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NASOGASTRIC TUBE DESIGN TO REDUCE CLOGGING AND SIMPLIFY FLUSHING

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ABSTRACT

Herein we present a new helical slit tip for the nasogastric (NG) tube to reduce clogging, as well as an accompanying modular in-line flusher to simplify flow restoration to a clogged tube. Nasogastric tubes are one of the most ubiquitous medical devices used in urgent and intensive care situations. Most commonly used to evacuate the stomach during cases of small obstructive bowel syndrome and surgical operations, the NG tube is prone to clogging. A detailed analysis of nasogastric tube obstruction in an *ex vivo* model was performed. The proposed NG tube tip is an improvement over the current state of the art. Clogging by suction to the mucosa is prevented by the continuous and helical nature of the suction area. Clogging by food particles is avoided by introducing slits rather than holes, and thus inhibiting close packing and clogging of the particulate on the suction tip. The modular in-line flusher is a device which combines into one push the many steps a caregiver usually takes to unclog the tube via flushing, with no disconnections required. Use of the redesigned NG tube and modular in-line flusher will reduce the need to troubleshoot and replace NG tubes, saving care providers' time, reducing hospital costs, and reducing patient discomfort.

INTRODUCTION

The redesign of the NG tube tip and development of a modular in-line flusher were motivated by the frequent clogging of the nasogastric tube. The use of NG tubes in medical care is pervasive; nasogastric intubation is one of the most common procedures performed in emergency rooms and operating theatres around the country. Unfortunately, NG tube placement has also been reported to be the most painful procedure performed in emergency departments [1]. Since the late 18th century, negative pressure through a tube has been used to evacuate stomach contents from patients [2]. While improvements have been made to materials to allow for flexible yet patent tubes, improvements to the design of the NG tube have primarily been incremental. The major exception is the introduction of the bilumen tube, which added a second lumen, called a sump line. This second lumen allows air into the stomach to reduce the chances of adhering tightly to the stomach mucosa. The Salem Sump™ NG tube by Covidien (see Figure 1) is the most popular NG tube in the U.S. market today [3].

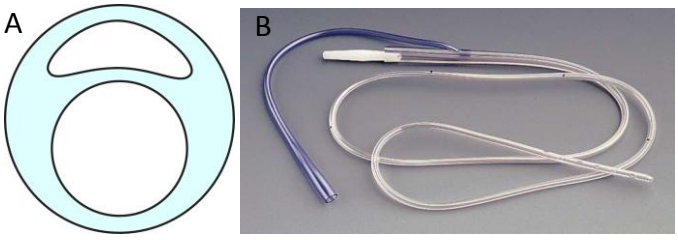

FIGURE 1: CURRENT NG TUBE. A) SALEM SUMP™ NG TUBE BY COVIDIEN [3]. B) CROSS SECTION OF NG TUBE SHOWING TWO LUMENS. UPPER LUMEN IS SUMP LINE AND LOWER, CIRCULAR, LUMEN IS SUCTION LINE.

Clinical Indications for Nasogastric Intubation

There are several medical indications that call for the placement of an NG tube. The most common conditions are small bowel obstruction (SBO) and upper gastrointestinal bleeding. See Figure 2 for a diagram of NG tube placement.

SBO occurs when intestinal content flow is obstructed by

a distal defect. The main mechanical cause of SBO is the presence of adhesions, which are abnormal bands of scar tissue that can form after surgery [4]. Approximately 30% of patients that undergo lower abdominal surgery will develop SBO due to adhesions [4]. Tumors of the abdominal cavity can also lead to SBO, accounting for about 20% of cases [5]. Hernias, abnormal protrusions of intestinal tissue through abdominal or pelvic structures, are the cause of about 10% of SBOs [5]. Finally, several medical conditions that cause the narrowing of the intestinal lumen can lead to SBO [6]. For SBO, NG tubes are used to decompress the stomach and relieve distention, providing comfort for the patient. Upper gastrointestinal bleeds also call for the use of NG tubes. In this case, NG tubes are used as a cleaning device, helpful in removing solid contents as well as clots and blood from the stomach. This is useful in assisting the healthcare team to locate and confirm the source of bleeding [7, 8]. Finally, NG tubes are currently used routinely to drain the stomach following uncomplicated gastrointestinal surgeries. Drainage with NG tubes provides bowel rest for the patient while their gastrointestinal system recovers from the surgery, and prevents respiratory complications associated with anesthesia.

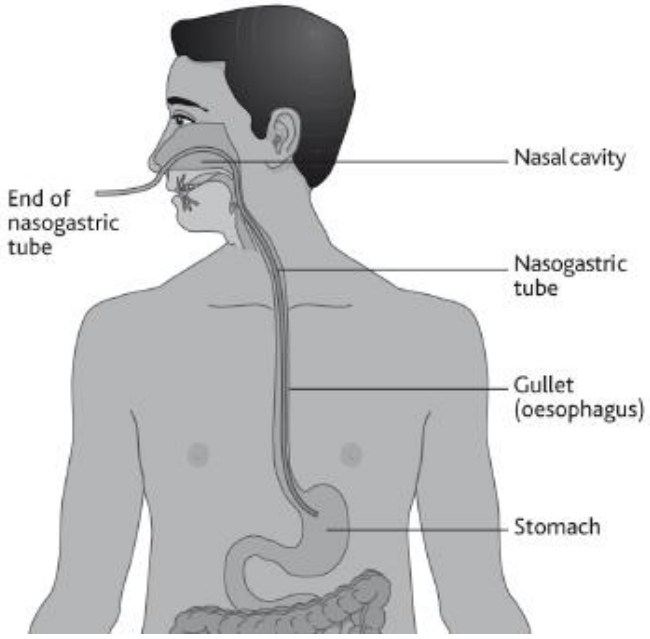

FIGURE 2: PLACEMENT OF NG TUBE.

Complications associated with NG tube placement have been well documented. Blind placement of NG tubes has led, in a small number of patients, to serious and sometimes life-threatening complications including pneumothorax, atelectasis, enteric perforation, and intracranial placement [9-11]. There has been much debate over the past decade over the appropriate use of NG tubes [12].

Design Motivation

This design sought to address problems that frequently arise during clinically appropriate use of the NG tube. Two main risks cause malfunction of the NG tube after placement: 1) adhesion to the stomach mucosa and 2) obstruction of the lumen by solid particles. These complications are ever-present, so much so that manufacturers of NG tubes recommend prophylactic flushing of the tubes on a regular basis. Furthermore, any healthcare practitioner or patient can attest to the unpleasant experience of having to replace a malfunctioning NG tube.

Current remedies to these complications involve intervention by a caregiver who first uses a syringe to force 10-15 cc of air down the sump line to help break the seal of the tube against the stomach wall. If the obstruction persists, the vacuum line is disconnected and 10-20 cc of water or saline is injected directly down the suction port. If this second attempt fails to restore function, the NG tube is removed and a new tube is placed [13]. These complications motivated the proposed NG tube redesign and modular in-line flusher.

