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Article

Laser Activated Flow Regulator for Glaucoma Drainage Devices

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Purpose: To assess the capabilities of a new glaucoma drainage device regulator in controlling fluid flow as well as to demonstrate that this effect may be titratable by noninvasive means.

Methods: A rigid eye model with two main ports was used. On the first port, we placed a saline solution column. On the second, we placed a glaucoma shunt. We then measured the flow and flow rate through the system. After placing the regulator device on the tip of the tube, we measured again with the intact membrane and with the membrane open 50% and 100%. For the ex vivo testing we used a similar setting, using a cadaveric porcine eye, we measured again the flow and flow rate. However, this time we opened the membrane gradually using laser shots. A one-way analysis of variance and a Fisher's Least Significant Difference test were used for statistical significance. We also calculated the correlation between the numbers of laser shots applied and the main outcomes.

Results: The flow through the system with the glaucoma drainage device regulator (membrane intact and 50% open) was statistically lower than with the membrane open 100% and without device ($P < 0.05$). The flow was successfully controlled by the number of laser shots applied, and showed a positive correlation (+ 0.9). The flow rate was almost doubled every 10 shots and statistically lower than without device at all time ($P < 0.05$).

Conclusions: The glaucoma drainage device regulator can be controlled noninvasively with laser, and allows titratable control of aqueous flow.

Translational Relevance: Initial results and evidence from this experiment will justify the initiation of in vivo animal trials with the glaucoma drainage device regulator; which brings us closer to possible human trials and the chance to significantly improve the existing technology to treat glaucoma surgically.

Introduction

Glaucoma is a progressive optic neuropathy characterized by optic disc damage, retina ganglion cell death, visual field loss, and high intraocular pressure (IOP).[1,2] It is currently the second leading cause of irreversible visual impairment around the world, with more than 60 million people affected.[2–4] The disease is typically asymptomatic, which means that even in developed countries, half of the cases are undiagnosed.[1,3] Despite the available pharmacological and technological treatments for the controlling of IOP, the number of individuals losing sight remains high.[3,4] The reasons of treatment failure are several and some of them are patient related (e.g., low adherence to the treatment, adverse reactions).

Glaucoma surgery is performed when the IOP lowering is inadequate to prevent or slow progression of the disease despite optimal medical treatment or appropriate laser treatment.[5–7] There are two main modalities of surgery: trabeculectomy and aqueous shunting, also known as glaucoma drainage devices (GDD).[8] The first is the most commonly performed worldwide.[7] However, recent data from Medicare claims as well as practice patterns surveyed by the American Glaucoma Society have shown a 43% decline in the number of trabeculectomies performed[9]; while the number of GDD (a technique traditionally reserved for refractory glaucomas or

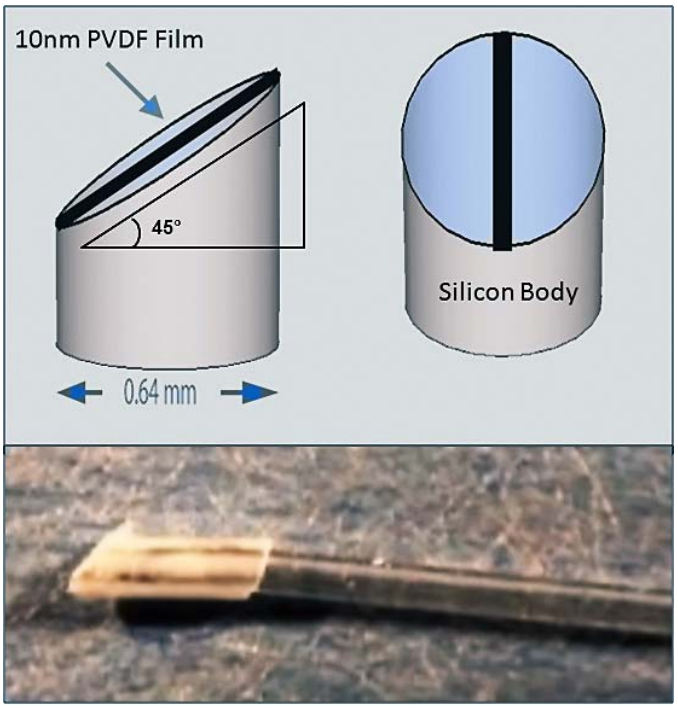

Figure 1. Basic GDDR design, materials and general diameters. The bottom picture depicts the device placed on an aqueous shunt tube.

