

# A Robotic Implant for Enterogenesis

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## INTRODUCTION

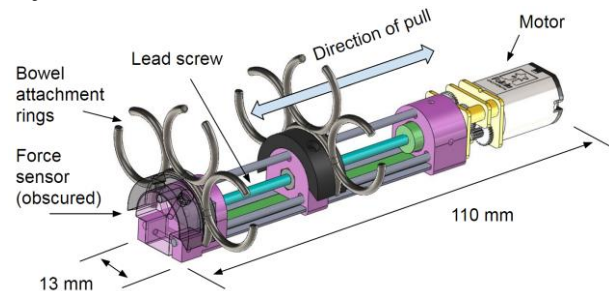
Short bowel syndrome (SBS) is a condition caused by surgical resection or disease of the small intestine [1]. SBS affects 24.4 out of 100 000 live births, and the mortality rate of the condition is high [2]. Of those that SBS affects, it is a highly lethal condition, with mortality reported to exceed 30% [3]. A minimum of 15-25 cm of bowel is required for survival [1]. Treatment options begin with paraenteral nutrition (PN) which is administered through a central venous catheter [2]. This method is effective at maintaining patient health but has many complications such as infection and PN-associated liver disease. Treatments attempt to lengthen the bowel to increase intestinal absorption, an important step toward self-sufficiency. Some surgical approaches to increase the effective length of bowel include: *Longitudinal lengthening* by dividing and connecting a piece of bowel longitudinally, creating two narrow sections of bowel and *serial transverse enteroplasty* which involves stapling the bowel on alternating sides, creating a zig-zag channel through the intestine. Both of these surgical options are limited in that they can only be applied to dilated bowel segments, which may be dysfunctional to begin with, as well as restricting the amount and location of extra length that can be created. Damage to the mesenteric blood supply and enteric leakage can also occur as a result of complex anastomosis [3].

Mechanotransduction has been successfully applied to bowel in in vivo animal experiments. Existing devices are placed inside the bowel and restrict bowel patency [3]. We have shown that axial force can be applied to tubular organs nonobstructively [4]. Although mechanotransduction is known to stimulate bowel growth, surgeons and scientists disagree on how much force should be applied to the organ. This paper presents a small robotic implant which has been developed for enterogenesis while maintaining bowel patency and motility. No bowel resection is required to implant the device. The device is both a research tool to collect strain and tensile force data as well as a prototype for clinical bowel growth. The technique of robotic, in vivo tissue engineering has the potential to substantially improve outcomes in the treatment of SBS.

## MATERIALS AND METHODS

The robotic implant (Figure 1) consists of three pairs of bowel attachment rings arranged radially about the robot. This arrangement applies traction to three segments of bowel simultaneously and so triples the length of induced bowel lengthening. An opening is made in each ring to allow the bowel to pass through the

ring during attachment as well as to avoid interrupting the blood supply at the point of attachment. The rings are removable, and are attached to the device body using snapping fasteners after being sutured to the bowel. Patient-specific rings of different sizes are manufactured, and interchangeable to find the right fit for the bowel during surgery. The rings translate along a lead screw to stretch an initial 20 mm length to 70 mm, a total displacement of 50 mm. A linear potentiometer (Spectra Symbol) monitors ring position. A force sensor (Honeywell Inc.) measures the tensile force being applied to the bowel. The implant is encased in medical grade silicone (Bentec Medical). The robot controller is implemented on a Sparkfun Orangutan microcontroller, which communicates wirelessly to a laptop by Bluetooth virtual serial port (BlueSmirf, Sparkfun). The control box fits in the pocket of a vest worn by the patient and is battery powered, allowing the patient freedom of movement. A graphical user interface (MATLAB 2014b) is used to control the position of the robot and set a force limit. As the robot stretches the bowel, if the force limit is reached, it will stop movement. Real-time position and force data are plotted on a laptop screen, allowing a physician to monitor the traction forces being applied to the bowel during adjustment.



**Fig. 1** - Implant schematic. The medical-grade silicone casing and control cable are not shown.

To determine the actuator torque needed for in vivo trials, an experiment with ex vivo sheep bowel was performed. Three segments of small intestine were sutured to the rings using six sutures per lumen on each ring as shown in Figure 2. The distance between the rings was initially 23 mm. This distance was incremented in steps of 0.5 mm until tissue or suture failure. Force data was recorded during the experiment.

