Final Report: SmartFlow Glaucoma Stent

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Submitted to Myron Spector and I.V. Yannas
for Course 2.782J

1.0 INTRODUCTION

In the United States, Glaucoma affects over three million people and has become the second leading cause for blindness. Currently, a barrage of different techniques are used to treat the underlying cause of most Glaucoma cases: high intraocular pressure (IOP). High IOP is the primary cause of open-angle glaucoma and is treated using a variety of drugs, laser surgeries, and traditional surgeries. This report presents the design of an implantable device which will allow for IOP to be measured and controlled using a wireless microelectromechanical systems (MEMS) based device.

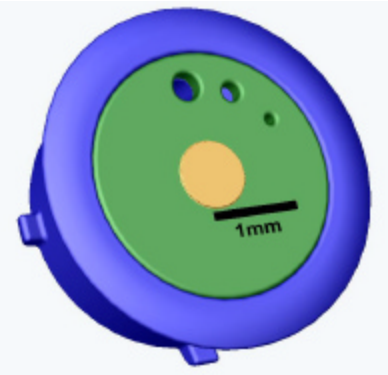

Figure 1 Front View of SmartFlow Implant

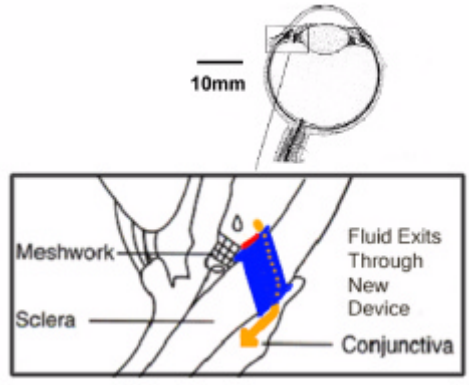

Figure 2 Device Inserted into Eye

2.0 DISEASE DESCRIPTION

Glaucoma is a disease that affects approximately three million Americans and is suspected in an estimated 65 million people worldwide. It is the second leading cause of blindness in the U.S. and the first leading cause of preventable blindness. Yet, only half of the estimated three million know they have the disease. African Americans are 6 to 8 times more likely to experience glaucoma than Caucasians. Other groups at high-risk are people over 60, diabetics, people with a family history of glaucoma, and people who are severely near-sighted.

2.1 Anatomy

Glaucoma is a disease characterized by damage to the optic nerve, leading to vision loss or complete blindness, if left untreated. In a normal eye, aqueous humor serves to supply the lens, cornea, and other anterior structures with nutrition and hydration. This fluid is produced by the ciliary body and enters the posterior chamber, the space behind the iris. Fluid then flows from the posterior chamber through the pupil and into the anterior chamber, which is located between the cornea and the iris, as shown in Figure 3. From the anterior chamber, fluid passes through the trabecular meshwork into Schlemm's canal and is transferred out of the eye through the conjunctiva to blood vessels and the lymphatic system. This fluid pathway is illustrated in Figure 4. A balance between the production and drainage of the aqueous humor maintains the intraocular pressure at its physiological level (10-20 mmHg).

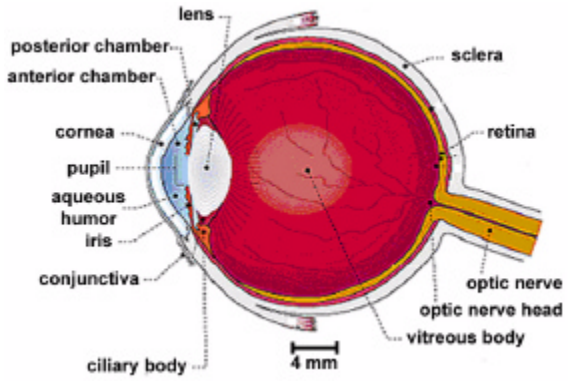

Figure 3 Structure of Human Eye

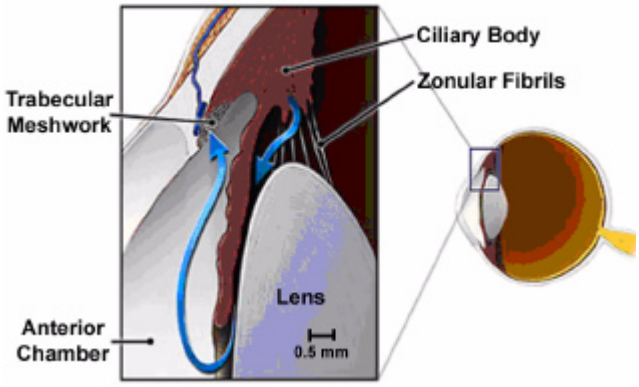

Figure 4 Detailed View of Important Structures

2.2 Pathology

The term glaucoma is applied to the condition in which damage to the eye has caused a loss in vision. Typically, the primary cause of the lost vision is intraocular pressure above the normal physiological range. The most common type of glaucoma is open angle glaucoma and affects 95% of glaucoma patients. It is considered a chronic disease that occurs over a period of time,

often decades. At its onset, open-angle glaucoma usually has no symptoms. There is no pain, no blurring of vision, and no ocular inflammation to alert a patient that they have the disease. However, as open-angle glaucoma progresses, it will slowly destroy peripheral vision. This is the point when certain symptoms begin to show including dimming of side vision, difficulty seeing in mildly bright light, sensitivity to glare, tunnel vision, difficulty seeing lower contrast print, or a “cloud” over vision. Most people begin to seek treatment at this stage of the disease, but the vision that has already been lost from glaucoma cannot be restored.

