Evaluation of Dimensional and Flow Properties of ExPress Glaucoma Drainage Devices

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Purpose: ExPress devices are available as P50 and P200 models, the numbers related to their luminal diameters in μm. We compared their Poiseuille’s Law-based theoretical resistance values with experimental values and correlated these with their luminal dimensions derived from electron microscopy.

Methods: Scanning electron microscopy was performed on P50 and P200 devices. Bench-top flow studies were performed to find the resistances of the devices. Devices were also incorporated into a perfused, ex vivo porcine sclera model to test and compare their control of pressure, with and without overlying scleral flaps, and with trabeculectomies.

Results: The luminal dimensions of the P200 device were 206.4 ± 3.3 and 204.5 ± 0.9 μm at the subconjunctival space and anterior chamber ends, respectively. Those of the P50 device were 205.0 ± 5.8 and 206.9 ± 3.7 μm, respectively. There were no significant differences between the P200 and P50 devices (all P > 0.05). The resistances of the P200 and P50 devices were 0.010 ± 0.001 and 0.054 ± 0.002 mm Hg/μL/min, respectively (P < 0.05). Equilibrium pressures with overlying scleral flaps were 17.81 ± 3.30 mm Hg for the P50, 17.31 ± 4.24 mm Hg for the P200, and 16.28 ± 6.07 mm Hg for trabeculectomies (P = 0.850).

Conclusions: The luminal diameters of both devices are externally similar. The effective luminal diameter of the P50 is much larger than 50 μm. Both devices have low resistance values, making them unlikely to prevent hypotony on their own. They lead to similar equilibrium pressures as the trabeculectomy procedure when inserted under the scleral flap.

Key Words: ExPress, aqueous humor, intraocular pressure, IOP, glaucoma, scanning electron microscopy, scleral flap

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The ExPress glaucoma drainage device was first approved by the US FDA for the treatment of glaucoma in 2002.1 It was designed for ease of insertion and the elimination of a sclerostomy and iridectomy, thus reducing postoperative inflammation and fibrosis when compared with a trabeculectomy. In early cases, it was implanted underneath bare conjunctiva but this resulted in complications such as hypotony, conjunctival erosion, and endophthalmitis.2–4 This implantation method was then changed to that under a trabeculectomy-style partial-thickness scleral flap,5 with significant reductions in the above complications and comparable IOP control compared with trabeculectomies.6–8

It is designed as a stainless steel, nonvalved tube with a disc-like flange at the subconjunctival space end and a spur-like projection at the anterior chamber end, both to prevent extrusion (Fig. 1). There are currently 2 models available, the P50 and the P200, the numbers related to their luminal internal diameters (ID) in μm. Both are otherwise externally similar and 2.64 mm in length. A previous R50 model has been discontinued, it had a 50 μm ID and 2.96 mm length. Being a nonvalved tube device, the resistance controlling aqueous humor flow and subsequent pressure drops would be significantly affected by its luminal diameter.5 From Poiseuille’s Law,

\[ P = \frac{128\mu LQ}{\pi d^4}, \]  

where \( P \) is pressure drop across the device, \( \mu \) is (aqueous humor) dynamic viscosity, \( L \) is device length, \( Q \) is (aqueous humor) flow rate, and \( D \) is luminal diameter. As

\[ R = \frac{128\mu L}{\pi d^4}. \]  

We can see that the resistance is affected by the length of the device, but more significantly by its luminal diameter. For example, if the luminal diameter increases by 4 times, the resistance is expected to decrease by 256 times, as mentioned by Estermann et al.9 However, when they experimented with actual devices, the resistance values they obtained with the P200 devices were only in the order of 6 to 7 times lower than the P50 devices. They attributed their findings mainly to experimental error. We were curious about this finding and thus wanted to replicate their experiment and also perform scanning electron microscopy on the devices to seek further explanation of the phenomena. We also decided to perform additional testing using an ex vivo porcine sclera model to test the devices further.