DESIGN REQUIREMENTS

Based on knowledge of the current NG tube frustrations listed above and discussions with medical practitioners who use NG tubes on a regular basis – including nurses, emergency room doctors, and surgeons - a list of design requirements was compiled. We sought to design and create a means of decompressing the stomach that met the following solution requirements:

1. Safe for the patient – as with all medical products, the product must do no harm to the patient. The failure mode must be “do nothing” and not harmful.
2. Reduce clogging – with a more reliable means of decompressing the stomach there is less need for replacing and troubleshooting NG tubes. Reduction of tube replacement improves patient safety.
3. Easy to unclog - less of the care-providers’ time is taken in unclogging blocked tubes.
4. Uses same placement technique as current NG tube – does not require extensive training or drastic change from current practice. The procedure for placing the NG tube must be acceptable to clinical practice.
5. Inexpensive – the current solution is very inexpensive (approximately $1) and so for a product of similar application, a large increase in price is to be avoided.
6. Comfortable for the patient – the placement of NG tubes is already a painful experience. The present solution must not increase the discomfort to the patient during placement or decompression and should minimize the need for the tube to be replaced.

In order to best achieve these design requirements, a two-pronged solution was developed: a redesigned nasogastric tube tip and a modular in-line flusher.

PRIOR ART

A patent review was performed in order to gain an understanding of prior art and possible alternative solutions from other applications.

U.S. and International Patents

There exist a large number of specific nasogastric-related U.S. patents. None adequately address the issue of clogging or easy flushing. Placement of tubes is addressed in [14] suggesting an alternative anatomically conforming nasogastric tube. Patent [15] addresses the possible injury to the patient caused by the sharp edges of the punch holes at the end of the tube, as well as the suction of mucosa by molding a number of regularly spaced longitudinal ridges on the outer surface, with suction holes at the bottom of the troughs. Another patent [16] addresses occlusion by the stomach lining, with inflatable cushions or balloons used as spacers. The use of small holes in the bore of large holes as a means of suctioning without clogging is presented in [17].

Beyond the re-design of nasogastric tubes specifically, [18] addresses the aspiration of fluids from body cavities in general, and details a tube end feature comprised of a tube with aspirating ports facing inwardly convolved around a support shaft, in order to prevent aspiration ports from contacting the body cavity. The removal of occlusions in drain devices is addressed in many different embodiments in [19].

Automatic flushing of systems is addressed in [20], with sensor-operated power assembly, relief valve and actuator.

An automatic valve system with multiple ports to address leakage of intestinal fluids associated with changing from suction to feeding to flushing with a nasogastric tube is described in an international patent [21].

Commercial Products

The most commonly available nasogastric tube is the Salem Sump™ PVC tube with two lumens, one for suction drainage and one for sump vent, available from Covidien [3]. These disposable sterile tubes are available in a variety of lengths and diameters. The tube is also available with an anti-reflux valve for the external port of the sump lumen which reduces the risk of exposure to gastric contents. These tubes are used for suction, decompression, irrigation and delivery of medication, but not enteral feeding. It is recommended that the tube dwell in the patient for 1-3 days, with proper care and maintenance, including saline flushing on a regular basis.

FAILURE MODES OF NASOGASTRIC TUBES

The functioning NG tube can be modeled as a network of resistors as shown in Figure 3. Critical parameters are the fluid resistances in the suction lumen, vent lumen, and tube tip. The resistance of the tube tip refers to the small resistance experienced by the fluid flow as it is drawn just into one of the holes at the distal end of the NG tube during operation. Preliminary bench level experiments have indicated that changing the resistance of the tube tip is the most promising method for solving clogging problems in NG tubes.

During use, the resistances of the vent lumen, suction lumen, and tube tip are functions of geometry and fluid properties. The geometry of the vent and suction lumens has already been optimized to minimize resistance. This leaves modification of the tube tip as a strategy for clog prevention.

The primary causes of tube clogging are food particles blocking the flow of fluid through the tube, and suction of stomach mucosa against the inlet holes to the tube. Thus, any tube tip design should prevent both clogging mechanisms.

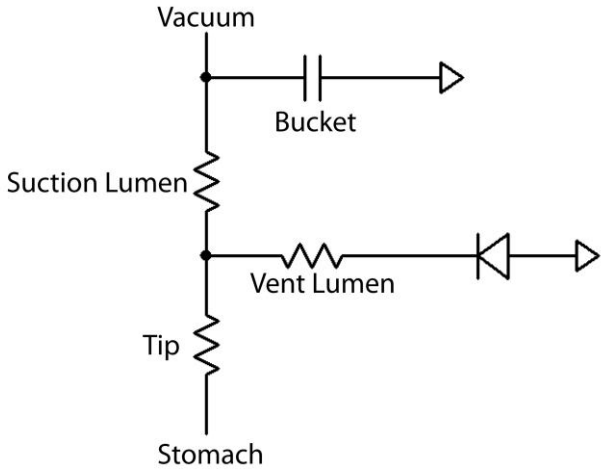

FIGURE 3: ELECTRICAL EQUIVALENT CIRCUIT DIAGRAM OF AN NG TUBE.

Clogging by Mucosal Suction

As the tip of the NG tube resides in the stomach, it is conceivable that one of the inlet holes to the tube would rest against the mucosal wall of the stomach. If a brief stoppage of flow occurs through that inlet hole, then the pressure drop across that hole will exert a force to hold the stomach mucosa against the tube. This force results in a suction of the mucosa into the hole and a continued stoppage of flow.

A current commercial Salem Sump™ NG tube has 11 inlet holes. As holes clog as described above, the tip resistance increases and the pressure drop across the unoccluded inlet holes increases. This leads to additional propensity for open holes to attract stomach mucosa and become occluded. All flow through the tube will stop if all of the inlet holes become simultaneously clogged in this manner or if mucosa is sucked through the most proximal hole into the lumen of the tube.

Mucosal suction can be prevented if the inlet hole geometry is such that the stomach is unable to form a complete seal over an inlet hole. In this situation, the stomach mucosa may slow the flow into the NG tube, but without a complete seal the tube will not suffer complete flow stoppage. Alternatively, problems from mucosal suction can be prevented by a tube tip geometry containing many holes, such that if one becomes clogged the resistance of the tube tip does not significantly change and tube performance is not decreased.

Clogging by Food Particles

The stomach contents contain particulate matter that can cause NG tubes to clog. If a solid particle is carried into an inlet hole by the flow of stomach contents it may become lodged in the hole. If the particle has appropriate size and shape, the inlet hole can become completely plugged by its presence, leading to a stoppage of flow through that inlet hole. If all of the inlet holes of an NG tube become clogged, a full stoppage failure can occur.

Clogging by food particles can be prevented by appropriately sizing inlet holes to minimize the chances of food particles from tightly packing in the hole. In this case, particles can become lodged in holes without causing complete blockages. The problem can be postponed by including many holes in the tip such that the tip is robust to some clogging of this type. A tube with holes has support material around the perimeter of the tube as well as along the tube's axial dimension. In contrast, a tube with slits does not have support along the axial dimension. This generally results in a greater fraction of orifice area on the surface of the tube. The greater the area of the holes, the longer it takes for food particles to significantly impede the flow of the tube.