high-risk of failure with trabeculectomy cases) has resurfaced as the preferred surgical approach, increasing from 17.5% to 50.8% of all the procedures in 2008 and representing a 184% increase in Medicare claims.[6,9,10] This change in trend is mainly due to bleb-related complications with trabeculectomy (e.g., leaks, infections, dysesthesia) as well as a significant higher failure during the first year of follow-up and a higher probability of needing further surgical interventions.[7,11]

GDDs have a different set of potential complications. One of the most common is early postoperative hypotony and hypotony-related events like anterior chamber shallowing, tube touching the lens or cornea, choroidal effusion, suprachoroidal hemorrhage and serous retinal detachment.[12,13] Regardless of the type of GDD used, 6.3% to 25% of the cases will present some degree of hypotony ($\leq$ 6 mm Hg).[14]

The glaucoma drainage device regulator (GDDR) is a novel implantable device that, when used in conjunction with regular GDD or other filtering glaucoma procedures, allows a noninvasive control of the aqueous flow, giving the physician more control over the rate of filtration and potentially averting immediate hypotony as well as better customization of the treatment in the long term. Therefore, the objective of the present study was to assess the ability of the device to control the flow as well as to prove that this capability may be titratable by noninvasive means.

Methods

The study was conducted at the laboratory of experimental surgery of the Rocky Mountain Lions Eye Institute, University of Colorado School of Medicine.

The GDDR has a simple design: It comprises a lumen and a specially fabricated semi-permeable nanofilm membrane covering one of the distal ends (Fig. 1). The device is then placed over the tip of the tube of the shunt in the anterior chamber, either at the time of the initial surgery or onto devices that have been previously implanted. Current commercially available shunts typically use a silicone tube with an outer diameter of 0.635 mm (23 GA) and an inner diameter of 0.31 mm (30 GA). Therefore, the described device has a lumen of 22 GA in order to allow it to slide easily over the tube, but at the same time providing a high coefficient of friction between tube and device to prevent slippage (but not enough to make insertion difficult). Furthermore, the GDDR main body is also made of silicone which, besides its proven biocompatibility, increases the cohesion between tube and device and prevents slippage. The tip of the implant is bevelled at a 45° angle, which facilitates the insertion of the shunt's tube into the anterior chamber. In case that the tube has been previously bevelled by the surgeon, the length of the main GDDR silicone body can be adjusted and trimmed accordingly, in order to ensure that the entire bevel and part of the main tube are covered by the device. The membrane at the distal end is made of a 10 nm film of polyvinylidene fluoride (PVDF), which prevents flow through the lumen of the shunt when implanted. Per the physician discretion, thermal, photodisruptive or ablative laser (e.g., Nd:YAG, Argon, PASCAL) can be used either directly or with the aid of a mirrored lens to create small ruptures in the anterior surface of the membrane, thereby allowing the passage of aqueous into the tube. By creating more holes in the surface of the membrane, the surgeon can increase the rate of flow in accordance with Pouiseille's law in which flow is proportional to the radius to the fourth power (Fig. 2).[15] This allows titration of flow based on the clinical needs of the patients. The membrane may also be

$$\Delta P = \frac{8\mu LQ}{\pi r^4}$$

Figure 2. Pouiseille's law formula that states that flow through a tube is proportional to the radius to the fourth power. Q in the equation signifies flow. R is the radius of the tube.

perforated by mechanical means such as a needle or other sharp instruments.

