, 10, and 25 $\mu\text{L}/\text{min}$). Flow was maintained for up to 20 minutes at each step so that resistance was calculated from steady-state flow and pressure conditions.

ed 3.5 mmHg to the measured pressure at each flow rate level (2, 5, 10, and 25 $\mu\text{L}/\text{min}$). The flow was maintained for up to 20 min at each step so that the resistance was calculated from steady-state flow and pressure conditions. Three-step experiments were performed in each tube: with a full-length intraluminal stent, after pulling the intraluminal stent by a half-length out of the tube, and after complete removal of the stent.

Statistical analysis

Friedman's test with *post hoc* analysis was used to compare the pressure and resistance among the tubes with a full-length intraluminal stent, with a half-length intraluminal stent, and without the intraluminal stent. In addition to the mean pressure and resistance level, the variance of pressure may provide information regarding the predictability of pressure; a lower variance may reflect a greater predictability. Therefore, to compare the pressure variance between the tubes with a full-length intraluminal stent, with a half-length intraluminal stent, and without an intraluminal stent, a Brown-Forsythe test was performed. All statistical analyses were performed using the PASW Statistics ver. 18.0 (SPSS Inc., Chicago, IL, USA). A *p*-value less than 0.05 was considered statistically significant.

Results

In the tubes with MicroMT, the mean corrected pressures with a full-length intraluminal stent were 13.2 ± 3.0 , 24.6 ± 8.1 , 43.8 ± 16.5 , and 98.1 ± 40.8 mmHg at flow rates of 2, 5, 10, and 25 $\mu\text{L}/\text{min}$, respectively. With a half-length intraluminal stent, the mean corrected pressures were 10.5 ± 2.4 , 16.7 ± 5.1 , 26.4 ± 8.6 , and 54.7 ± 21.2 mmHg at flow rates of 2, 5, 10, and 25 $\mu\text{L}/\text{min}$, respectively. Without the intraluminal stent, the mean corrected pressures were 6.4 ± 0.2 , 7.0 ± 0.2 , 8.0 ± 0.4 , and 10.9 ± 0.9 mmHg at flow rates of 2, 5, 10, and 25 $\mu\text{L}/\text{min}$, respectively. The mean outflow resistance ranged from 3.6 ± 1.5 to 3.8 ± 1.7 mmHg/ $\mu\text{L}/\text{min}$ with a full-length intraluminal stent, from 2.0 ± 0.9 to 2.2 ± 1.1 mmHg/ $\mu\text{L}/\text{min}$ with a half-length intraluminal stent, and was 0.2 ± 0.0 mmHg/ $\mu\text{L}/\text{min}$ without the intraluminal stent ($p < 0.001$, with full-length stent > with half-length stent > without stent by *post hoc* analysis) (Table 1).

For Finetube MT, the mean corrected pressures with a full-length intraluminal stent were 12.5 ± 3.9 , 21.8 ± 9.6 , 37.6 ± 19.1 , and 82.0 ± 46.5 mmHg at flow rates of 2, 5, 10, and 25 $\mu\text{L}/\text{min}$, respectively. With a half-length intraluminal stent, the mean corrected pressures were 9.6 ± 2.4 , 14.9 ± 5.9 , 23.9 ± 11.5 , and 49.9 ± 27.5 mmHg at flow rates of 2, 5, 10, and 25 $\mu\text{L}/\text{min}$, respectively. Without the intraluminal stent, the mean corrected pressures were 6.2 ± 0.2 , 6.4 ± 0.2 , 6.8 ± 0.2 , and 7.9 ± 0.3 mmHg at flow rates of 2, 5, 10, and 25 $\mu\text{L}/\text{min}$, respectively. The mean outflow resistance ranged from 3.0 ± 1.9 to 3.2 ± 1.9 mmHg/ $\mu\text{L}/\text{min}$ with a full-length intraluminal stent, 1.8 ± 1.2 mmHg/ $\mu\text{L}/\text{min}$ with a half-length intraluminal stent, and 0.1 ± 0.0 mmHg/ $\mu\text{L}/\text{min}$ without an intraluminal stent ($p < 0.001$, with full-length stent > with half-length stent > without stent by *post hoc* analysis) (Table 2).

The pressure variances in the MicroMT and Finetube MT tubes are presented in Fig. 4A and 4B. The pressure variances decreased based on the intraluminal stent retraction; the variance was highest with a full-length intraluminal stent and lowest without an intraluminal stent ($p < 0.001$ at all flow rates).