TIP PROTOTYPE

To achieve the goal of preventing both types of clogging expected in an NG tube, several designs were proposed. Each was rapid prototyped for *ex vivo* testing. (See Appendix A for all tip designs)

The proposed tip design – that which was simplest and most reliable - employed helical slits as inlet holes as seen in Figure 4. The tube tip has four slits, arranged radially and symmetrically around the tube. The helical slits are 1.5 mm wide and have a 40 mm pitch.

The helical slit tip design prevents clogging with food particles by taking advantage of principles of granular packing theory, a topic that is studied to understand the flow of granular products through hoppers [22]. By making one dimension of the slit much greater than the largest dimension of the particulate, a single particle cannot clog the opening. In addition, due to the fractal nature of stomach particulate, close packing of multiple particles in a groove is unlikely to occur, and fluid is likely to leak through. Testing confirmed this idea as designs that contained inlet holes at the bottom of helical grooves instead of slits failed to prevent clogging by food particles, as the food particles filled the inlet holes. Thus long slits are an important characteristic of a successful tip.

The exact dimensions and materials used to create this prototype were chosen to be similar to a 16 French Salem Sump™ NG tube. Early prototypes were stereolithography models made from DSM Somos 11120 (Vaupell, Hudson, NH), and the final prototypes were PolyJet Connex models made from 95 Shore A Tango Gray (Five Star Plastics, Eau Claire, WI).

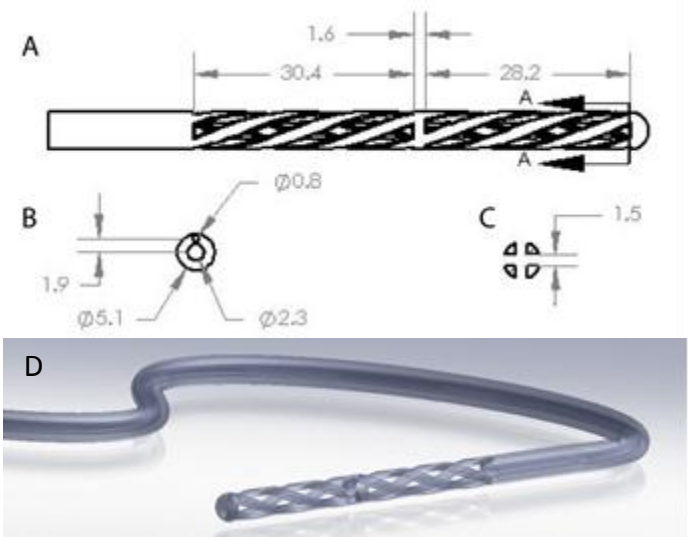

FIGURE 4: HELICAL SLIT TIP DESIGN. A) DIMENSIONED DRAWING OF TUBE TIP FEATURING HELIX WITH A 40 MM PITCH. ALL CORNERS ARE BROKEN TO 0.2 MM. B) CROSS SECTION OF PROXIMAL END OF TIP FEATURING SUCTION AND SUMP LUMENS. C) CROSS SECTION OF HELICAL PORTION NEAR DISTAL END OF TIP (A-A) SHOWS THE INCREASED SURFACE AREA THE SLIT DESIGN ALLOWS. ALL UNITS ARE MM. D) RENDERING OF PROPOSED TIP REDESIGN.

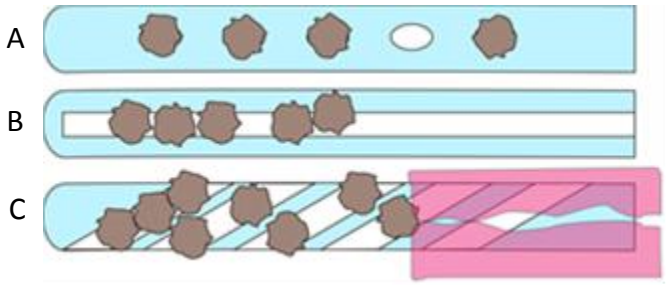

FIGURE 5: HELICAL SLIT CLOG PREVENTION SCHEMATIC. A) PARTICULATE CLOGGING OF CURRENT NG TUBE B) SLITS CANNOT BE CLOGGED BECAUSE OF GRANULAR PACKING C) MUCOSAL SUCTION IS PREVENTED BY THE HELICAL NATURE OF THE SLITS.

TESTING AND VALIDATION OF NEW TIP

Prevention of Mucosal Suction

Rapid-prototyped NG tube geometry testing was conducted in a three-stage fashion using porcine stomachs. Stage one involved the assessment of tip geometry blockage while suctioning water. In this test, the goal was to force failure and then investigate the mechanism of the failure. A vacuum regulator was set-up to provide 80-100 mm Hg vacuum pressure from the wall. Each geometry was installed at the distal end of a PVC tube and inserted into a plastic bag with a water-filled stomach in a beaker (Figure 6A). A standard Teflon tube with 1/32" inner and 1/16" outer diameters was used as the standard sump for all experiments. The bag was sealed from the exterior to limit the sump

experienced by the system. The test was allowed to run for 30 seconds without intervention, followed by a period of 30 seconds of manual massage. The test was stopped when the water was fully drained or the tip experienced blockage. When blockage occurred, the system was dismantled and the cause of the blockage was documented. The testing revealed that larger tip geometries, such as baskets or cages, not only clogged within the testing period, but also had the potential to cause mucosal injury by tightly sealing to the mucosal wall. Furthermore, larger tip geometries have the inconvenient feature of requiring deployment after insertion. The helical grooved tip, on the other hand, was the only geometry that did not clog or damage the stomach mucosa. These results motivated the inclusion of this feature in the final design.

Prevention of Particulate Clogging

After stage one of testing, variations of the helical tip geometry were developed and a second round of testing was conducted. The helical grooved tip was retested, along with a rapid-prototyped straight grooved tip. The test set-up was similar, but instead of using water, the stomach lumen was pre-filled with a mixture resembling native stomach contents. The mixture was composed of 2 cups of water, 12 tablespoons of flour, 3 tablespoons of corn starch, and 2 crumbled crackers (Figure 6B). This mixture was designed to provide a fluid with increased viscosity and with particulate matter that would closely resemble the type of fluid that would be difficult for an NG tube to aspirate in a real patient. The test was performed as in stage one, until drainage or blockage occurred. In these tests, only the helical slit design resisted particulate clogging while the designs featuring discrete holes all quickly became occluded by crackers. Therefore helical slits are included in the final tip design.

Comparing to Industry Standard

Again the helical slit tip geometry was taken and variations on it were developed including the generation of a tip with straight slits. This round of prototypes was made from PolyJet 95 Shore A Tango Gray, a material exhibiting similar mechanical properties to the current industry standard. Due to the softer material, additional supporting struts were incorporated into both the helical and straight slit geometries.