The distinctive feature in open-angle glaucoma is that the angle between the iris and cornea is normal. However, the drainage passage from the trabecular meshwork to Schlemm's canal is clogged. The initial cause of glaucoma is still unclear, although research indicates possible causes to be an excessive release of pigmentation, buildup of proteins and other chemicals, or flaking of the iris and other actions. These actions all lead to blockage of the trabecular meshwork which prevents drainage of aqueous humor out of the eye. When the blockage is severe, aqueous humor accumulates in the anterior and posterior chambers causing high IOP. A high IOP causes reduction of blood flow and increased pressure on the optic nerve. This elevated pressure may gradually interrupt the metabolic processes of cells in the optic nerve, leading to a progressive destruction of nerve. The result is permanent damage to the optic nerve, which causes degeneration of vision and eventually complete loss of vision.

2.3 Current Treatment Methods

There are many glaucoma treatments currently on the market. The first level of treatment includes a large number of eye drops and pills that either help reduce the production of intraocular fluid or increase the drainage of intraocular fluid. These drugs have a wide range of side effects including: allergies, headaches, reduced pulse and blood pressure, depression, and many others. Marijuana is another drug that is touted as reducing the effects of glaucoma; however, this is a hotly debated subject.

If drugs do not work well or produce many side effects, the next step is typically laser surgery. Laser Peripheral Iridotomy (LPI) is a surgical procedure where a laser beam burns a hole in the iris that acts as a drain for intraocular fluid. Lasers are also used in a procedure called trabeculoplatsy, which focuses a laser to selectively heat and shrink tissues around the trabecular meshwork, allowing for increased drainage. While laser surgery is relatively effective, it often requires post-operative medication and can cause the formation of cataracts in many cases. Furthermore, half of the patients receiving laser treatments have an increase intraocular pressure two years after surgery. Since not all laser surgeries can be repeated, conventional surgery is usually required to reduce the high IOP.

Multiple options are available should laser surgery be ineffective. These include destructive surgeries, device implants, as well as more conventional surgery like trabeculectomy procedures. Destructive surgeries attempt to reduce the amount of fluid production by destroying the fluid producing ciliary bodies. Currently, the main form of glaucoma implant device is known as a shunt or valve. These devices typically are comprised of a polymer tube inserted

into the anterior chamber of the eye that is connected to a patch placed between the conjunctiva and sclera. Fluid flows out through the tube and is released into the blood stream through the conjunctiva. While these devices are generally effective at lowering IOP, they often require additional drugs, have a limited lifetime due to tissue growth, and may cause IOP to drop below a dangerous level.

The gold standard surgical procedure, a trabeculectomy, creates a new passageway through the sclera of the eye, which allows aqueous humor to bypass the trabecular meshwork and escape the eye. This filter allows drainage of fluids from inside the eye to a “pocket” between the conjuctiva and the sclera where fluid is absorbed by blood vessels. The flap created in this procedure prevents low intraocular pressure and also prevents infectious agents from entering the eye. This procedure has its share of problems. Often, the healing process of the eye closes the filtration site due to scarring. The patients are at risk to infection, bleeding, double vision, as well as loss of vision. Also, a third of the patients that undergo this procedure develop cataracts within five years.

3.0 DEVICE DESCRIPTION

The SmartFlow glaucoma implant is designed to increase and maintain the fluid outflow from the eye in order to decrease the intraocular pressure and prevent damage to the optic nerve. The usage of current glaucoma implants serve to reduce pressure and prevent further damage to the optical nerve; however, damage to the optical nerve head is permanent and vision will not improve with any current or research device. Currently, no devices have been designed to repair the degenerated nerve due to the extremely complex geometry of the optical nerve head. Pressure reduction implants are typically used after failure of noninvasive treatments. Current glaucoma drainage devices on the market include the Ahmed valve implant, the Baervelt implant, and the Molteno implant. A wide variety of experimental devices are in