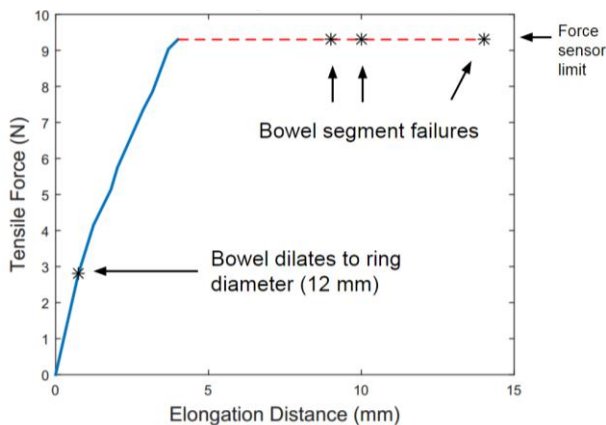
To determine the appropriate pig size for in vivo trials and the best position of the implant in the intestinal cavity, positioning was evaluated inside the carcasses of two pigs (Yorkshire Swine, 5 kg, 45 kg). The rings were attached to the small intestine (Figure 4). The size of the implant and implant placement were assessed for feasibility in an in vivo model.



**Fig. 2** – Ex vivo test on sheep bowel. Three segments of small intestine are sutured to the rings with six sutures each.

## RESULTS

The starting diameter of the sheep bowel was 9 mm, and the ring diameter was 12 mm. Figure 3 presents the force versus elongation distance of bowel. As the bowel was stretched, the diameter of the lumen dilated gradually to match the diameter of the rings (both diameters equal at 2.8 N). Bowel segments failed at 9, 10 and 14 mm of elongation (suture tear out). Force sensor saturation is 9.3 N force. All failures occurred at higher than 9.3 N force, therefore failure forces were not recorded. No flexing of the implant was observed during the tensile test.



**Fig. 3** – Tensile test results of ex vivo sheep small intestine.

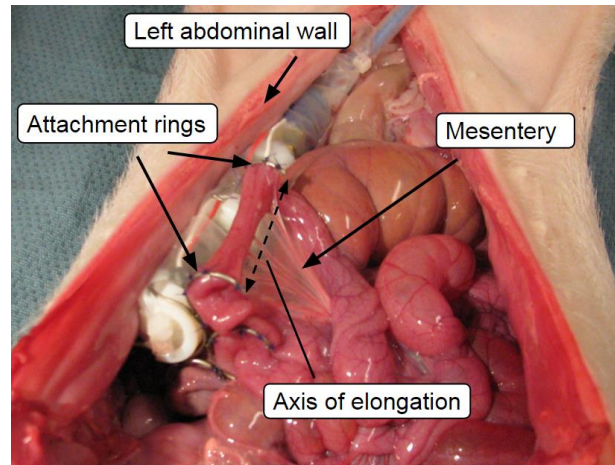
The implant fit easily in both carcasses. Three segments of bowel were selected such that they could be positioned parallel to each other in the rings, without causing a kink due to bending of the bowel. Implant position along the left abdominal wall of the 5 kg pig carcass is shown in Figure 4, and no impingement of bowel was noticed. The three-ring arrangement fit easily to the three segments of small intestine. The opening in the rings allowed the bowel to be attached to the device while preserving the mesenteric blood supply.

## DISCUSSION

Ex vivo testing indicates that the displacement, force range and size of the current prototype are appropriate to proceed to in vivo testing. Three segments of bowel can be stretched a maximum of 5 cm which will create a potential for 15 cm of growth. This amount of growth could be sufficient to wean a child from PN and so return to normal life.

As the bowel was stretched, it was noticed that the bowel diameter dilated to match the larger diameter of the rings. This suggests the use of oversized rings to avoid constriction of the lumen, maintaining bowel

patency throughout the procedure. Bowel absorption can be monitored during treatment and an informed decision will be made when enough extra bowel has grown before the implant is removed.



**Fig. 4** – Implant inside a fresh dead 5 kg pig. Transverse view showing three implant rings sutured to small intestine, mesentery preserved.

While the device fits inside the abdominal cavity of the 5 kg pig (equivalent to a 6 month old child), the top of the device approaches the bottom of the kidney. To reduce risk, initial in vivo testing will be performed using 15 kg pigs, which possess a longer abdominal cavity. Pig size will be reduced in future experiments.

An animal protocol has been developed and approved by IACUC (Institutional Animal Care and Use Committee) for in vivo, ten day survival studies in a swine model. The device will be surgically implanted and each day following the surgery, the implant will be commanded to stretch the bowel, without applying excessive force. We will investigate the use of the D-xylose and Schilling tests to assess improved intestinal absorption [1]. On day 10, the stretched bowel will be harvested from the animal, its length measured, and compared to the initial measured bowel. Histological analysis will be used to assess muscle cell proliferation and inflammatory response. Results will be compared to a control pig.

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