In Vitro Testing

A model of intraocular aqueous flow was constructed using an eye model especially designed to evaluate the flow through an aqueous shunt with and without the implant (Fig. 3A). The model consisted of a rigid sphere with two main ports: The first served to infuse normal saline (BSS) into the sphere in order to maintain a constant pressure of 20 mm Hg along all parts of the system. The intra-system pressure was measured at all times using an industrial grade differential pressure manometer (HD750, Extech Instruments, Nashua, NH, USA) with a resolution of up to 0.001 psi (0.05 mm Hg). A commercially available aqueous shunt (Baerveldt BG 101-350, Abbot Medical Optics, Abbott Park, IL, US) was attached to the second port. The flow of BSS through the system was measured using a flow rate measuring instrument for 30 seconds and the measurement was repeated three times. After the control was established, we placed the GDDR over the end of the tube. This time, the flow rate was measured in three different modalities: First we assess the flow with the GDDR membrane intact. A second measurement was done after placing enough laser spots in order to ensure that at least 50% of the membrane was disrupted. A third measurement was done after opening the membrane completely with laser. An Nd:YAG laser (YC-1600, NIDEK Inc., Fremont, CA) was used for opening the PVDF membrane with the following parameters: Power: 4.3 mJ, single pulse. Means and standard error of measurement were calculated for each group. A one-way analysis of variance (ANOVA) test was used to identify differences in the variability of the means of the four groups, using a P value of less than 0.05 for statistical significance. A Fisher's unprotected Least Significant Difference test (FLSD) was used to assess statistical difference between means within study groups.

Ex Vivo Testing

Using a cadaveric porcine eye and similar setting than before, we tested the GDDR in order to assess the flow through the system in function of the number of laser spots applied (Fig. 3B). Using a corneal paracentesis we placed an infusion line with BSS in order to ensure a constant intraocular pressure of 20 mm Hg. The pressure was monitorized constantly as before. Through a second paracentesis, we placed the tube of a standard shunt. At this time, the flow rate was measured for 60 seconds, 3 times. The eye was inspected for signs of leakage before each measure-

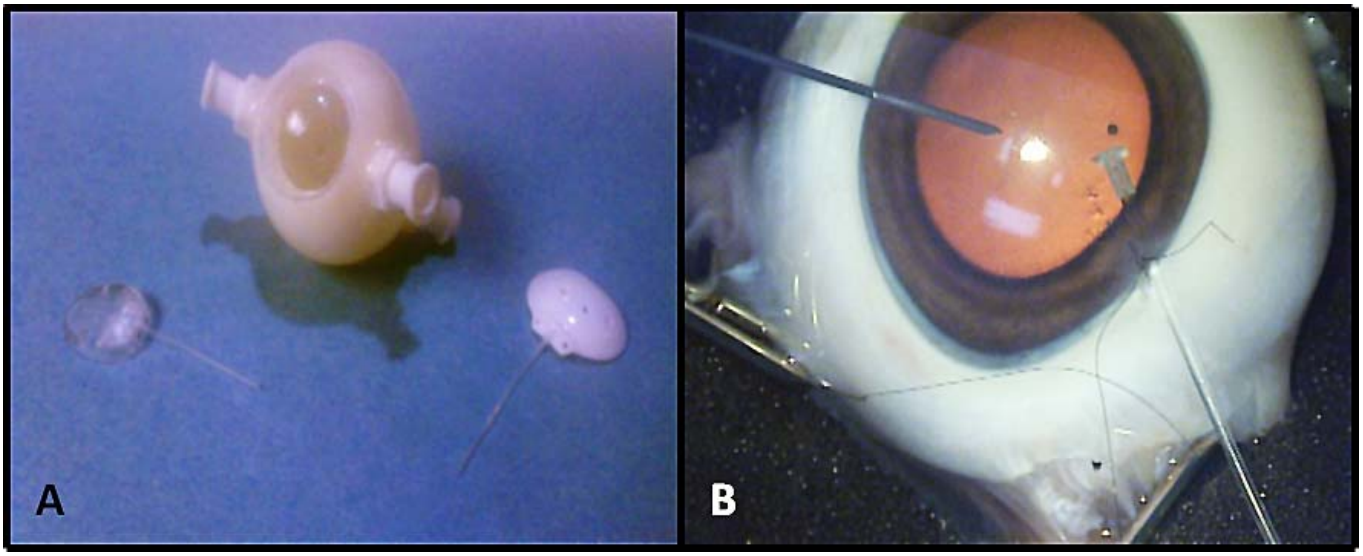

Figure 3. (A) basic materials and in vitro model for testing the GDDR. (B) Ex vivo model of a porcine eye in which the tube with the device and the infusion line are in place.

