Automated Uretero-intestinal Anastomosis with Absorbable Staples

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Abstract

When the muscle layer of the bladder is invaded by cancer, the entire bladder must be removed using radical cystectomy. This procedure is currently performed using sutures, and can vary considerably between different patients and surgeons. There is a need to streamline this procedure, making it more uniform. Using SolidWorks and rapid prototyping, a stapler was created to fire two concentric rings of staples, replacing the sutures currently used in this procedure. Due to the high salt concentrations in urine, it was necessary to design absorbable staples to be used in conjunction with this stapler. Polymer composites were generated by heating poly-lactic acid (PLA) and poly-caprolactone (PCL) in different ratios and cross-linking them with varying amounts of dicumyl peroxide (DCP). A 90:10 ratio of PLA to PCL with 10 parts per hundred (phr) of DCP exhibited the best staple material properties. Tensile testing showed that the 90:10 PLA:PCL with 10 phr DCP mixture had an elastic modulus of between 49MPa and 377MPa, compared to sutured constructs that had elastic moduli of 0.008MPa to 0.013MPa. These results indicate that the polymer constructs would be strong enough to withstand tensile stresses in the body, but as they are currently fabricated, too brittle to be bent and formed into staples.

Introduction

Bladder cancer is a widespread illness in the United States, with over 70,000 new cases diagnosed and over 14,000 deaths in 2010 alone[1].In cases where cancer has invaded a portion of a patient's bladder wall, a radical cystectomy must be performed to remove the affected tissue[2]. For future urine storage, the preferred solution is to replace the original bladder with a neobladder constructed from a portion of the large intestine, which is attached to the two ureters. With this method, the patient is able to store and excrete urine. This makes the neobladder preferable to a urostomy bag, which requires frequent draining and replacement. Currently, a manual suturing technique is utilized to attach the neobladder to the ureters, but this method is time-consuming and given the small dimensions of the ureters, can be difficult for the surgeon. Additionally, the success of this surgery is dependent on the skill of the surgeon, leading to heterogeneous results among recovering patients. The goal of this research was to design a circular stapler that could effectively attach the ureters to the neobladder tissue in a system that is easy to use for the surgeon, safe for the patient, and effective in creating a water-tight seal between the neobladder and ureter tissue. In addition, staples are necessary to be used with the stapler design which do not damage or irritate the tissue and can be absorbed by the body within 1-2 months of implantation. Ureters vary from 7.0 to 10.0mm in diameter depending on the patient, and the stapler must be able to accommodate for these size differences while still creating a water-tight seal. During this procedure, the stapler and staples must also cause minimal damage to the surrounding tissue of the ureter and bladder.

Materials and Methods

Stapler

In order to join the ureter and neobladder tissue together, a stapler with appropriate dimensions had to be created which could both fix tissues in place and fire staples. The design created focuses on securing tissues in the head (upper) portion and firing staples using the firing mechanism (lower) portion of the stapler.

The firing mechanism consists of five main parts: springs (Fig 1-1), washers (Fig 1-2), flange actuator (Fig1-3), pin and handle (Fig1-4), and concentric rods (Fig1-5). All of these are enclosed in plastic casing cannibalized from the Ethicon® stapler used for colorectal surgery. The firing mechanism is used to translate the outer rod (continuous with the firing teeth) up and down the inner rod (continuous with the needle). When the handle (Fig1-4) is depressed, it rotates through the gap in the flange actuator (Fig1-3), also continuous with the outer rod), pushing the outer rod up. To provide tactile feedback during surgery, compressive springs (Fig1-1) are held in place by washers (Fig1-2) and provide resistance as the handle is compressed.