Scanning electron microscopy was performed to look at the dimensions and structural details of the ExPress devices. This was followed by bench-top flow studies to look
at the resistance of the devices, to enable a comparison with the study by Estermann et al.\(^9\) We then incorporated the devices into a porcine sclera model to test and compare their control of pressure, with and without overlying scleral flaps. Finally, we looked at the most suitable stab incision sizes for the insertion of the devices, as a measure to minimize external leakage that could lead to additional drops in pressure.

**METHODS**

For the following experiments, we used ExPress P50 and P200 devices (4 units each) which were provided by Alcon Inc. (Fort Worth, TX).

### Electron Microscopy

Two samples each of the ExPress device models were imaged using a scanning electron microscope (Quanta 200F; FEI, Hillsboro, OR). The stainless steel ExPress devices were uncoated for the scanning process, so as not to affect the subsequent flow studies. We selected the most perpendicular images to minimize parallax errors when measuring the relevant dimensions using ImageJ software (US National Institutes of Health, Bethesda, MD). At least 6 measurements in different orientations or positions were taken for each dimension and the mean and SD obtained.

### Flow Studies

The setup we used was based on that described by Estermann et al.\(^9\) ExPress devices were attached to the bottom end of a manometer, pressure from the head of water would provide flow through the device during testing. The amount of fluid collected enabled flow rate and resistance to be calculated. The manometers were constructed from three 60 mL syringe barrels which were cut and glued together. We slightly modified the original method by implanting the devices using their preloaded injectors onto 0.8 mm thick silicone sheets (HT-6240; Rogers Corporation, Rogers, CT). These sheets were then bound with rubber bands to the syringe barrel manometer which had its bottom end removed (Fig. 2A). In initial tests, we found that there was often leakage (in up to 50% of attempts) around the ExPress devices when using laboratory film, as used by Estermann and colleagues.

After attaching the silicone sheets and ExPress devices, the manometer was filled with Balanced Salt Solution (BSS; Alcon Laboratories Inc.), which was then allowed to flow and flush the system for 15 minutes. Water tightness around the ExPress devices was checked with a microscope during this time, if in doubt the devices were removed, implanted in new silicone sheets, and remounted to the manometer. The height of BSS was then set at 6.8, 13.6, 20.4, 27.2, and 34.0 cm (equivalent to 5, 10, 15, 20, and 25 mm Hg) and the dripping fluid was collected in a beaker on an enclosed precision scale (GF-300; A&D Instruments Ltd, Abingdon, UK) over a period of 15 minutes for each level. During the test, the level of BSS in the manometer, and thus pressure, was kept constant by addition from a BSS bottle and tube. From the amount of BSS collected, we derived the flow rate, which in turn enabled us to derive resistance by dividing pressure over flow rate. The experiments were all performed at room temperature (20 to 21 C).

### Porcine Sclera Model

We incorporated the ExPress devices into a porcine sclera model. In setting up this model, eyes from 6- to 12-month-old mixed breed pigs were used. Whole pig heads were obtained from an abattoir and the eyes enucleated and used within 36 hours of slaughter.\(^9\) The eyes were discarded if they had any discernible damage on them. These eyes were sectioned horizontally and the iris, lens, vitreous, and choroid removed. The scleral segments were then cut into 18 mm diameter asymmetrical discs, to include a small section of limbus and cornea. These discs were then mounted on a Barron artificial anterior chamber, normally used in corneal transplant surgery (Katena Products Inc., Denville, NJ). One inlet port of the artificial anterior chamber was attached to the infusion pump (Cole-Parmer, Vernon Hills, IL) and pressure transducer (model 162PC01D; Honeywell International, Morristown, NJ) (Fig. 2B). This pressure transducer was connected to an interface board/voltmeter (model VM110; Velleman NV, Gavere, Belgium) and personal computer. The other inlet port of the artificial anterior chamber was closed. Nonexpansile, low compliance silicone tubing (outer diameter 6 mm, ID 3 mm) was used throughout the system. The working fluid used was BSS. Before the actual experiment, we calibrated the pressure transducer and measured the resistance of the Barron artificial anterior chamber and silicone tubing. This was done by infusing BSS at 50, 100, 200, 300, and 400 mL/h through the system with the 2 tissue pedestal openings open to the atmosphere. The tissue pedestal openings and the pressure transducer inlet port were positioned at the same level. The resistance was determined from the slope of the pressure versus flow rate line. Before the start of each experimental run, the chamber was pressurized to around 20 mm Hg before a scleral flap was fashioned on the mounted sclera. A 250 μm Accurate Depth blade (BD, Franklin Lakes, NJ) was used to outline a 4 × 3 mm rectangle. A crescent knife was then used to dissect