An identical test setup was used as described for stage two of testing. To quantify the performance of each design, we allowed the experiment to run for 6 minutes and recorded each occurrence of an obstruction. At each minute, each set-up was manually manipulated so as to increase the chances of clogging. The aim was to promote clogging for each design by creating the harshest possible conditions, an environment not likely to be experienced by a winning design *in vivo*, but if successful would ensure proper function of the design in most clinical settings. Thus every 60 seconds, the stomach system was moved, rotated, or gently compressed to simulate the tube being placed in different locations within the stomach. Figure 6C shows the results from our study, indicating that the helical slit tip was the most successful, clogging only once per six minutes of testing; while the straight slit tip and the standard NG tube clogged 3 and 4 times, respectively. Thus our design, shown in Figure 7, outperformed the Salem Sump™ NG tube by a factor of 4.

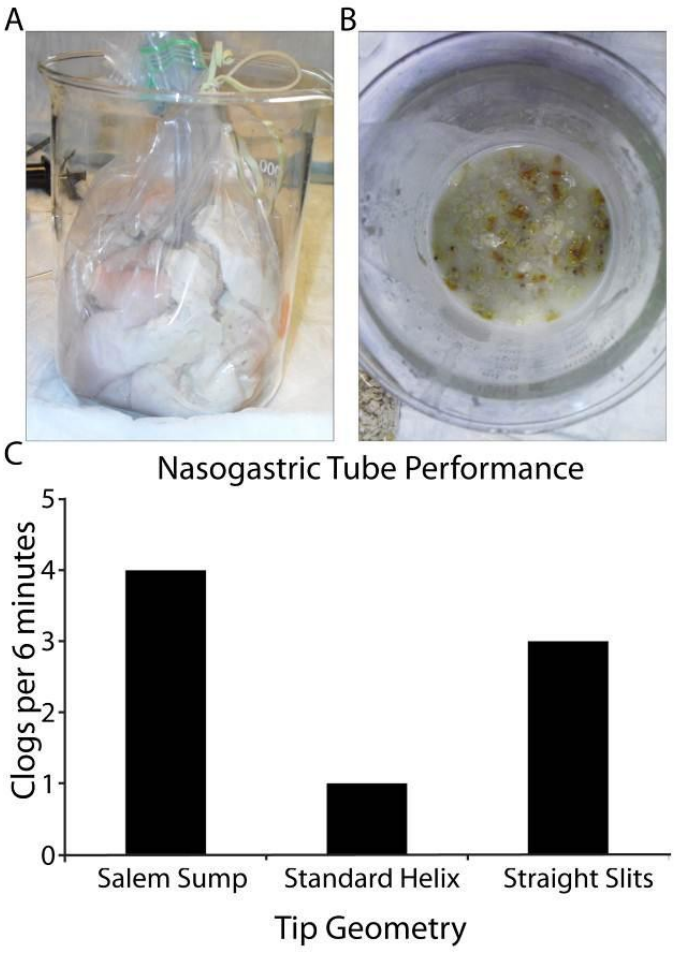

FIGURE 6: NG TUBE TESTING. A) PORCINE STOMACH SEALED INSIDE PLASTIC BAG WITH NG TUBE AND SUMP LINE PLACED. B) SIMULATED STOMACH CONTENTS USED FOR STAGES 2 AND 3 OF TESTING. C) PERFORMANCE OF NG TUBE TIP GEOMETRIES IN STAGE 3 OF TESTING.

MODULAR IN-LINE FLUSHER

We expect that the redesign of the tip will significantly impede the occurrence of blockage. Nonetheless, we recognized the potential of the NG tube to eventually become occluded. To this end we sought to simplify the process of remedying a blocked NG tube, and have developed a modular in-line flusher.

Motivation for Flusher

In current practice, the nurse (or patient) first identifies diminished flow to the collecting bucket. The nurse then disconnects the anti-reflux valve from the sump filter and sends a bolus of air down the sump line. Presumably, if the blockage is caused by the tip of the NG tube adhering to the

stomach mucosa, this burst of air temporarily relieves the negative pressure difference at the tip and allows the tube to disengage from the stomach wall. If the flow does not improve, the nurse then disconnects the NG tube from the vacuum line and flushes the central lumen with 10-20cc of water from a prepackaged and preloaded syringe. This stops the vacuum, and flushes the blockage back into the stomach. If this does not work, the current NG tube is removed and a new NG tube must be placed.

Flusher Prototype Requirements

In addition to the design requirements detailed previously, we sought to design a simple, modular, flushing solution that can quickly be employed by caregivers to restore function to clogged tubes. Functionally, the device must disconnect the vacuum line in order to relieve negative pressure at the tip as well as to ensure that the flush goes to the NG tube and not the bucket. The device should then inject water through the NG tube at a rate greater than 2ml/s, then reconnect the NG tube to the vacuum. Once the flush is complete the device should reload and reset for subsequent flushes.

Hand Flusher Prototype

After considering a variety of automatic sensing and flushing systems as described in Appendix B, the modular in-line flusher was determined to be the most appropriate design for flushing NG tubes. In the final implementation of the flushing system we designed a flusher that is powered by the operator. The device accomplishes all of the valving and fluid injection in a single motion. Furthermore, since the system is closed, the risk of exposure to stomach contents is eliminated. Figure 7 shows the final prototype and CAD drawings of the device. Kinematics of the forces acting on the flusher are discussed in detail in Appendix C.

Figure 7B shows the flusher in the rest position. The line from the vacuum enters on the left and passes through the normally open lower pinch valve to the NG tube on the right with virtually no added resistance. A line between the syringe and reservoir also passes through the lower valve and in the normal position the spring loaded syringe draws water from a reservoir also connected through the left. A line from the syringe passes through the upper normally closed pinch valve preventing the vacuum from sucking fluid from the syringe and reservoir. Figure 7C shows the flusher in the firing configuration; the lower valve is closed, isolating the vacuum and the reservoir from the syringe and NG tube. The upper valve opens and the syringe pushes water through the NG tube. Once complete, a spring force returns the valve to its normal configuration and reloads the syringe.

The hand flusher is limited in that it does not detect a blockage or perform preventative maintenance of the NG tube. However, it allows for a flush to be delivered by the nurse or the patient in a matter of seconds. The device is modular and could be added to patient lines when clogging complications are expected.

The design of the manifold went through several generations of modifications, simulations and builds before the present configuration was reached. Some of the considered embodiments involved different valving mechanisms in the manifold (e.g. slide valve, stopcock, roller valves) and use of various flexures in place of the hinge that connects the follower to the manifold (Appendix D).