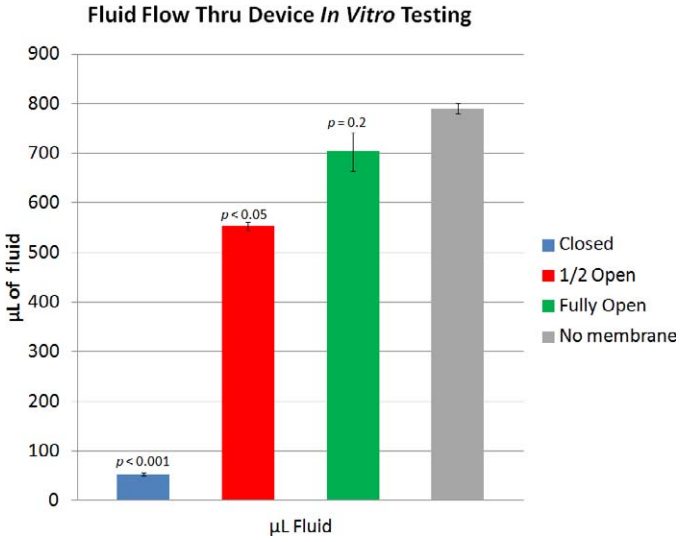

Figure 4. Comparison chart about the BSS flow through the system in the in vitro model. A statistical significant difference between the flow through the system in its closed and 50% open position is shown against the flow through the system without device.

ment. Once the controls were established, we tested the flow through the system with the GDDR in place. First with an intact membrane, then serial measurements were done after applying laser spots which increased by a factor of 10 up to 50 spots (Nd:YAG, 4.3 mJ/burst single shot). Two additional measurements were done after 100 laser spots and again with no GDDR. The same Nd:YAG laser and parameters than in the in vitro testing were used in this part of the experiment. Means and standard error of measurement were calculated for each group. A one-way ANOVA test was used to identify differences in the variability of the means of the four groups, using a P value of less than 0.05 for statistical significance. A Fisher's unprotected Least Significant Difference test was used to assess statistical difference between means within study groups.

Results

In Vitro Testing

The results from the in vitro test are summarized and plotted as a graph in Figure 4. The BSS drained through the shunt without the GDDR in place was 790 ± 170 µL with a flow rate of 26.3 ± 0.5 µL/sec; conversely to the fully closed position of the GDDR, in where the fluid drained through the semipermeable membrane measured only 53.3 ± 5 µL with a mean flow rate of 1.7 ± 0.19 µL/sec ($P < 0.001$). The amount of BSS drained through the shunt is significantly increased when passed from the closed to the 50% open position of the GDDR: mean flow 553 ± 15 µL, flow rate: 18.4 ± 0.5 µL/sec but still significantly lower than the flow through the shunt without GDDR ($P < 0.05$). Finally, the flow through the device increased again after further opening the membrane completely to 703 ± 60 µL, flow rate of 23.4 ± 2 µL/sec. There was no difference in flow and flow rate between the aqueous shunt without GDDR and the fully open position of the GDDR ($P = 0.2$).

Ex vivo testing

The results from the ex vivo test are summarized and plotted as a graph in Figure 5. After setting the model, we measured the flow and flow rate through the aqueous shunt without GDDR in 1500 ± 60 µL and 25 ± 20 µL/sec, respectively. The results were in concordance to the assessment of the system without GDDR done in vitro. There was no measureable flow with the intact membrane. However, after applying the first 10 laser spots, we started measuring consistent flow and flow rates, which almost doubled after every increase in the number of spots applied (up to 30 spots). The flow and flow rate continued to increase after 40 and 50 spots and significantly increased after 100 spots. Nevertheless, all measurements were significantly lower than the flow and flow rate measured without GDDR in place ($P < 0.01$). The correlation between spots and flow showed a positive correlation ($R = 0.9947$, $P < 0.01$, $t = 42.31$, $DF = 19$).

Discussion

During the last decade, there have been sensible changes in the surgeons' preferences regarding how they approach the initial surgical treatment of glaucoma. This is due, in part, to evidence from prospective randomized trials such as the Tube versus Trabeculectomy Study in which patients who underwent aqueous shunt placement were more likely to achieve IOP control, had lower rates of failure and avoid complications, compared to trabeculectomy after three years of follow-up.[7,8,16,17]

As a general rule, although all commercially available aqueous shunts share a common design consisting of a silicone tube and an episcleral endplate;[11] we can divide the existing shunts into two broad categories: valved (Ahmed Glaucoma Valve,