Discussion

The present study demonstrated that silicone tubes with intraluminal stents used in MT-devices induced consistent and predictable pressures and resistances at various flow rates. In addition, when the intraluminal stent was partially and completely removed, the pressure and resistance gradually decreased. Therefore, GDDs using these tubes may contribute to safe and effective control of IOP with stepwise reduction.

Ocular hypotony is an important complication of GDD implantation, especially during the early postoperative period. To prevent this complication, various procedures have been introduced [1-7]. One of these involves tube ligation with or without intraluminal or extraluminal stents during the surgery [1-4,6,7]. However, tube ligation may not produce a predictable pressure level; when the ligation is too tight or too loose, unexpected high or low pressure levels can occur, respectively. Other procedures, such as fenestrations or slit formations, are performed to prevent postoperative peaks in IOP after tube ligation [4]. However, Rietveld and van der Veen [17] showed that adjustable pressure regulation by focal tube constriction, similar to tube ligation, was disappointing because the maintenance of steady pressure levels at a given flow rate was difficult. They suggested that tube ligation to regulate pressure is trustworthy only with a highly sophisticated microarchitecture under well-controlled conditions.

Given that an intraluminal stent can induce occlusion in the entire area of the tube, it may provide more predictable pressure control compared to that of focal tube constriction. However, intraluminal stents have not been widely used. This may be because the silicone tubes of conventional GDDs, such as the Ahmed Glaucoma Valve (New World Medical, Rancho Cucamonga, CA, USA) and the Baerveldt Glaucoma Implant (Abbott Laboratories, Abbott Park, IL, USA), cannot provide the proper pressure to prevent ocular hypotony with the intraluminal stent because their internal diameters are too large. The inner diameters of the silicone tubes of the conventional GDDs are approximately 300 μm . Therefore, a 3-0 nylon thread with a diameter between 200 and 250 μm can be used as an intraluminal stent. However, results from a previous study show that the conventional silicone tube with a 3-0 polypropylene intraluminal stent do not successfully prevent ocular hypotony [18]. Sheybani et al. [19] also reported that a con-

Table 1. Flow, pressure, and resistance of the silicone tube of a MT type glaucoma shunt device (MicroMT) with and without an intraluminal stent (n = 30)

Flow ($\mu\text{L}/\text{min}$)	With full-length stent			With half-length stent			Without stent			<i>p</i> -value [†]
	Pressure (mmHg)	C-pressure (mmHg)*	Resistance (mmHg/ $\mu\text{L}/\text{min}$)	Pressure (mmHg)	C-pressure (mmHg)*	Resistance (mmHg/ $\mu\text{L}/\text{min}$)	Pressure (mmHg)	C-pressure (mmHg)*	Resistance (mmHg/ $\mu\text{L}/\text{min}$)	
0	3.0 $\pm$ 0.2	6.0 $\pm$ 0.2		3.1 $\pm$ 0.3	6.0 $\pm$ 0.3		3.0 $\pm$ 0.2	6.0 $\pm$ 0.2		
2	10.2 $\pm$ 3.0	13.2 $\pm$ 3.0	3.6 $\pm$ 1.5	7.5 $\pm$ 2.4	10.5 $\pm$ 2.4	2.2 $\pm$ 1.1	3.4 $\pm$ 0.2	6.4 $\pm$ 0.2	0.2 $\pm$ 0.0	<0.001
5	21.6 $\pm$ 8.1	24.6 $\pm$ 8.1	3.7 $\pm$ 1.6	13.8 $\pm$ 5.1	16.7 $\pm$ 5.1	2.2 $\pm$ 1.0	4.0 $\pm$ 0.2	7.0 $\pm$ 0.2	0.2 $\pm$ 0.0	<0.001
10	40.8 $\pm$ 16.5	43.8 $\pm$ 16.5	3.8 $\pm$ 1.7	23.4 $\pm$ 8.6	26.4 $\pm$ 8.6	2.1 $\pm$ 0.9	5.0 $\pm$ 0.4	8.0 $\pm$ 0.4	0.2 $\pm$ 0.0	<0.001
25	95.1 $\pm$ 40.8	98.1 $\pm$ 40.8	3.7 $\pm$ 1.6	51.7 $\pm$ 21.2	54.7 $\pm$ 21.2	2.0 $\pm$ 0.9	7.9 $\pm$ 0.9	10.9 $\pm$ 0.9	0.2 $\pm$ 0.0	<0.001

MT = membrane-tube.