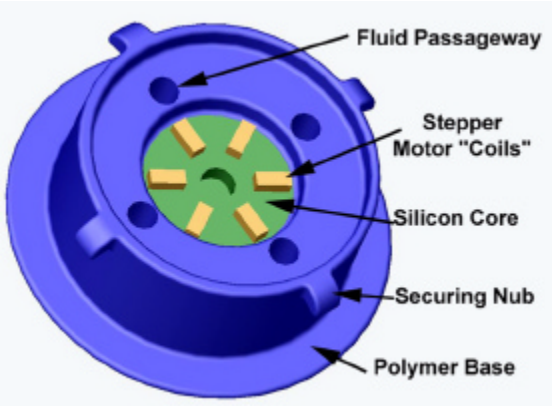

Figure 5 Internal View of Device

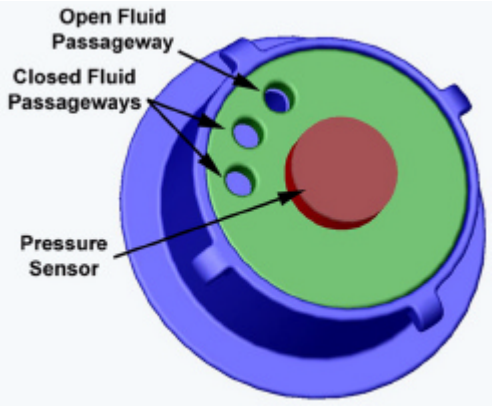

Figure 6 Rear View of Device

development to improve control of high IOP, including stainless steel shunts, specialized MEMS improvements to existing valved shunts, and a collagen based trabecular mesh generation device.

The basic construction of the device, shown in Figure 5, consists of a silicon MEMS core structure (shown in green) with four cylindrical holes passing through the body, while the remainder of the main structure consists of a expanded-polytetrafluoroethylene (shown in blue) to reduce biocompatibility issues. Each of these holes acts as a separate conduit for aqueous humor to flow from inside the eye to a small bleb structure in the conjunctiva of the eye. To control the flow of aqueous humor through the holes, separate movable disks are added to the inner and outer surfaces of the device. These disks are solid with a series of holes that allow fluid to flow through the desired passageway while preventing undesired flow through the other holes. The disk on the inner side of the device has three holes of equal diameter to the main passageway as shown in Figure 6. The disk on the outer side of the device has one hole of equal diameter to the main passageway, one hole with a diameter of 1/2 of the passage, and one hole with a diameter of 1/3 of the passage. This configuration is illustrated in Figure 8. The differently sized holes act as constrictors to the fluid flow, allowing for simple discrete control of the pressure-flow characteristics of the device. Main dimensions of the device are a diameter of 3mm for the core section, maximum diameter of 4mm, a total thickness of 1mm, and main fluid passageway diameter of 0.3mm. Total weight of the device

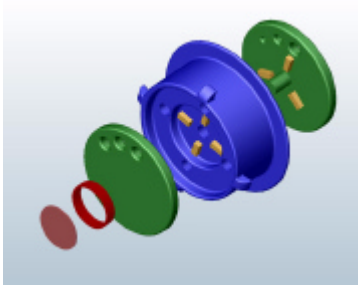

Figure 7 Exploded Rear View of Device

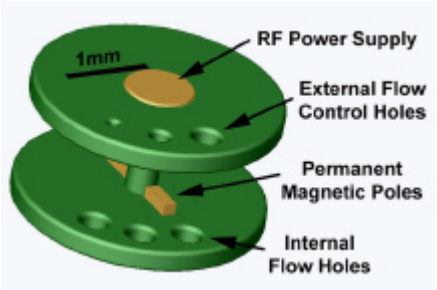

Figure 8 Internal Disks

would be approximately 14mg.

To allow for control of the disks, a MEMS stepper motor is proposed as represented by the gold colored bars in Figure 5 and Figure 7. Stepper motors make use of several magnetic and electrically coupled circuits to create precise and discrete motion. While rotary stepper motors are common in macro-scale industries, their transfer to the micro-scale has been somewhat more difficult but is preceding quite rapidly for similar meso-scale applications. Since this device is more on a meso-scale (~200um - 1000um) rather than the current research's micro-scale (~1um - 100um), the device will be slightly easier to construct and operate.

As an improvement to the existing diagnostic procedure, a fairly standard MEMS pressure sensor will be incorporated into the inner surface of the device. The pressure sensor is shown as a red cylinder in Figure 7. These features are easily incorporated into the main structure using monolithic MEMS fabrication techniques.Traditional measurement uses tonometry to measure pressure externally by direct contact with the cornea or by an air puff. These measurements can require considerable time to numb the eye and can incur some discomfort on the patient.

In order to operate the device, some power source is required. It is currently impossible to incorporate any form of chemical, electrical, or thermal power storage in a device of this scale. Many concerns also exist with the compatibility and safety of such systems in biological environments. To avoid these problems, an external radio frequency (RF) power source can be used to supply power to the device at discrete instances such as a visit to the doctor's office. This technology is currently used in a number of places including tags that prevent theft at department stores and libraries. Within the RF signal, power can be supplied to the device as well as transmission of commands or signals to read the pressure sensor, move the disks, and other operations. RF signals at the low power required for these operations should be below the threshold necessary to cause damage to tissue.

To assist in the installation and fixation of the device, several geometric features have been added to the inner and outer faces of the device. On the outer surface, a thin curved lip protrudes from the sides of the device to prevent over insertion of the device into the eye during installation. On the inner surface, four small protruding nubs are used to prevent the device from exiting the incision due to an increase in intraocular pressure. All edges on these features are properly smoothed to prevent irritation of the sclera and conjunctiva. Permanent fixation will occur with these physical features in the direction normal to the eye's surface and with the assistance of the normal healing procedure in directions tangent to the eye's surface. This technique is used to hold several different devices in place in various eye surgeries, including the plana clip and plates for many glaucoma shunts and many designs for glaucoma and brain implants.