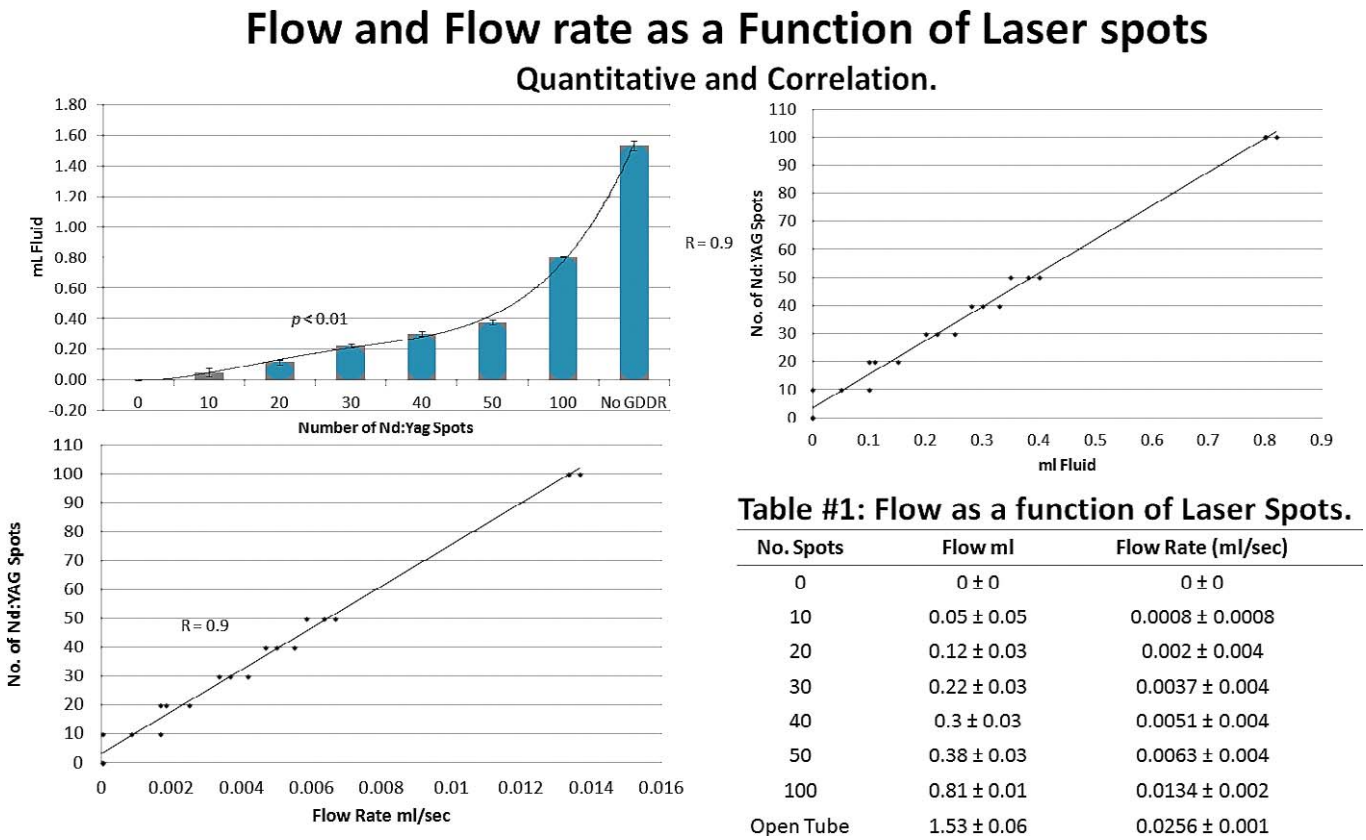

Table #1: Flow as a function of Laser Spots.

No. Spots	Flow ml	Flow Rate (ml/sec)
0	0 ± 0	0 ± 0
10	0.05 ± 0.05	0.0008 ± 0.0008
20	0.12 ± 0.03	0.002 ± 0.004
30	0.22 ± 0.03	0.0037 ± 0.004
40	0.3 ± 0.03	0.0051 ± 0.004
50	0.38 ± 0.03	0.0063 ± 0.004
100	0.81 ± 0.01	0.0134 ± 0.002
Open Tube	1.53 ± 0.06	0.0256 ± 0.001

Figure 5. Graphic chart about the flow and flow rate through the system in function of the number of laser spots applied to the surface of the membrane. A positive correlation was observed in both flow and flow rate and the number of laser applied. The bar graph shows a non-linear correlation predicted by the Pouiseille's law.