*C-pressure (corrected pressure), the pressure adjusted based on the assumption that the pressure at the 0 $\mu\text{L}/\text{min}$ flow would be 6 mmHg (known estimated episcleral venous pressure); †Friedman's test for pressure, C-pressure, and resistance according to the stent status. With full-length > with half-length > without stent by *post hoc* analysis.**Table 2.** Flow, pressure, and resistance of the silicone tube of a MT type glaucoma shunt device (Finetube MT) with and without an intraluminal stent (n = 30)

Flow ($\mu\text{L}/\text{min}$)	With full-length stent			With half-length stent			Without stent			<i>p</i> -value [†]
	Pressure (mmHg)	C-pressure (mmHg)*	Resistance (mmHg/ $\mu\text{L}/\text{min}$)	Pressure (mmHg)	C-pressure (mmHg)*	Resistance (mmHg/ $\mu\text{L}/\text{min}$)	Pressure (mmHg)	C-pressure (mmHg)*	Resistance (mmHg/ $\mu\text{L}/\text{min}$)	
0	2.5 $\pm$ 0.2	6.0 $\pm$ 0.2		2.4 $\pm$ 0.2	6.0 $\pm$ 0.2		2.3 $\pm$ 0.2	6.0 $\pm$ 0.2		
2	9.0 $\pm$ 3.9	12.5 $\pm$ 3.9	3.2 $\pm$ 1.9	6.0 $\pm$ 2.4	9.6 $\pm$ 2.4	1.8 $\pm$ 1.1	2.5 $\pm$ 0.2	6.2 $\pm$ 0.2	0.1 $\pm$ 0.0	<0.001
5	18.3 $\pm$ 9.6	21.8 $\pm$ 9.6	3.2 $\pm$ 1.9	11.3 $\pm$ 5.9	14.9 $\pm$ 5.9	1.8 $\pm$ 1.12	2.7 $\pm$ 0.2	6.4 $\pm$ 0.2	0.1 $\pm$ 0.0	<0.001
10	34.1 $\pm$ 19.1	37.6 $\pm$ 19.1	3.2 $\pm$ 1.9	20.3 $\pm$ 11.5	23.9 $\pm$ 11.5	1.8 $\pm$ 1.1	3.1 $\pm$ 0.2	6.8 $\pm$ 0.2	0.1 $\pm$ 0.0	<0.001
25	78.5 $\pm$ 46.5	82.0 $\pm$ 46.5	3.2 $\pm$ 1.9	46.3 $\pm$ 27.5	49.9 $\pm$ 27.5	1.8 $\pm$ 1.1	4.2 $\pm$ 0.3	7.9 $\pm$ 0.3	0.1 $\pm$ 0.0	<0.001

MT = membrane-tube.

*C-pressure (corrected pressure), the pressure adjusted based on the assumption that the pressure at the 0 $\mu\text{L}/\text{min}$ flow would be 6 mmHg (known estimated episcleral venous pressure); †Friedman's test for pressure, C-pressure, and resistance according to the stent status. With full-length > with half-length > without stent by *post hoc* analysis.