4.0 FDA DEVICE CLASSIFICATION

To ensure its safety and efficacy, the SmartFlow device will undergo a series of tests consisting of both non-clinical lab tests and well-controlled clinical trials. The non-clinical lab tests will provide data in regards to material biocompatibility, mechanical performance, and biological function. The SmartFlow device is classified as a Class III device since it is a new design having insufficient data in regards to its safety and efficacy. The device is an internally implanted device that will come in contact with the sclera and conjunctiva for greater than 30 days. Thus, according to the FDA-modified version of the International Organization for Standardization's (ISO) standard for evaluation of biological medical devices, the ISO 10993-1 “Biological Evaluation of Medical Devices, Part 1: Evaluation and Testing,” the following

tests will need to be conducted: irritation, sensitization, cytotoxicity, systemic toxicity, hemocompatibility, pyrogenicity, implantation, mutagenicity.

The clinical trials will compare the performance of two types of eyes - one implanted with our device and one having undergone a trabeculectomy. Our device will be evaluated in a randomized controlled multi-center investigation involving 200 patients within the U.S. Half of the patients will receive the device implant while the other half will proceed with the trabeculectomy procedure. Several testing measures have been established in order to evaluate the safety and efficacy of both methods. These measures include, but are not limited to:

1. The level of intraocular pressure (IOP) during the post-operative period and its improvement relative to the level of IOP during the pre-operative period.
2. The degree of visual acuity following the procedure and its improvement relative to pre-operative visual acuity.
3. Average number of anti-glaucoma medicines required to achieve the desired IOP relative to the pre-operative IOP.
4. The frequency and nature of complications that arise during the post-operative period. Such complications can include blockage of the drainage site due to the formation of excessive fibrosis or blood clots.

5.0 KEY TECHNICAL DESIGN ELEMENTS

5.1 General Design

One of the key features of the SmartFlow device is the ability to control the flow in a variety of ways that have been unavailable in existing devices. The first control method is the addition of multiple, independent fluid passageways. Typically, passageways in glaucoma devices will become clogged in seven years due to growth of fibrous and healthy tissues, as well as the buildup of proteins and other chemicals. When implanted in elderly patients, a seven year lifetime may be sufficient; however, many patients are being diagnosed with glaucoma at a younger age. A typical seven year device lifetime will require the patient to receive multiple surgeries over many years with increased scarring and likelihood of complications. To prevent these problems, the SmartFlow device includes four separate fluid channels. Assuming that the lifetime of an independent passageway is comparable to or better than existing devices, the SmartFlow will have an effective lifetime of 28 years, decreasing the number of required surgeries and reducing the risk of further complications. Furthermore, material and medicinal treatments will be considered for the SmartFlow to further reduce the likelihood of clogging issues.

The second method used to control fluid flow is the presence of three separate constrictors placed on the rotating disks. These constrictors can be rotated over the main fluid passageway to change the pressure-flow characteristics. Using the basic fluid mechanics principles of

mass conservation and Bernoulli's equation, the following equations can be derived to show the time based relationship between constrictor dimension, pressure drop, and volume of fluid in the eye.

$$\Delta V = \frac{\pi}{4} \cdot D^2 \cdot \sqrt{2 \cdot \rho_{aqueous} \cdot (P_{high} - P_{desired})} \cdot \Delta t$$

$$\Delta V = V_{eye} \cdot \left(1 - c \cdot \frac{P_{high}}{P_{desired}}\right)$$

ΔV	Change in eye volume
D	Constrictor Diameter
c	Pressure-Volume Constant
P_{high}	High IOP Value
$P_{desired}$	Desired Low IOP Value
Δt	Time to Decrease Pressure

Several assumptions were made in this analysis, including the following:

- a linear state relationship exists between pressure and volume instead of a complex non-linear function
- the properties of the aqueous humor can be approximated as those of water
- flow occurs in the non-viscous regime
- pressure decreases following a linear relationship.

Based on these formulas and assumptions, the constrictors were sized to 0.3mm, 0.2mm, and 0.1mm, which provide an approximate pressure relief time of 8 hours, 16 hours, or 60 hours. Since the device will remain within the conjunctiva, steady state operation of the implant will remain at a constant pressure vale after the pressure relief time. The constrictors of the device will only allow fluid to flow when an increase in pressure is seen inside the eye. These formula and values require further testing and analysis to more accurately predict fluid performance.