New World Medical Inc, Rancho Cucamonga, CA) and non-valved (Baerveldt; Molteno, Molteno Ophthalmic LTD, Dunedin, New Zealand; Krupin, E. Benson Hood Lab Inc, Pembroke, MA; among others).[11,18,19] After implantation, the flow rate and absorption of aqueous humor depend mainly on the area of the end-plate and the thickness of the fibrous encapsulation that forms around it.[19–21] Thinner and large surface areas are usually associated with lower postoperative IOP.[7,11] Therefore, before the development of the fibrous capsule (3–6 weeks after the surgery), the aqueous flows almost unrestrictedly through the shunt, favoring ocular hypotony unless additional measures are taken. These include modification to the tubes with additional sutures near the plate or stents placed inside the tube's lumen by the surgeons at the time of the surgery.[18,21] These maneuvers must be done meticulously because, if complete occlusion of the tube is not achieved, the risk of postoperative hypotony is high.[18] These surgical techniques are time-consuming; the results are directly linked to the surgeon's expertise and they can potentially need additional invasive procedures in order to eliminate the obstruction (laser or surgery).[18] In some cases, these obstructions can cause ocular hypertension severe enough to require immediate reoperation.[19] Additional venting stab incisions may be done on the anterior side of the tube, in order to reduce this tendency; however, this increases the incidence of postoperative hypotony as well.[19] All non-valved shunts must typically have one or all of these modifications.

According to the manufacturer, the Ahmed glaucoma valve (AGV) is a valved shunt that includes a Venturi-based valve designed to minimize the likelihood of hypotony before the fibrous capsule formation.[22,23] Although the a real Venturi effect has never been fully demonstrated, the theory says that the valve is intended to open when the IOP is between 8 to 10 mm Hg in order to maintain IOP at or above this mark at all time.[21] Despite the fact that large prospective randomized studies like the Ahmed Baerveldt Comparison Study (ABC study) and the Ahmed versus Baerveldt study (AVB study) showed

Table 1. Flow as a Function of Laser Spots: A Summary of the Means ± Standard Deviation of the Results

No. Spots	Flow μL	Flow Rate (μL/sec)
0	0 ± 0	0 ± 0
10	50 ± 50	0.8 ± 0.8
20	120 ± 30	2 ± 4
30	223 ± 30	3.7 ± 4
40	303 ± 30	5.1 ± 4
50	376 ± 30	6.3 ± 4
100	806 ± 10	13.4 ± 2
Open Tube	1533 ± 60	25.6 ± 1

lower rates of early postoperative complications and lower risk of hypotony-related complications with the use of the AGV than with its non-valved counterpart,[22,24–26] the reality is that early postoperative hypotony and its related complications still continues to present a clinical problem after a valved shunt implantation, with an incidence that range between 3% to 19.4% of the cases.[21,22] Moreover, the AGV does not eliminate the risk of other complications associated with hypotony such as suprachoroidal hemorrhage and choroidal detachments.[23,27] The reason is not well understood. However, in vitro studies have shown that valved implants may not completely close after initial priming, and that they may function more as a flow-restriction device than like a true valve with an open/close mechanism that response to pressure changes.[28,29] In addition, hypotony may also result from defective valves, destruction of the mechanism during priming (over-primed) or excessive peritubular filtration at the anterior chamber insertion site.[30,31]

The GDDR device is a new aqueous flow-regulating device that obviates all of these drawbacks, while potentially offering new therapeutics modalities. In the in vitro results, the semipermeable membrane of the device was able to significantly decrease the flow and flow rate through the shunt's tube, meaning that the device can serve as substitute for sutures and stents for hypotony prevention, especially in those eyes at a particular risk of suprachoroidal hemorrhage (intracapsular aphakic eyes). By being easier and faster to slide the device onto the tube, operating time is reduced and proficiency in its application is gained quickly. The in vitro study also demonstrated that both the flow and flow rate can be reestablished completely by disrupting enough membrane. In an ideal scenario, this property should allow the clinician effectively regulate the amount of aqueous filtering through the shunt, according to the level of fibrosis seen on the end-plate and not depend to an all-or-nothing effect with the sutures. Furthermore, the ex vivo study demonstrated that the device can have a titratable effect. This means that the level of flow and flow rate can be adjusted actively according to the patients needs by selecting the right amount or increasing the original amount of laser applied to the device's membrane. This is a property not seen before with aqueous shunts devices.