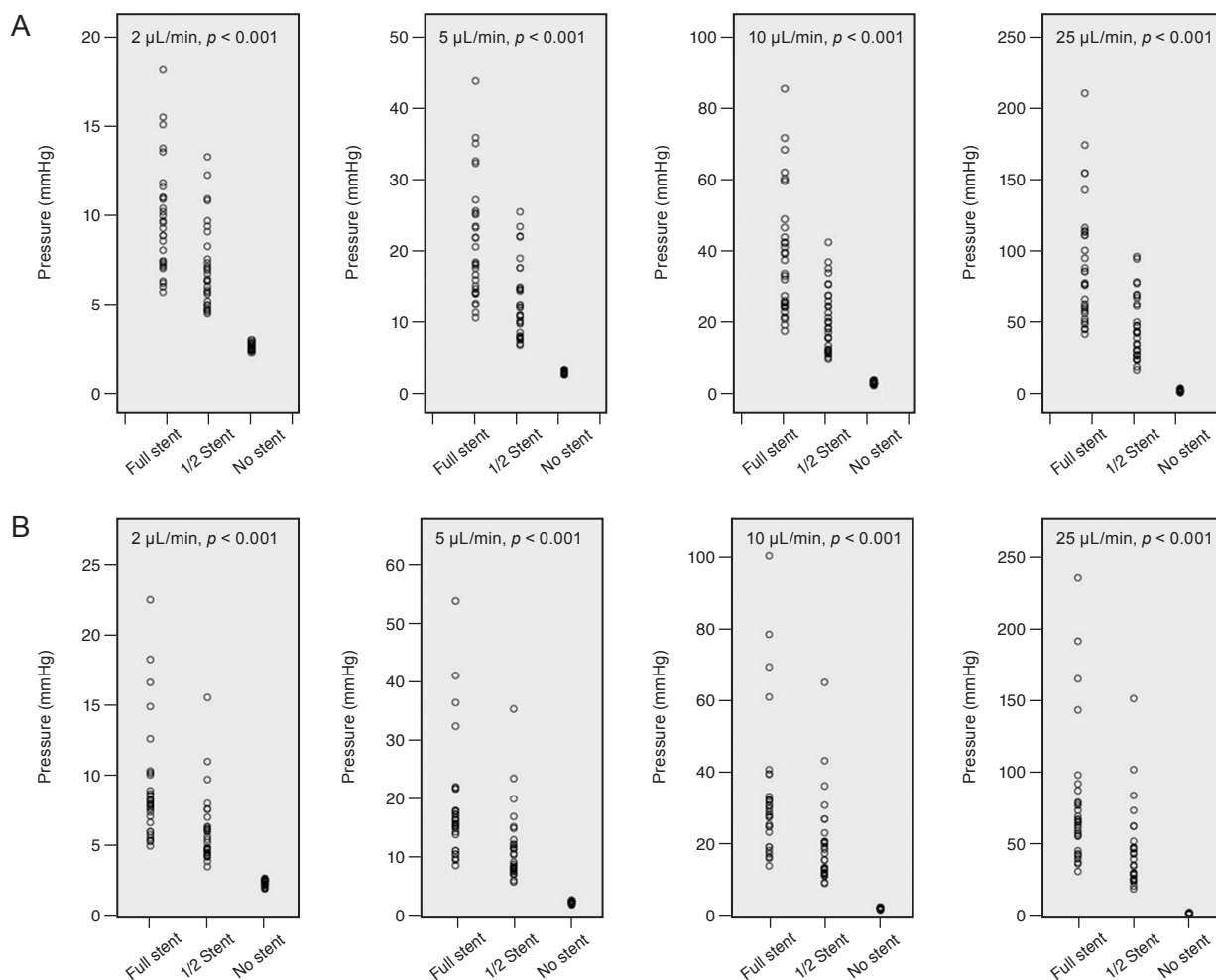


Fig. 4. Pressure variances in the tubes of membrane-tube (MT) type glaucoma shunt devices at each flow rate (2, 5, 10, and 25 $\mu\text{L}/\text{min}$). (A) MicroMT and (B) Finetube MT. The pressure variances decreased according to the intraluminal stent retraction ($p < 0.001$ at all flow rates, Brown-Forsythe test).

ventional tube with intraluminal 4-0 and 5-0 suture threads only provides pressures of 1.16 and 0.3 mmHg, respectively, at the flow rate of 2.5 $\mu\text{L}/\text{min}$. Therefore, intraluminal stenting of conventional tubes by using 3-0, 4-0, and 5-0 suture materials may not prevent ocular hypotony. The 2-0 nylon thread with a diameter of 300 to 350 μm may completely obstruct the lumen of the tube, but it is not easily inserted or may not be insertable into the lumen. For this reason, GDDs with an intraluminal stent have not been widely used for the prevention of postoperative ocular hypotony. Therefore, we hypothesized that a smaller tube with an intraluminal stent is a good alternative to conventional tubes.

The results from the present study demonstrated that for a physiologic flow rate of 2 $\mu\text{L}/\text{min}$ with an episcleral ve-

nous pressure of 6 mmHg, the mean pressures formed by the tubes of MicroMT were 13.2 and 10.5 mmHg with full-length and half-length intraluminal stents, respectively. With the tubes of Finetube MT, the mean pressures were 12.5 and 9.6 mmHg with full-length and half-length intraluminal stents, respectively. These pressure levels may be appropriate for the control of IOP with a minimal risk of ocular hypotony. When the flow rate increased, the pressure increased accordingly. However, the resistance remained consistent irrespective of the flow rate. In addition, when the intraluminal stents were partially and completely removed, the variance of pressure also decreased. This finding may be explained by the level of pressure; a higher level may tend to have a higher variance. These results suggest that the tubes of MT-devices may confer a consis-

tent and predictable IOP level. To validate these *in vitro* experimental results, we analyzed the clinical data of MT-devices and found that 1 year after the surgery, mean IOP decreased from a preoperative value of 23 to 15 mmHg after MicroMT implantation and from 33 to 17 mmHg after Finetube MT implantation without ocular hypotony [8,9].