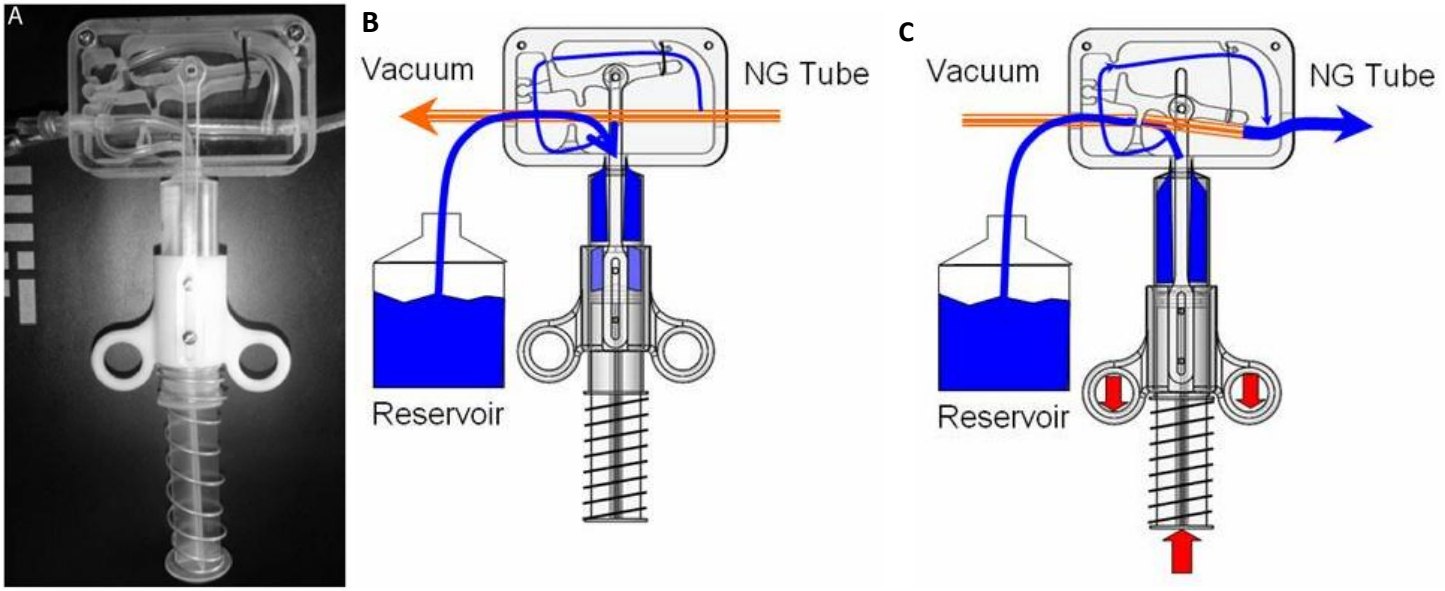

FIGURE 7: MODULAR IN-LINE FLUSHER. A) IMAGE OF RAPID PROTOTYPE. B) SCHEMATIC OF THE HAND FLUSHER IN NORMAL NON-FIRING POSITION. C) SCHEMATIC OF THE HAND MODEL IN THE FIRING CONFIGURATION.

FUTURE WORK

The current rapid prototyped tip design has given us great insight into the design of a robust and reliable NG tube. Future work will focus on designing a manufacturing process for the more complicated tip geometry that is amenable to mass production. We believe that this may be accomplished through a two part system in which the tip and tube are joined after manufacturing, or a one part solution in which the tip is formed in the tube itself using a radially moldable design or rotating mandrel in the injection molding process.

Similarly, the modular in-line flusher design will be iterated and designed into a form that allows for ease of manufacturing. In a commercial product the manifold would likely be an injected molded clamshell with an integral syringe built-in. A custom tubing insert would simply be laid into the clamshell and closed. The follower would likely be connected to the manifold with a bi-stable flexure rather than a hinge. The sleeve could be made more ergonomic by increasing the ring hole size, or by replacing the rings with a handle like grip. The dimensions of the device could be improved so that the device lays more inline than orthogonal to the line. And finally, the length of tubing between the flusher and the NG tube could be increased without increasing the required flush volume by having the flush line enter the main vacuum line near the NG tube. Parts that are currently adjustable for prototype purposes will be replaced with fixed parts. To encourage only correct implementation, Poka-Yoke features will be included at the ports for correct configuration of input tubing.

CONCLUSIONS

In summary, the NG tube tip and modular in-line flusher presented here represent a significant improvement over conventional NG tubes. Clogging by suction to the mucosa is prevented by the continuous and helical nature of the suction area. Clogging by food particles is avoided by introducing slits rather than holes, and thus inhibiting close packing and clogging of the particulate on the suction tip. The modular in-line flusher is a simple device which combines into one push the many steps a caregiver usually takes to unclog the tube via flushing, without having to disconnect the system.

The new helical slit tip has the potential to be applied in a number of other body cavity aspiration situations where clogging is a current problem. The flushing device can also be used in a variety of applications beyond flushing of NG tubes. In any application where regularly flushing a line is important, the flusher can provide an inexpensive and expedient solution. For example, the flusher could be used together with a feeding tube to regularly rinse the tube. Similarly, in minimally invasive surgeries where both a rinse and a vacuum line are needed, a flusher device that utilizes the same pathway for flushing and vacuuming can help minimize the number of independent lines needed at the surgical site. Importantly, we believe the current design will greatly reduce the need to replace a malfunctioning NG tube, reducing the risk to the patient and preventing unnecessary discomfort. The new helical slit tip and modular in-line flusher are readily adoptable in the hospital setting. They represent a very small change to current practice for nasogastric intubation which will turn into significant savings in time and money for the hospital.

ACKNOWLEDGMENTS

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APPENDIX A: TIP PROTOTYPES

Stage 1 of tip design – prevent mucosal suction

Tips were rapid prototyped with stereolithography in DSM Somos 11120. Parts built with normal resolution, light sanding and glass bead finish.

FIGURE A1: STAGE ONE OF TIP DESIGN. A) CAGE B) BASKET WITH LARGE HOLES C) BASKET WITH SMALL HOLES D) HELICAL GROOVE TIP.

Stage 2 of tip design – prevent particulate clogging

Tips were rapid prototyped with stereolithography in DSM Somos 11120. Parts built with normal resolution, light sanding and glass bead finish.

FIGURE A2: STAGE TWO OF TIP DESIGN. A) STRAIGHT GROOVE WITH HOLES B) HELICAL GROOVE WITH HOLES.

Stage 3 of tip design – comparing to industry standard

Tips were rapid prototyped with PolyJet and standard finishing. Material was Tango Gray, 95 Shore A durometer.

FIGURE A3: STAGE THREE OF TIP DESIGN. A) STRAIGHT SLITS B) STANDARD HELIX C) MOLDABLE HELIX.

APPENDIX B: POTENTIAL DESIGNS

Electrical Blockage Detector and Flusher

A flow or pressure sensor detects a blockage and activates a valve manifold that interrupts the flow to the bucket and connects an actuated syringe loaded with water to the NG tube. Upon flushing, the syringe reloads from a reservoir through a one-way valve. The main limitation with this design is complexity and cost.

Pneumatic Blockage Detector and Flusher

We designed an inexpensive pneumatic automatic flushing system that detects a drop in line pressure when the flow through the NG tube slows and automatically delivers a bolus of water. The flush is powered by the vacuum pressure in the line. The device would be used with an intermittent vacuum, and when the vacuum is turned off the device would reload and reset. The limitations of this design are both the magnitude and repeatability of the blockage signal; the change in pressures due to flow occlusion is small and would require a sensitive trigger to be effective. This limitation is a consequence of the resistance of the fluid being much larger than the resistance between the regulator and the device. A countermeasure could be a sensitive trigger that reacts to the small change in pressure. However, because the vacuum pressure to the NG tube system is not tightly set or regulated, there is no absolute firing pressure that can be readily defined. The device would also only work with a periodic vacuum system.