Although the current results support the efficacy and the titratable effect of the device, the results should be taken with caution since they are the result of an ideal laboratory environment. In a real human eye, the achieved flow rate with the minimum number of laser shots would be still too high as for effectively decrease the rate of hypotony after a GDD implant. Furthermore, in an in vivo setting, there are a number of additional factors that should be considered (e.g., fibrin, blood, lens particles, inflammatory cells) before assessing the real flow rate of the device, because it may vary according to the presence or absence of such factors. Further studies are on their way in order to address all this issues and to better understand the number of shots and laser parameters needed to emulate a more physiological aqueous flow.

In theory, larger diameter tubes than those currently used for aqueous shunting could be employed with the GDDR in place. This would allow for greater flow which could be held "in reserve" for years after implantation, and accessible with noninvasive laser when the patient's disease may be worsening and require lower IOP. Without the GDDR, larger diameter tubes would not be feasible secondary to intolerably high rates of hypotony. Another potential use of the GDDR device would be to direct flow to separate reservoirs. For example, a larger bore membrane could have two or more lumens, each leading to a separate reservoir. One side of the tube could be opened initially by lasering the GDDR membrane on one side, allowing flow to occur to this first reservoir. As clinical needs dictates, the membrane covering the second lumen could be opened, leading to the second reservoir. This would allow the surgeon to implant two or more reservoirs at the time of the initial shunting procedure, but to limit the flow to the second reservoir until such time as further reduction of intraocular pressure is needed. The membrane could be lasered first over one of these lumens, leaving the other drainage pathway as a reserve for when the patient's clinical need requires further lowering of intraocular pressure.

In summary, glaucoma has reached epidemic proportions worldwide and continues to blind patients despite technological and pharmaceutical advances in the field. Surgical management of the disease has changed dramatically in the last decade and now, more surgeons favor the use of aqueous shunts as their primary surgical procedure. Regardless the model or commercial brand, postoperative hypotony and hypotony-related complications continue to be a common clinical problem. The GDDR devices can be controlled noninvasively with all types of laser, and allows titratable control of aqueous flow. Furthermore, the device can open new treatment modalities and options, not currently available with the existing design of aqueous shunt devices.

Acknowledgments

A preliminary version of this study has never been presented as a paper or poster or submitted for publication. The Authors JO and RB have a patent application pending for the disclosed device. RVM do not have financial or economic interest to disclose at this time. There were no funds or grants allocated to this research project. The authors state that they have full control of all primary data and they agree to allow *Translational Vision Science & Technology Journal* to review their data upon request.