5.2 MEMS Technology

MicroElectroMechanical Systems, known commonly as MEMS, is a new technology used to create tiny devices. Typically, these devices tend to be on the range of several microns to several millimeters across and are typically made from silicon or glass wafers. These devices can incorporate moving parts and "electrical, optical, fluidic, chemical, and biomedical elements" and can respond to inputs such as "chemical, light, pressure, vibration, and acceleration." To create devices on a wafer, MEMS technology employs techniques such as chemical vapor deposition, etching, oxide growth, and sintering to create devices on the base wafer. Since these processing techniques can only create geometries in two dimensions, three dimensional geometries are created by layering materials. These techniques can create features as small 0.25 micron in the wafer plane with thicknesses varying from a few angstroms to millimeters. Because of these capabilities, devices can be small enough to fit inside blood vessels or manage an array of tiny optical switches. Devices can be designed with both functional components that act on the biological system, as well as sensors that can give real-time diagnostic feedback on device performance.

5.3 Pressure Sensor

The pressure sensor used on the device will be made of silicon and use MEMS strain gauge pressure sensor technology. Throughout many industries, MEMS pressure sensors are commonly used and are a reliable way to measure pressure. By placing the pressure sensor on the surface of the device facing the inside of the eye, direct measurement of the intraocular pressure can be made using the elastic deflection of a thin silicon layer called the diaphragm. A typical diaphragm pressure gage contains a capsule divided by a diaphragm, as shown in the schematic in Figure 9. One side of the diaphragm is exposed to the external measured pres-

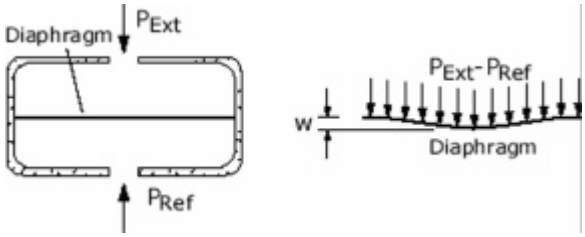

Figure 9 Diaphragm Pressure Sensor Schematic

sure, P_{Ext}, and the other side is connected to a known pressure, P_{Ref}. The pressure difference, $P_{Ext} - P_{Ref}$, mechanically deflects the diaphragm. The membrane deflection can be measured in any number of ways. For example, it can be detected via a mechanically-coupled indicating needle, an attached strain gage, a linear variable differential transformer (LVDT), or with many other displacement/velocity sensors. Due to the size of the SmartFlow device, the only viable pressure sensor technology is a strain gauge. Strain gauge pressure sensors can be directly incorporated into the surface by creating a strain gauge directly on the surface of the diaphragm. Deflection of the diaphragm induces a change in stress at the strain gauge, which causes a change in resistance of the strain gauge wires. This resistance can be measured and converted into strain, stress, and deflection. Once known, the deflection can be converted to a pressure loading using plate theory.

5.4 Stepper Motor

Although there are many motors available in the market, a stepper motor is used in the SmartFlow for several reasons. A stepper motor is a type of brushless DC motor that is applied for accurate positioning as well as good torque control. In the glaucoma implant, precise movement of the two plates is necessary for pressure management. The openings on both plates must match up to the hole in the body of the device for it to accurately change the amount of fluid that is released from the anterior chamber. Since a stepper motor rotates in discrete steps, it can be designed so that it can only rotate to the exact position where a different sized opening will line up with the specified hole.

Another reason for using a stepper motor in the SmartFlow is that the motor can generate high torque when used at very low speed. Since the device is implanted internally in the eye, there is a possibility that proteins or cells can get stuck in the crevice between the plates and the body of the device. This could prevent the plates from rotating. However, with high torque, the rotating plates can theoretically "loosen" up the cells and proteins, allowing for unrestricted movement. Finally, the last reason for using a stepper motor is that brushless motors typically have much longer rated life times than the brushed motors. Because changing the implant requires invasive surgery, it is ideal to use parts that have a lower rate of failure.

One concern of the stepper motor is whether or not it can be made small enough to fit on the implant. Recent discoveries in MEMS technology show that micro-scale stepper motor can be prepared. Thus, it is definitely possible to make a motor that fits in a 3mm or less diameter crevice below the top plate.

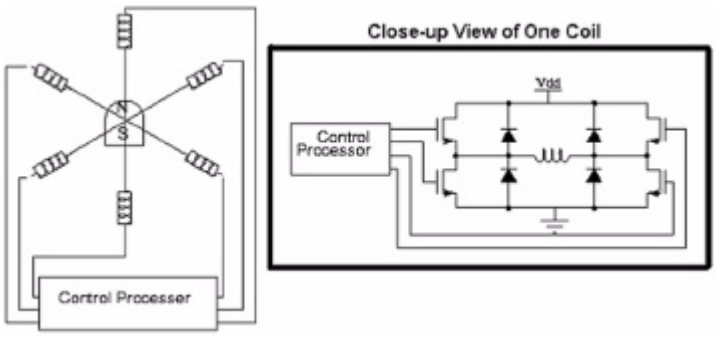

Figure 10 Schematic of a Bipolar 12 Half-Step Stepper Motor

As shown in Figure 10, a bipolar 12 half-step stepper motor requires 12 equal steps to make one full rotation. The stepper motor is designed to make 12 steps because there are three openings in the plates that have to be able to turn onto each of the four holes in the body of the device. To make such a motor, six coils are placed in a circle on the main body of the device with each coil directly connected to the opposing coil on the circle. The center of this circle is a rotating magnet situated on the movable silicon disks. The same current flows through coils directly opposite of each other, thus forming opposite magnetic poles relative to the magnet in the middle. When the direction of current flow changes, the magnetic poles are switched. With this knowledge, a control processor can direct the rotation of the magnet by changing the direction of current that flows through each set of coils in a certain order. Figure 10 shows a close-up view of a set of coils. The current direction can be altered by changing the gate voltages of the MOSFETs, which indirectly turns on two opposite diodes resulting in a current flow change. Figure 11 shows the first six positions of the rotation sequence in which the magnetic field of the coils should be in order to rotate the magnetic 12 equal steps.