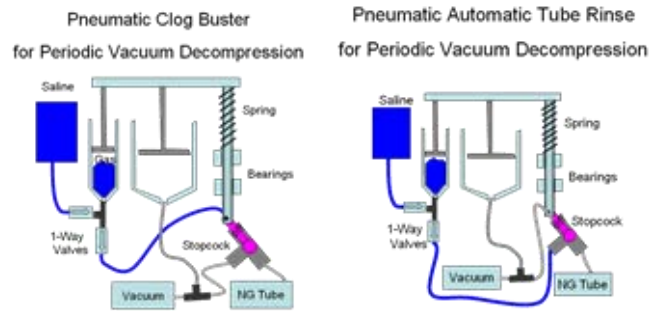

FIGURE B8: (LEFT) SCHEMATIC OF A PNEUMATIC BLOCKAGE DETECTOR AND FLUSHER AND (RIGHT) PNEUMATIC PERIODIC FLUSHER. NOTE THAT THE DESIGNS ARE SIMILAR, ONLY DIFFERING IN THEIR CONNECTIONS.

Pneumatic Periodic Flusher

By modifying the design of the automatic detector and flusher, we designed a system that uses a periodic vacuum signal to automatically introduce a flush in the beginning of each vacuum pulse. When we built a bench level prototype of the device we found that the supplied vacuum pressure (about 30-100mm Hg) was too low to provide an energetic flush. A countermeasure would be to use a large hydraulic ratio. However, a large hydraulic ratio increases both the size and cost of the device. This device would also be limited to use with a periodic vacuum signal.

FIGURE B9: BENCH LEVEL PROTOTYPE OF THE AUTOMATIC RINSE DEVICE. THE NG TUBE CONNECTS TO THE BOTTOM, THE RESERVOIR TO THE RIGHT AND THE VACUUM BEFORE THE BUCKET CONNECTS TO THE SYRINGE IN THE CENTER. THE RIGHT SYRINGE IS USED AS AN AIR SPRING THAT IS USE TO RESTORE THE LEFT FLUSH SYRINGE WHICH DRAWS FLUID FROM A RESERVOIR TO THE RIGHT. WHEN THE VACUUM IS TURNED ON THE SYRINGE BLOCKS THE VACUUM LINE THROUGH THE PINCH VALVE ON THE TOP OF THE LEFT SYRINGE.

Detailed Explanation of Pneumatic Detector and Flusher

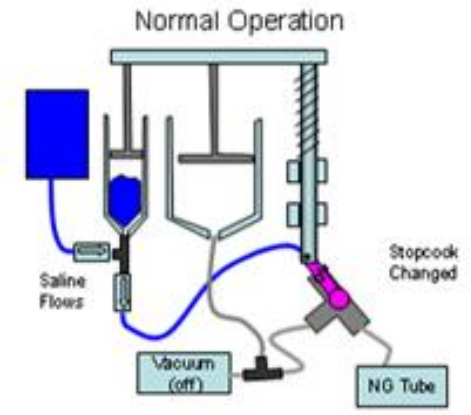

FIGURE B10: THE DETECTOR AND FLUSHER IN NORMAL OPERATION.

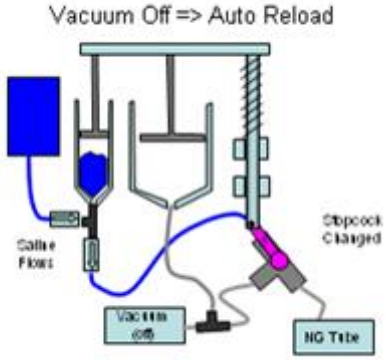

FIGURE B12: WHEN THE PERIODIC VACUUM TURNS OFF THE VACUUM AUTOMATICALLY RELOADS.

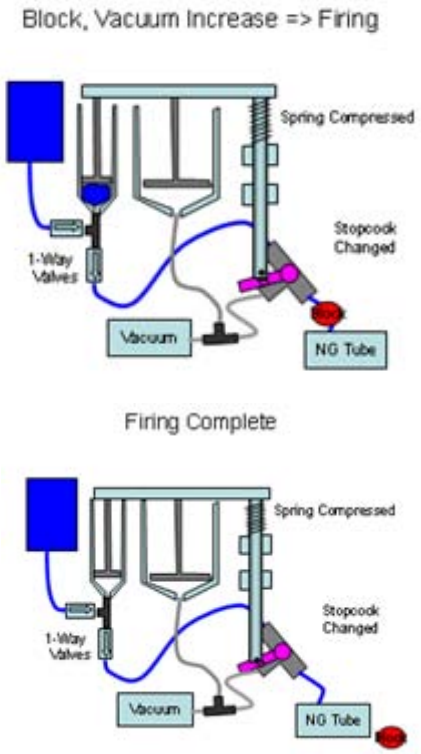

FIGURE B11: THE DETECTOR FIRING WHEN IT DETECTS A CLOG.

APPENDIX C: HAND FLUSHER DESIGN KINEMATICS AND FORCES

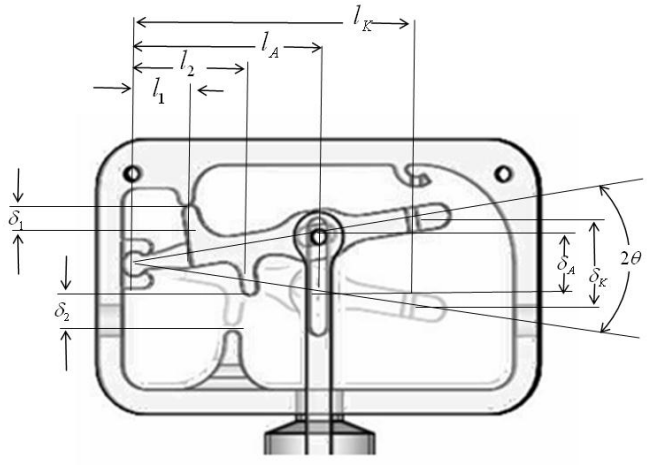

FIGURE C13: DEFINING THE LENGTH USE IN THE FORCE AND KINEMATIC ANALYSIS.

For small angles (we set the total angle of actuation to be 15^o):

$$\frac{l_1}{l_2} = \frac{d_1}{d_2} = \frac{2.5\text{mm}}{5\text{mm}}$$

Choosing l_2 to be 25mm sets l_1 at 12.5mm. If we set the actuation point to the center of the manifold (l_A = 40mm), then the movement of the actuation point is:

$$d_A = 2l_A q = 2(40\text{mm})\left(\frac{7.5^o}{180^o}p\right) = 10.5\text{mm}$$

We place a rubber band to provide the force to pinch the upper valve 60mm from the hinge (i.e l_k=60mm), so that there is still room for the moving part to pass a tube.