An additional advantage to using an intraluminal stent is that it can allow stepwise IOP control through retraction of the stent. When the tube is focally constricted by ligation, only two-staged pressure control is available through post-operative removal of the ligation. However, after ligation removal, IOP can drop abruptly, causing ocular hypotony. In contrast, by using small silicone tubes with intraluminal stents, sudden decreases in IOP can be prevented because the stent can be retracted in a stepwise manner while monitoring the IOP; in the present study, stent retraction induced a stepwise and gradual decrease in the mean and variance of pressure. After the implantation of the MT-device, the intraluminal stent can be retracted if the pressure needs to be lowered. Our clinical results show that retracting the intraluminal stent half the length of the tube after the operation reduced the IOP by an additional 3 to 5 mmHg, and complete removal of the stent 4 weeks after the operation induced an additional 40% reduction in IOP without ocular hypotony [8,9].

In conclusion, the tubes of an MT-device provided pressure and resistance sufficient for IOP control with a minimal risk of ocular hypotony. Furthermore, it could provide stepwise reduction of IOP by retraction of the intraluminal stent. Therefore, these tubes may be a useful option for safe and effective control of IOP.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

References

1. Barton K, Feuer WJ, Budenz DL, et al. Three-year treatment outcomes in the Ahmed Baerveldt comparison study. *Ophthalmology* 2014;121:1547-57.
2. Bailey AK, Sarkisian SR Jr. Complications of tube implants and their management. *Curr Opin Ophthalmol* 2014;25:148-53.
3. Tribble JR, Brown DB. Occlusive ligature and standardized fenestration of a Baerveldt tube with and without anti-metabolites for early postoperative intraocular pressure control. *Ophthalmology* 1998;105:2243-50.
4. Sherwood MB, Smith MF. Prevention of early hypotony associated with Molteno implants by a new occluding stent technique. *Ophthalmology* 1993;100:85-90.
5. Tong L, Frazao K, LaBree L, Varma R. Intraocular pressure control and complications with two-stage insertion of the Baerveldt implant. *Ophthalmology* 2003;110:353-8.
6. Kee C. Prevention of early postoperative hypotony by partial ligation of silicone tube in Ahmed glaucoma valve implantation. *J Glaucoma* 2001;10:466-9.
7. Lee JJ, Park KH, Kim DM, Kim TW. Clinical outcomes of Ahmed glaucoma valve implantation using tube ligation and removable external stents. *Korean J Ophthalmol* 2009;23:86-92.
8. Ahn BH, Hwang YH, Han JC. Novel membrane-tube type glaucoma shunt device for glaucoma surgery. *Clin Exp Ophthalmol* 2016;44:776-82.
9. Han JC, Hwang YH, Ahn BH. Membrane-tube-type glaucoma shunt device for refractory glaucoma surgery. *Graefes Arch Clin Exp Ophthalmol* 2017;255:163-9.
10. Kim C, Kim Y, Choi S, et al. Clinical experience of e-PTFE membrane implant surgery for refractory glaucoma. *Br J Ophthalmol* 2003;87:63-70.
11. Choi YJ, Kim CS, Ahn BH. A comparison of the clinical effect between e-PTFE membrane-tube implant and Ahmed glaucoma valve implant for the treatment of refractory glaucoma. *Korean J Ophthalmol* 2003;17:106-13.
12. Kim MK, Hwang YH, Ahn BH. Implantation of a modified baerveldt glaucoma implant with a smaller tube and intraluminal stent. *Korean J Ophthalmol* 2017;31:90-1.
13. Bae HB, Kim CS, Ahn BH. A membranous drainage implant in glaucoma filtering surgery: animal trial. *Korean J Ophthalmol* 1988;2:49-56.
14. Kim DW, Hwang YH, Ahn BH, et al. Safety and efficacy of a membrane-tube-type glaucoma shunt device: an animal trial. *Curr Eye Res* 2017;42:890-6.
15. Sohn SW, Noh MD, Lee JH, et al. Performance of and pressure elevation formed by small-diameter microtubes used in constant-flow sets. *Korean J Ophthalmol* 2016;30:225-33.
16. Francis BA, Cortes A, Chen J, Alvarado JA. Characteristics of glaucoma drainage implants during dynamic and

- steady-state flow conditions. *Ophthalmology* 1998;105:1708-14.
17. Rietveld E, van der Veen AJ. Postoperative pressure regulation in glaucoma shunt surgery: focal tube constriction is not the answer. *J Glaucoma* 2004;13:216-20.
 18. Hoare Nairne JE, Sherwood D, Jacob JS, Rich WJ. Single stage insertion of the Molteno tube for glaucoma and modifications to reduce postoperative hypotony. *Br J Ophthalmol* 1988;72:846-51.
 19. Sheybani A, Reitsamer H, Ahmed II. Fluid dynamics of a novel micro-fistula implant for the surgical treatment of glaucoma. *Invest Ophthalmol Vis Sci* 2015;56:4789-95.