References

1. Furtado JM, Lansingh VC, Carter MJ, et al. Causes of blindness and visual impairment in Latin America. *Surv Ophthalmol*. 2012;57:149–177.
2. Quigley HA. Glaucoma. *Lancet*. 2011;377:1367–1377.
3. Zambelli-Weiner A, Crews JE, Friedman DS. Disparities in adult vision health in the United States. *Am J Ophthalmol*. 2012;154:S23–30. e21.
4. Quigley HA, Broman AT. The number of people with glaucoma worldwide in 2010 and 2020. *Br J Ophthalmol*. 2006;90:262–267.
5. Schwartz AL, Anderson DR. Trabecular surgery. *Arch Ophthalmol*. 1974;92:134–138.
6. Joshi AB, Parrish RK II, Feuer WF. 2002 survey of the American Glaucoma Society: practice preferences for glaucoma surgery and antifibrotic use. *J Glaucoma*. 2005;14:172–174.
7. Gedde SJ, Schiffman JC, Feuer WJ, Herndon LW, Brandt JD, Budenz DL. Three-year follow-up of the tube versus trabeculectomy study. *Am J Ophthalmol*. 2009;148:670–684.
8. Gedde SJ, Schiffman JC, Feuer WJ, Herndon LW, Brandt JD, Budenz DL. Treatment outcomes in the tube versus trabeculectomy study after one year of follow-up. *Am J Ophthalmol*. 2007;143:9–22.
9. Ramulu PY, Corcoran KJ, Corcoran SL, Robin AL. Utilization of various glaucoma surgeries and procedures in Medicare beneficiaries from 1995 to 2004. *Ophthalmology*. 2007;114:2265–2270.
10. Chen PP, Yamamoto T, Sawada A, Parrish RK II, Kitazawa Y. Use of antifibrosis agents and glaucoma drainage devices in the American and Japanese Glaucoma Societies. *J Glaucoma*. 1997;6:192–196.
11. Gedde SJ, Panarelli JF, Banitt MR, Lee RK. Evidenced-based comparison of aqueous shunts. *Curr Opin Ophthalmol*. 2013;24:87–95.
12. Minckler DS, Francis BA, Hodapp EA, et al. Aqueous shunts in glaucoma: a report by the American Academy of Ophthalmology. *Ophthalmology*. 2008;115:1089–1098.
13. Gedde SJ, Herndon LW, Brandt JD, Budenz DL, Feuer WJ, Schiffman JC. Surgical complications in the Tube Versus Trabeculectomy Study during the first year of follow-up. *Am J Ophthalmol*. 2007;143:23–31.
14. Kee C. Prevention of early postoperative hypotony by partial ligation of silicone tube in Ahmed glaucoma valve implantation. *J Glaucoma*. 2001;10:466–469.
15. Mc EW. Application of Poiseuille's law to aqueous outflow. *AMA Arch Ophthalmol*. 1958;60:290–294.
16. Gedde SJ, Singh K, Schiffman JC, Feuer WJ. The Tube Versus Trabeculectomy Study: interpretation of results and application to clinical practice. *Curr Opin Ophthalmol*. 2012;23:118–126.
17. Singh K, Gedde SJ. Interpretation and misinterpretation of results from the tube versus trabeculectomy study. *Int Ophthalmol Clin*. 2011;51:141–154.
18. Sarkisian SR Jr. Tube shunt complications and their prevention. *Curr Opin Ophthalmol*. 2009;20:126–130.
19. Rose GE, Lavin MJ, Hitchings RA. Silicone tubes in glaucoma surgery: the effect of technical modifications on early postoperative intraocular pressures and complications. *Eye (Lond)*. 1989;3(Pt 5);553–561.
20. Downes RN, Flanagan DW, Jordan K, Burton RL. The Molteno implant in intractable glaucoma. *Eye (Lond)*. 1988;2(Pt 3);250–259.

21. 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.
22. Christakis PG, Tsai JC, Kalenak JW, et al. The Ahmed Versus Baerveldt Study: three-year treatment outcomes. *Ophthalmology*. 2013;120:2232–2240.
23. Huang MC, Netland PA, Coleman AL, Siegner SW, Moster MR, Hill RA. Intermediate-term clinical experience with the Ahmed Glaucoma Valve implant. *Am J Ophthalmol*. 1999;127:27–33.
24. Christakis PG, Kalenak JW, Zurakowski D, et al. The Ahmed Versus Baerveldt study: one-year treatment outcomes. *Ophthalmology*. 2011;118:2180–2189.
25. Budenz DL, Barton K, Feuer WJ, et al. Treatment outcomes in the Ahmed Baerveldt Comparison Study after 1 year of follow-up. *Ophthalmology*. 2011;118:443–452.
26. Barton K, Gedde SJ, Budenz DL, Feuer WJ, Schiffman J. The Ahmed Baerveldt Comparison Study methodology, baseline patient characteristics, and intraoperative complications. *Ophthalmology*. 2011;118:435–442.
27. Coleman AL, Hill R, Wilson MR, et al. Initial clinical experience with the Ahmed Glaucoma Valve implant. *Am J Ophthalmol*. 1995;120:23–31.
28. Prata JA Jr, Mermoud A, LaBree L, Minckler DS. In vitro and in vivo flow characteristics of glaucoma drainage implants. *Ophthalmology*. 1995;102:894–904.
29. Francis BA, Cortes A, Chen J, Alvarado JA. Characteristics of glaucoma drainage implants during dynamic and steady-state flow conditions. *Ophthalmology*. 1998;105:1708–1714.
30. Schwartz KS, Lee RK, Gedde SJ. Glaucoma drainage implants: a critical comparison of types. *Curr Opin Ophthalmol*. 2006;17:181–189.
31. Stein JD, McCoy AN, Asrani S, et al. Surgical management of hypotony owing to overfiltration in eyes receiving glaucoma drainage devices. *J Glaucoma*. 2009;18:638–641.