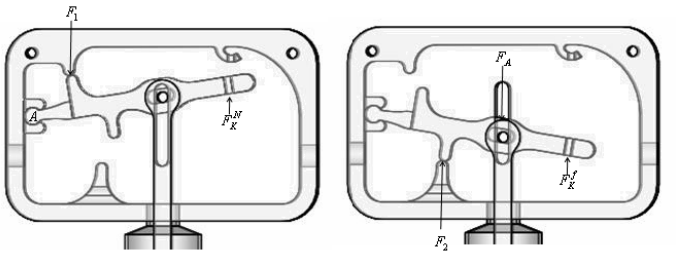

FIGURE C14: DEFINING THE FORCES THAT THE MANIFOLD EXPERIENCES IN THE NORMAL (LEFT) AND FIRING (RIGHT) POSITIONS. THE FORCE F_1 COMES FROM A SINGLE SMALL TUBE (2.5MM OD) THAT HAS A PINCHING FORCE OF 15N. THE FORCE F_2 IS FROM THE COMBINED PINCHING OF TWO OF 2.5MM OD TUBES EACH REQUIRING 10N. THE FORCE F_K COMES FROM THE RUBBER BAND THAT KEEPS THE SMALLER TUBE NORMALLY PINCHED. NOTE THAT THE SPRING FORCE IS GREATER IN THE FIRING POSITION.

In the normal position - Figure C.2 (left) - sum of the moments about the hinge (point A) yields:

$$F_K^N = F_1\left(\frac{l_1}{l_K}\right) = 15\text{N}\,\frac{12.5\text{mm}}{60\text{mm}} = 3.125\text{N}$$

The spring force in the firing position is greater than the spring force in the normal position:

$$F_K^f = F_K^N + K_R d_K > F_K^N$$

Where K_R is the spring constant of the rubber band that holds the system closed.

From the sum of the moments about the same point in the firing configuration, and assuming the spring force in the firing position is about 4N, the manifold actuation force is:

$$F_A = \frac{F_2 l_2 + F_K^f l_K}{l_A} = \frac{20\text{N}(25\text{mm}) + 4\text{N}(60\text{mm})}{25\text{mm}} = 18.5\text{N}$$

Due to the automatic refill spring that sits on the syringe, only a portion of the squeeze force is transmitted to the manifold. If we define the refill spring force F_S, the actuation force for the whole system is:

$$F = F_A + F_S > 18.5\text{N}$$

Since this actuation force is created by the resistance of the fluid, we consider the appropriate combined resistance of the syringe, flush line and NG tube to get a 2 ml/s flush. The driving pressure of the fluid in the syringe is given by:

$$\Delta P = P_{syringe} - P_a = \frac{F_A}{A_{syringe}} = \frac{18.5\text{N}}{325\text{mm}^2} = 570\text{mbar}$$

From the relationship between pressure, flow and resistance in a linear model we can estimate the appropriate resistance:

$$R = \frac{\Delta P}{Q} = \frac{570\text{mbar}}{2\text{ml/s}} = 285\,\frac{\text{mbar}}{\text{ml/s}}$$

Note that since the resistance of the lines depends linearly on the viscosity of fluid passed through the lines, and as the viscosity of air is far greater than that of water, a system designed for water will not work for air; the resistance will be too low and very high flow rate is required to generate an actuation force that will close the manifold.

APPENDIX D: HAND FLUSHER MANIFOLD FLEXURE DESIGN

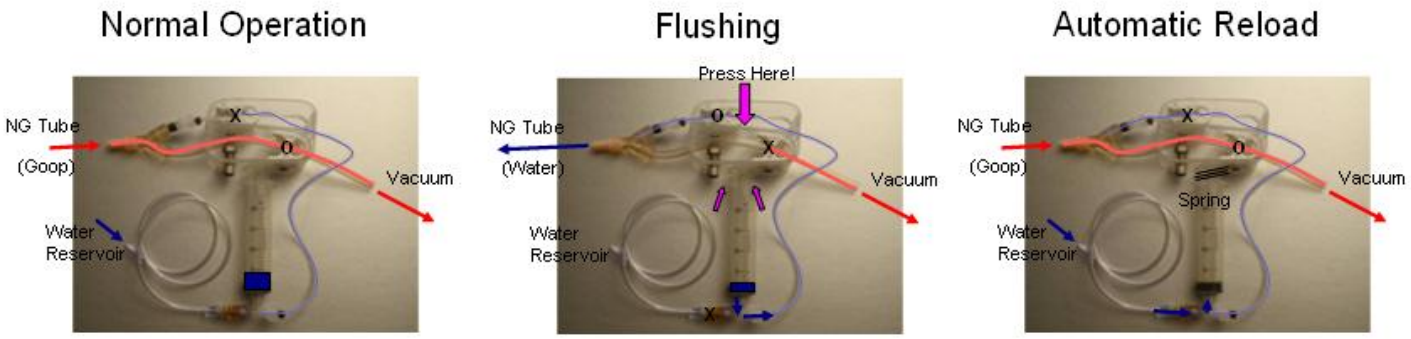

FIGURE D1: A SCHEMATIC SHOWING THE OPERATION OF THE ORIGINAL BENCH LEVEL (OPERATIONAL) HAND FLUSHER PROTOTYPE. THE DEVICE WAS ASSEMBLED WITH A STRIP OF ACRYLIC, A HEAT GUN, AND SOME WELD-ON 4 GLUE.

Prior to arriving at the final embodiment (which uses a hinge) flexures were considered to connect the follower to the manifold:

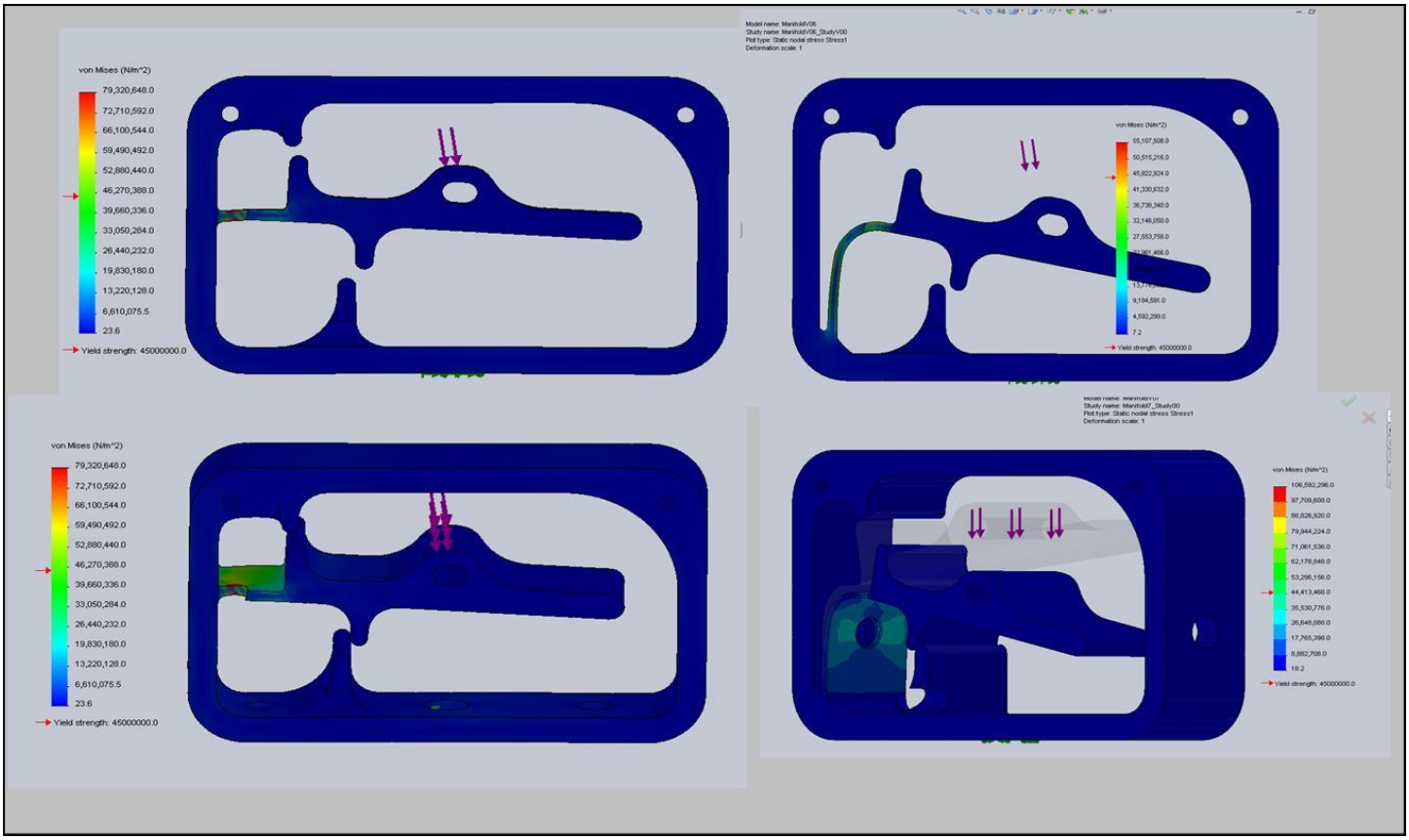

FIGURE D2: FINITE ELEMENT ANALYSIS OF TWO OF THE FLEXURES CONSIDERED FOR THE MANIFOLD.

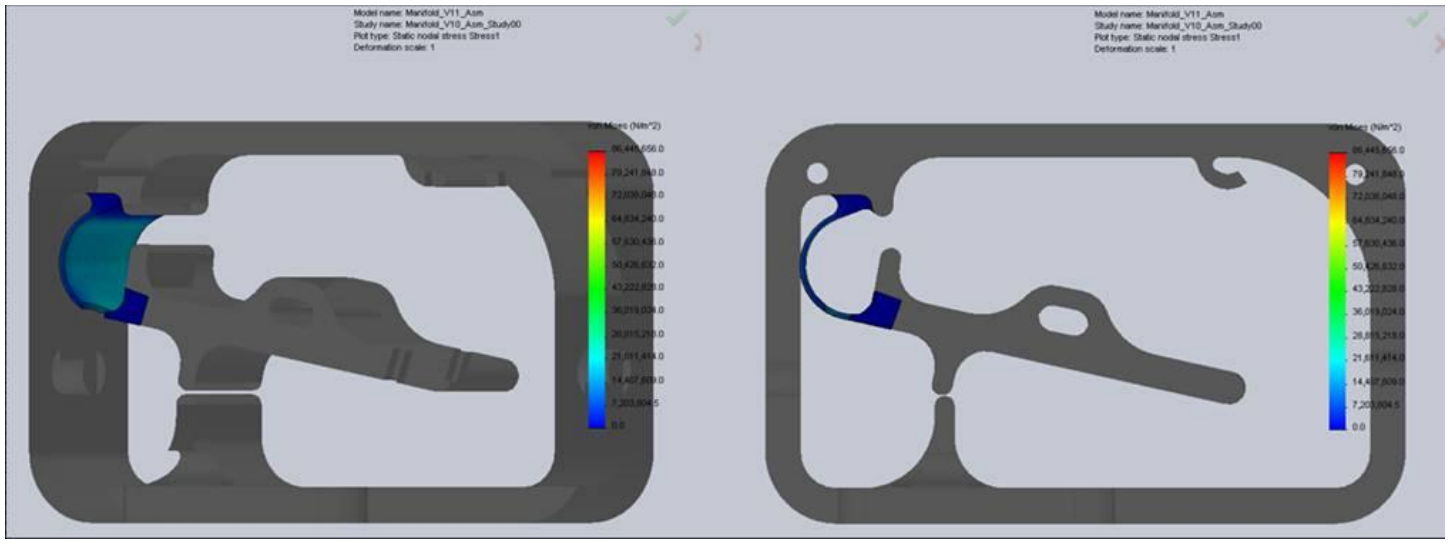

FIGURE D3: FEA OF A FLEXURE THAT WAS ULTIMATELY BUILT OUT OF ACRYLIC AND TESTED. THE ACRYLIC FLEXURE PROVED BRITTLE, AND HAD POOR RESISTANCE TO TORSION, WHICH PREVENTED THE PINCH VALVES FROM WORKING CORRECTLY WHEN THE UPPER TUBE WAS NOT EXACTLY CENTERED.

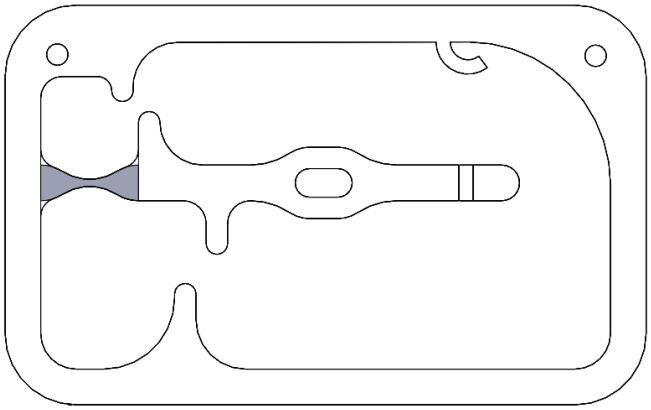

FIGURE D4: THE FINAL FLEXURE THAT WAS TRIED FOR THE MANIFOLD. THE MATERIAL TRIED WAS POLYCARBONATE COVERED ACRYLIC WHICH STILL PROVED TO BE TOO BRITTLE. THIS CONFIGURATION MAY HAVE WORKED IF THE ENTIRE MATERIAL WERE POLYCARBONATE.

Enter numbers in **BOLD**, results are in **RED**		
RR	**7**	Radius of hourglass
sigmax	**70**	maximium allowable stress
w	**.7*25.4**	Width of web
E	**3.20E+03**	Modulus of elasticity [acrylic N/mm^2]
t	**1.000000**	Minimum thickness of web
L	**10**	Distance from web to tip
Max stress driven design		
Maximum theta (rad, deg)	**0.133875**	**7.67**
Motion at end of tip	**1.338748**	

FIGURE D5: THE SPREADSHEET FROM FUNDAMENTALS OF DESIGN, USED TO DESIGN THE FLEXURE IN FIGURE D14 OUT OF ACRYLIC.