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**FIGURE 1.** Scanning electron micrograph of ExPress P200 device (scale bar = 500 μm). The disc-like flange lies under the scleral flap in the subconjunctival space, whereas the spur and labeled orifices lie in the anterior chamber.
below the flap up to the limbus. This flap was then reflected. After each stab incision in the following interventions, any remaining air in the anterior chamber was removed by a gentle bolus of BSS. The same researcher (A.S.) who prepared the porcine eyes performed all the interventions and read all the results.

![Diagram of ExPress device](image)

**FIGURE 2.** A, Setup for fixed pressure method of testing ExPress devices. The manometer level was kept constant by addition from a BSS bottle and tube (not shown). B, Setup for equilibrium pressure without a flap experiment. The scleral flap was not repositioned or sutured after device insertion. C, Setup for index of external leakage experiment. Scleral flaps were not repositioned or sutured, and no BSS was added to the manometer during the test. BSS indicates Balanced Salt Solution.

![Photograph of ExPress device](image)

**FIGURE 3.** A, Photograph of ExPress device in situ (arrow) and reflected scleral flap. B, Diagram of ExPress device under a sutured flap. C, Typical pressure curve in equilibrium pressure with an overlying flap experiment. The pressure leveled out after the flap opened to allow flow.
Equilibrium Pressure Without an Overlying Scleral Flap

This part of experiment was carried out to compare the control of pressure by the devices on their own, without the contribution by overlying scleral flaps. ExPress devices \((n = 8)\) were inserted after 27 G stab incisions (Figs. 2B, 3A). Scleral flaps were not repositioned or sutured after device insertion. The flow rate was set at 3 \(\text{mL/min}\) and the pressure tracing reset. The resulting equilibrium pressures were observed. This was defined as a steady pressure with fluctuations within 0.5 mm Hg of each other for at least 5 minutes. Each ExPress device was used for 2 runs.

Equilibrium Pressure With an Overlying Scleral Flap

We compared equilibrium pressures between ExPress devices and a trabeculectomy. For the ExPress devices \((n = 8)\), a 27 G stab incision through the scleral bed was performed, after which they were inserted using their injector. Each device was used for 2 runs. For the trabeculectomies \((n = 8)\), after creating a scleral flap, a sclerostomy was created using a 0.75 mm diameter scleral punch. In all cases, the scleral flaps were sutured down adequately with two 10/0 nylon sutures, as in Figure 3B. The sutures were tied to achieve adequate tightness while avoiding creasing or stretching of the scleral flap. The flow rate was set at 3 \(\mu\text{L/min}\) and the pressure tracing reset. A typical trace is shown in Figure 3C, showing a gradual increase in pressure until the flap opened to allow flow.