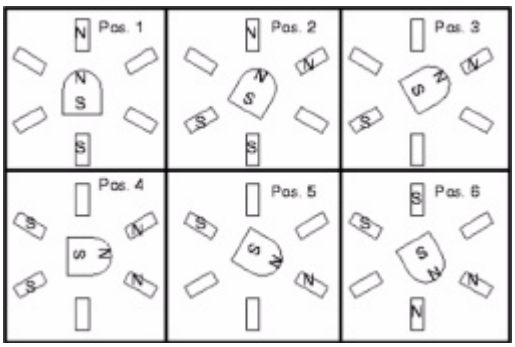

Figure 11 Sequence of the First Six Magnetic Positions of a Bipolar Stepper Motor

5.5 Radio Frequency Power Supply

There are many ways to power the pressure sensor and the stepper motor in the SmartFlow such as using an internal battery or a device that converts micro-movements of the eye into power. However, these methods are not feasible due to the different constraints of the device. Using a battery would provide enough power for normal operations but the life-time of a battery is much shorter than the expected life-time of the implant. Since the device is permanently implanted in the eye, installing a new battery would require invasive surgery. Furthermore, a battery that could last a fairly long time would be too big to fit on the SmartFlow. Having a device that can convert micro-movements of the eye into power would ensure a life-time worth of energy. However, if such a device is fitted on the implant, it would be too small to generate enough power in order to operate the pressure sensor and the stepper motor.

An alternative power supply would be a circuit that can transfer energy through EM-waves. This technology can be implemented on the micro-scale, and has the ability to generate an adequate amount of power. However, it requires an external mechanism to supply the RF energy so when the external device is not present, the SmartFlow will not have any power. Since glaucoma patients typically see an optometrist regularly, the external device can be used at that time to provide power for the device to adjust the pressure regulation accordingly.

Before building a viable RF power circuit, a theoretical understanding of the technology is needed. Inductive coupling between two coils transports energy by passing a current through one coil. This current generates a magnetic field around the coil, which can be gathered by the other coil when the two coils are brought in close proximity. The second coil gathers as much of the magnetic energy in the field as possible to induce a new current in the second coil. This current can be used to power the electronics in the device without requiring physical contact between the power supply and device. In addition to transmitting energy through EM-wave, it is also possible to transmit information super positioned on top of the carrier wave. However, this type of communication is the most difficult to understand because the carrier signal contains both the energy and the data. Although the glaucoma device needs to be able to receive

both energy and information through the RF signal, this section will only focus on how energy is sent to the receiver coil, and how energy is converted for the electronics.

In general, the transmitted energy is not entirely harvested by the receiver coil. Only a portion of the energy E_L is stored in the inductance L and the parasitic capacitance C_{PAR} of the receiver while some of the energy E_R is dissipated through the resistance R_S of the receiver coil. The efficiency of the receiver coil is given by

$$Q = \frac{E_L}{E_R} = \frac{1}{R_s}\sqrt{\frac{L}{C_{PAR}}}$$

which can be altered by changing the geometry of the receiver coil.

Besides increasing the efficiency of the receiver coil, it is also important to maximize the total amount of energy that is inductively coupled. The point at which the coupled energy is maximized is when the transmitter and the receiver are tuned to the same frequency. To set the resonance frequency of the receiver coil, a tuning capacitor C_{TUNE} can be placed in parallel to establish a matching frequency with the transmitter. The equation for the resonance frequency is shown below.

$$\omega_0 = \sqrt{\frac{1}{L\cdot(C_{PAR} + C_{TUNE})}}$$

Since the receiver coil is usually a planar coil on a micro-scale, the exact physics of the device requires more in depth calculation since the coil's radius at each turn is significantly different. In addition, at such a small scale, the parasitic capacitances between the wires become considerably large. Experiments can be done to determine the optimal number of turns in each coil.