Index of External Leakage With Different Stab Incision Sizes

This part of the experiment was carried out to compare the amounts of paratubal leakage after 27 and 25 G stab incisions (sizes recommended in the packaging leaflet). Occluded ExPress devices were inserted after making stab incisions in the scleral bed with 27 or 25 G needle stabs (Fig. 2C). The nominal outer diameters of these needles were 0.41 mm (27 G) and 0.51 mm (25 G). The externally identical ExPress P50 and P200 devices (1 each) were occluded with short segments of broken-off introducer wire in their lumens. Any remaining gaps were sealed off using cyanoacrylate glue to cover the flanged external

### Table 1. Summary of Device Dimensions

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>P50</th>
<th>P200</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, whole (mm)</td>
<td>2.56 ± 0.01</td>
<td>2.56 ± 0.01</td>
<td>(P = 0.772) (example in Fig. 4A)</td>
</tr>
<tr>
<td>Width, tube section ((\mu\text{m}))</td>
<td>377.0 ± 8.5</td>
<td>379.3 ± 7.0</td>
<td>(P = 0.465) (example in Fig. 4A)</td>
</tr>
<tr>
<td>Length, complete tube section (from flange to side orifice) (mm)</td>
<td>1.36 ± 0.02</td>
<td>1.35 ± 0.03</td>
<td>(P = 0.434) (example in Fig. 4A)</td>
</tr>
<tr>
<td>Internal diameter, subconjunctival space end ((\mu\text{m}))</td>
<td>205.0 ± 5.8</td>
<td>206.4 ± 3.3</td>
<td>(P = 0.564) (examples in Figs. 4B, C)</td>
</tr>
<tr>
<td>Internal diameter, anterior chamber end ((\mu\text{m}))</td>
<td>206.9 ± 3.7</td>
<td>204.5 ± 0.9</td>
<td>(P = 0.434) (examples in Figs. 4D, E)</td>
</tr>
</tbody>
</table>

For the electron microscope we used, the manufacturer quotes an error in magnification (and measurement) of ± 1.5%.

FIGURE 4. A, Profile of 2 ExPress P200 devices \((\times 78\text{ magnification})\). Subconjunctival space ends of (B) P50 and (C) P200 devices \((\times 100\text{ magnification})\). The external dimensions and lumens are similarly sized. Anterior chamber ends of (D) P50 \((\times 160\text{ magnification})\) and (E) P200 devices \((\times 200\text{ magnification})\). The external dimensions and lumens are similarly sized.
After the devices were inserted through the incisions, the scleral flaps were not repositioned or sutured. Pressure in the manometer was increased to 20 mm Hg, this time no BSS was added to the manometer during the test. The whole apparatus was left for 1 hour for pressure to stabilize, after which the pressure was noted.

Results are shown as mean ± SD. Statistical analysis was performed using Prism 4 software (GraphPad Software Inc., San Diego, CA). The unpaired t test was used when comparing 2 groups, whereas 1-way ANOVA ± Bonferroni multiple comparison posttest was used when comparing 3 groups. *P* < 0.05 was considered statistically significant.

**RESULTS**

**Electron Microscopy**

A summary of the dimensions of the devices is shown in Table 1 and some actual images are shown in Figure 4. There were no significant differences between the external dimensions and luminal IDs of the P50 and P200 devices (all *P* > 0.05).

**Flow Studies**

Resistance values are shown in Table 2 and Figure 5. The overall resistance of the P50 devices was 0.054 ± 0.002 mm Hg/µL/min and of the P200 devices was 0.010 ± 0.001 mm Hg/µL/min (*n* = 4 each, *P* < 0.001).

**Porcine Sclera Model**

Equilibrium pressures without overlying scleral flaps were 0.63 ± 0.59 mm Hg for the ExPress P50 and 0.25 ± 0.38 mm Hg for the ExPress P200. There was no significant difference between the ExPress P50 and ExPress P200 devices (*P* > 0.05). Equilibrium pressures with sutured overlying scleral flaps were 17.81 ± 3.30 mm Hg for the ExPress P50, 17.31 ± 4.24 mm Hg for the ExPress P200, and 16.28 ± 6.67 mm Hg for the trabeculectomy (*P* = 0.850) (Fig. 6). For the index of external leakage experiment, preinsertion and postinsertion pressure values with the different stab incision sizes are shown in Table 3. There was no significant difference in leakage between the 27 and 25 G stab incisions.

**DISCUSSION**

**Electron Microscopy**

The external dimensions of the P50 and P200 devices were similar to each other and consistent with the nominal dimensions supplied by the manufacturer. Interestingly, we found that the lumens of both P50 and P200 models also had the same dimensions (around 200 µm in diameter), at both subconjunctival space and anterior chamber ends. We subsequently approached Alcon Inc. to inquire about this finding. They confirmed our findings and showed how the P50 differs from the P200 only in having a 150 µm diameter bar lying across its lumen in the middle of the device, as
in Figure 7. This inner bar was not seen on our electron micrographs. This design has implications on fluid flow and pressure, as will be discussed in the next section.

### Flow Studies

The resistances and flow rates of the 2 ExPress models were consistent with fixed resistance characteristics, and similar to that reported by Estermann et al., which were 0.016 mm Hg/µL/min for the P50 and 0.009 mm Hg/µL/min for the P200. We also found that the difference in resistance values between the P50 and P200 devices could not be explained just on the basis of their descriptions, where from Poiseuille’s Law a 4-fold increase in inner diameter from 50 to 200 µm would reduce resistance by 256 times. In our experiment, the P200 device resistance was only around 5 times less than that of the P50 device. However, we now know that the P50 device has 200 µm diameter circular lumens at both ends and an inner constriction leading to 2 smaller tapering channels centrally (Fig. 7), thus making Poiseuille’s Law inapplicable to its case. In fact, this law is not applicable for ExPress devices in general as the side orifice (Fig. 1) also disrupts the constant circular cross-section assumption. Instead, there is no single law to calculate the resistance of these more complex devices and experimental determination is required.

### Porcine Sclera Model

When examining equilibrium pressures without overlying scleral flaps, both ExPress device models offered minimal resistance to flow. This is in keeping with the results of our flow studies and initial clinical ExPress device implantations without cover under a scleral flap, when significant numbers of hypotony (up to 91%) occurred. Following the findings, implantation of the devices under the scleral flap was recommended.

With overlying sutured scleral flaps, we found that pressures did not differ between the ExPress devices and a typical trabeculectomy. This finding is consistent with those of many clinical studies. However, we can say that ExViro device implantations result in less variability in pressure readings. This may be due to lumen size variations: ExPress devices have lumen size measurements with small tolerances (Table 1), as compared with making a sclerostomy with a punching device or knife. In practice, even with same-sized punching devices, variations in sclerostomy sizes occur due to differences in scleral tissue tension or sharpness of the instruments (eg, if the cutting process is performed more than once).

When we looked at the amount of paratubal leakage occurring after insertion of the devices, the amounts were significant but similar after either 27 or 25 G needle stabs. It is likely that the spur enlarges the scleral opening during insertion, which leads to a poorer fit around the body and subsequent leakage. However, we found that subjectively more manipulation was needed to insert the device after the smaller 27 G needle stab, which could traumatize surrounding local tissue. We therefore think that 25 G needle stabs are better for inserting ExPress devices, at least in this model.

There are limitations to this laboratory study. The in vitro findings may not correlate exactly with results in actual living eyes, where the resistance of the overlying conjunctiva and bleb are present, making our findings applicable mainly for the early postoperative stage of surgery before wound healing has developed. In addition, other issues such as total ocular compliance and tissue hydration may come into play in vivo. As such, the findings from this experiment need to be corroborated by those from experiments in vivo.

### CONCLUSIONS

Overall, this experiment has provided insight into some matters related to the control of aqueous humor flow and pressure by ExPress devices. These should be borne in mind before the usage of these devices. The effective luminal diameter of the P50 is much larger than 50 µm. Poiseuille’s Law is not applicable for estimating resistance in ExPress devices as they do not have constant circular cross sections. Their low resistance values make them unlikely to prevent hypotony on their own and they lead to similar equilibrium pressures as the trabeculectomy procedure when inserted under the scleral flap.
flap. Insertion of these devices after a 25 G stab incision allows less tissue manipulation.

REFERENCES