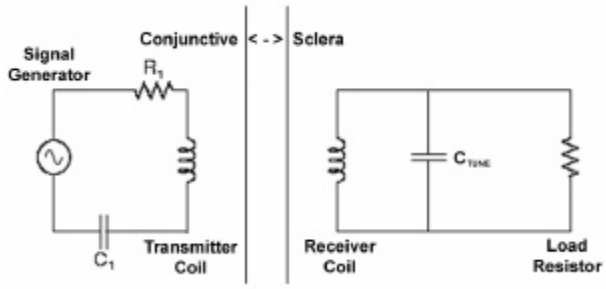

Figure 12 Circuit Schematic for RF Power Supply

Figure 12 shows a very simple circuit schematic for the RF-power supply. The circuit that needs to be placed near the eye has a signal generator that determines the amount of power and the frequency of the energy sent to the implant. The RLC circuit will generate an energy

peak around ω_o converting the signal to a magnetic field. The resulting field is then picked up by the receiver coil. From the equation above, C_{TUNE} is adjusted so that the circuit in the implant would be able to take in energy at ω_0. The converted current will then be used to operate the stepper motor and the pressure sensor, which are all represented by the load resistor.

5.6 Fixation

Fixation of the device is physically provided by the outer rim and the four inner nubs that protrude from the main body of the device. These nubs secure the device and prevent the device from sliding out of the scleral tissue, while the outer rim prevents the device from sliding into the eye. On the inner edge, four nubs were chosen instead of a solid rim to ease insertion of the device into the eye. A solid rim would require a larger force to expand the scleral tissue during insertion, while the four smaller nubs more easily allow for local deflection of the tissue around each nub.

The use of expanded-polytetrafluoroethylene (e-PTFE) on the main body of the device provides further fixation. Advantages of using PTFE are its nearly universal chemical resistance, insolubility in all known solvents below 300 °C, high thermal stability, continuous service temperature range from -270 to 260 °C, low adhesion, low coefficient of friction, outstanding electrical and dielectric properties, and resistance to stress cracking and wear. It is also highly inert, biocompatible, and structurally compatible with scleral tissue due to its lower modulus of elasticity. A 20-micron average pore size e-PTFE material is used to reduce the wound healing response, promote neovascularization, and increase stability. The microporous fluorocarbon material will allow host cells to penetrate and proliferate providing anchorage between the scleral tissue and the implant.

5.7 Sterilization

Sterilization of implants is necessary to prevent infection that can lead to serious illness or death. The device is defined sterile after the removal of all living organisms. The SmartFlow glaucoma implant will be sterilized using autoclaving, which involves exposure to saturated steam under pressure. Steam sterilization kills microorganisms by destroying metabolic and structural components essential to their replication. Sterilization is achieved by exposing the implant to saturated steam at 121 °C using a pressure-rated sterilization chamber. The materials used in our device are safe for autoclaving at high temperatures under pressure. The advantages of autoclaving are efficacy, speed, process simplicity, and lack of toxic residues.

6.0 MATERIAL DESCRIPTION

The choice of biomaterials is critical in determining the biocompatibility and the success of the device. The aim is to delay the wound healing response and fibrosis, while retaining structural performance. Fibrous capsule formation typically occurs between three to six post-oper-

ative weeks. During this time, protein and cell deposition on the material surface can clog the drainage holes or create a fibrous capsule around the device leading to failure of the glaucoma drainage implant. Micromovement of the smooth device against the scleral surface also contributes to glaucoma implant failure by stimulating low-level activation of the wound healing response, increased collagen scar formation, and increased fibrous capsule thickness. The biocompatibility of the material therefore determines the success rate of the glaucoma device.

SmartFlow is made of polycrystalline silicon wafers (shown in green and red in Figure 13) to incorporate a MEMS stepper motor and pressure sensor. Silicon is a semiconductor material with a high melting temperature, function over a wide temperature range, and the ability to oxidize. Oxidation serves as a good chemical barrier to protect silicon from biological fluids.

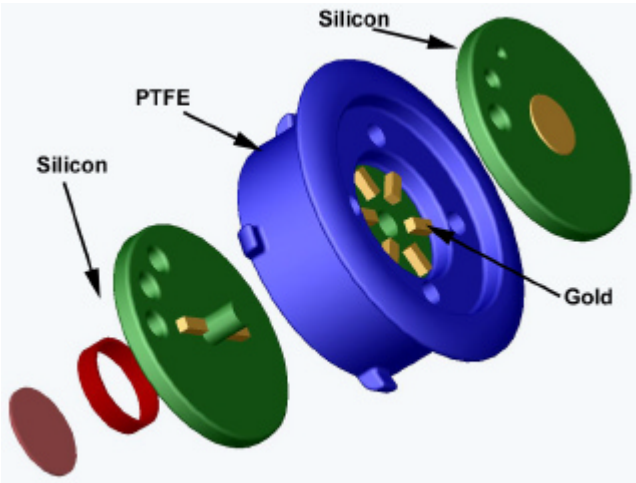

Figure 13 Detail of Materials in Exploded Device View

While silicon is ideal for device construction, it represents one of the more non-biocompatible materials. To prevent biological contact with the silicon, the main body of the device is constructed using a biocompatible polymer. Suggested polymers include silicone due to its adherence to the silicon and e-PTFE due to its fixations benefits. Both polymers are biocompatible and provide a closer modulus match than the silicon core.

The discs of the implant contain holes which allow the flow of aqueous humor from the anterior chamber of the eye to the conjunctiva. Current methods to prevent clogging of similar devices use drugs such as 5-fluorouracil (5-FU) and mitomycin. However, reduction in fibrosis is only temporary and the toxicity of these drugs can also lead to other adverse effects. SmartFlow will use a biomimetic coating over the silicon discs, which is advantageous to the synthetic materials currently used. A biomimetic coating will make the device biocompatible and prevent clogging of the holes. The coating is formed by synthesizing phosphorylcholine (PC) molecules and attaching the molecules onto the surface. Phosphorylcholine is a phospho-

lipid found in the cellular membrane of red blood cells. Its hydrophobic tail and hydrophilic head is a key factor for resistance of the cell membrane to protein adsorption. Attachment of PC molecules onto the surface will allow the synthetic material to mimic a biological one leading to long term biocompatibility of the device.

7.0 IMPLEMENTATION

7.1 Surgical Procedure

Before the surgery takes place, a general or local anesthetic will be administered to the patient. Under anesthesia, the eye will be “prepped” for surgery through the use of sterilizing solutions. In addition, a small hook-like instrument will be used to hold the eyelids apart during the procedure. These measures are taken to ensure that the eye is entirely comfortable during the operation and to minimize any motion of the eye.

The surgeon will begin the procedure by grasping the conjunctiva and making a 3mm incision through the thin tissue so that the pocket found between the sclera and the conjunctiva can be revealed. Initial entry from this pocket into the anterior chamber takes place using a Beaver super-sharp blade. A Kelly trabecular “hole” punch is then used to remove a small part of the sclera thus allowing aqueous fluid to exit from the anterior chamber through this newly-formed passageway. Once the opening in the scleral bed has been created, a syringe-like device called an introducer will be used to implant the device. The device will be temporarily attached to the end of the introducer's needle such that once the device is implanted in the desired location, the surgeon can push down upon the top of the introducer, which will release the device from the end of it's needle-like structure. Once fixation is complete, the incision made in the conjunctiva is stitched together.

7.2 Post-Operative Maintenance

Following surgery, the patient will undergo a series of routine post-operative check-ups to monitor both the functionality of the device and the health of the eye. When a patient arrives at the office for a check-up, the patient's head will be aligned and fixed in a special stand containing the electronics that will be needed to power and communicate with the implanted device. Once the RF power source is turned on, there will be wireless power transfer to the device, and the device controller will route power to the pressure sensor. This controller will monitor and record the current pressure and the status of the disk alignment in the device. It will then transmit the pressure and configuration data to an external computer.

External logic in the computer, the experience of the physician, and any other accompanying tests, such as tonometry or goniometry may be used to determine if any changes to the device configuration are needed. The following actions will be taken, depending on the state of the device:

1. If the IOP is too low, then the disk can be rotated to a smaller-sized hole. In extreme cases where the smallest-sized hole still results in unacceptable low IOP levels, medication will be used to the adjust the IOP or emergency surgery can be performed.
2. If the IOP is too high, then the disk can be rotated to a larger hole to allow for increase fluid flow. In cases where the largest hole is currently being used and high IOP is still occurring, the current passageway is assumed to be clogged and the disk is rotated to a new unclogged hole. If the largest hole still results in unacceptable IOP levels, then medication will be required to adjust the IOP.
3. If the IOP levels are within the acceptable range, then no changes in the device configuration will take place. One complete rotation of the device can be used to prevent fibrous growth from entangling the disk.

Once the necessary changes have been made, the device system will be shutdown, and the RF power source will be removed from the device. The check-up visit will conclude with the scheduling of a follow-up visit in the near term if changes were made during the current visit or in the long term if no changes were made during the current visit.

8.0 CONCLUSION

The current treatments for open-angle glaucoma leave a number of patients without acceptable solutions. As discussed above, there is a clear deficiency in medical device solutions for open-angle glaucoma. Current devices are not lifetime solutions and do not represent a viable solution for many patients. By utilizing MEMS technology and state-of-the-art materials, this product provides a glaucoma solution and addresses problems seen in other glaucoma medical devices on the market today. The benefits of the SmartFlow device include flow regulation to prevent a low or high IOP and multiple holes to address issues of clogging. An additional benefit is the incorporation of a pressure sensor into the device, which allows for closed loop monitoring and diagnosing of the patient's status. By incorporating RF power and the stepper motor, low power can be safely supplied to the device to allow adjustment of the IOP.

Future work needs to be done finalizing the choice of design materials and testing the device in clinical trials. Rigorous testing is required to ensure that any unproven technologies present no safety concerns to the patient and operated as predicted. In addition, verification is required for the SmartFlow solutions for clogging of the device. This verification is required both for the fibrous growth reducing drugs and mechanical clog removal.

In a fairly developed marketplace, the SmartFlow Glaucoma stent provides an innovative solution and is a viable product for a clearly defined market. By utilizing MEMS technology and state-of-the-art materials, this product provides a glaucoma solution and addresses problems seen in other glaucoma medical devices on the market today.

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Source for Figure 3: http://members.aol.com/MonT714/tutorial/the_eye/index.html

Source for Figure 4: http://www.ahaf.org/glaucoma/about/AqueousHumor.htm