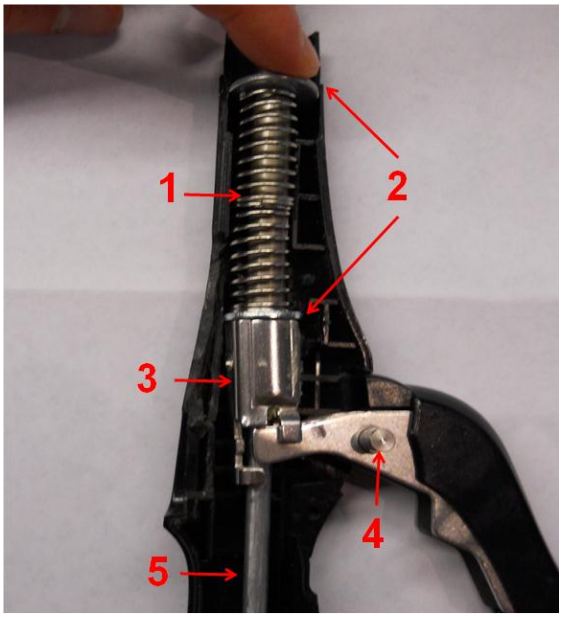

Figure 1 - Firing mechanism

The upper part of the stapler, or the stapler head, is necessary to secure tissues in place and bend staples as the firing mechanism operates. The stapler head also consists of five main parts: two sides of ring clamp (Fig2-1, one pictured), anvil (Fig2-2), needle (Fig2-3), staple cartridge (Fig2-4), and firing teeth (Fig2-5). During surgery, the anvil head (Fig2-2) is inserted into the end of the ureter. The ureter tissue is secured in place around the anvil with the two halves of the ring clamp (Fig2-1). The anvil is secured to the firing mechanism via the needle (continuous with inner rod) using a lock and key fitting. The needle must pierce through the neo-bladder tissue before being connected to the anvil. This positions the ureter tissue just above and in contact with the neobladder tissue. The staple cartridge (Fig 2-4) holds the staples in place just above the firing teeth (Fig 2-5). As the firing mechanism actuates, the firing teeth pass through the staple cartridge, driving the staples through the neo-bladder and ureter tissue into the ring clamp,

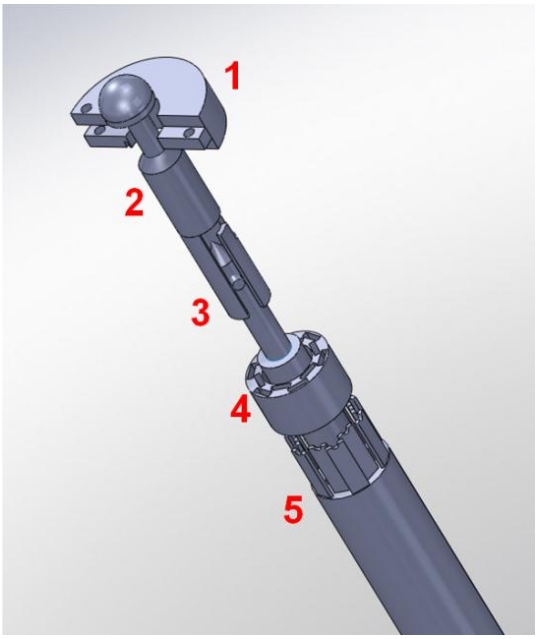

Figure 2 Stapler head (exploded view)

where the staple ends are bent over within the ring clamp divots. This fully secures the two tissues together.

Because it was not possible to fabricate all stapler parts out of metal, it was not possible to fire metal staples. The metal staples obtained from other staplers were also not sized correctly to be fired in this stapler. A comparison control test was done to test the tensile strength of sutures holding two pieces of rubber together using the MTS Insight Electromechanical 5kN tensile testing machine at a crosshead speed of 50.8 mm/min. When the stapler's metal pieces have all been fabricated correctly, two pieces of rubber secured with staples (fired from the stapler) can be tensile tested and compared to this control

Professional prototyping companies and machines were utilized to fabricate parts for the stapler based on SolidWorks designs of each part. Metal parts made of Aluminum 6061 T-651 were fabricated by Proto Labs Inc. located in Maple Plain, MN[3]. Plastic parts made of Accura 60 were fabricated using the ViperSi2 3D rapid-prototyping printer located in the Wisconsin Institute for Discovery on the UW-Madison campus. Part dimensions for all fabricated pieces are listed in Appendix A.

Staples

The Ethicon® stapler is used to anastomose intestinal tissues using metal staples. However, metal staples are not biocompatible in the urinary tract. When exposed to the high salt concentrations, the metal in these staples can cause stones to precipitate out of the urea. In order to circumvent this problem, absorbable staples made from a polymer composite are necessary for the successful operation of a stapler in uretero-intestinal anastomosis.

Both poly-lactic acid (PLA) and poly-caprolactone (PCL) are polymers that are FDA approved for use in the body[4]. PLA is a rigid polymer while PCL is flexible. In order to generate staples, the material used must be sturdy enough to be pushed through two layers of tissue, but flexible enough for the legs to be bent when they reach the ring clamp. According to the Semba et al. paper, a 70:30 mixture of PLA: PCL creates a sturdy but flexible material. The Semba et al. paper also suggests using .1 to .2phr of dicumyl peroxide (DCP) to crosslink the two polymers.

To evaluate the material properties of PLA and PCL composites, the two polymers were mixed in 50:50, 70:30, and 90:10 PLA: PCL ratios by weight. First, the appropriate weight of PLA was measured and placed on a metal mixing pad on a hot plate at 180°C. When the PLA was completely melted, the corresponding amount of PCL was mixed in and stirred with a metal rod and/or razor. The resulting polymer mix was then cross-linked by adding 0, 0.1, 10, or 20 parts per hundred (phr) of DCP. Approximately 30 seconds after the DCP was added, the molten polymer mix was transferred to a polydimethylsiloxane (PDMS) mold to cool for 5 minutes at room temperature into rods approximately 1-2mm in thickness and 1cm long.

These rods were tested qualitatively using manual bending, pulling, and compression to assess their material properties. To quantitatively test these materials, they were tensile tested on the MTS Insight electromechanical tensile test machine at a crosshead speed of 50.8 mm/min.

Results

Stapler

The staple-firing teeth were able to translate 1.2 centimeters up through the staple cartridge to fire staples into two tissue pieces. The metal staples used for testing were too small for our staple cartridge, but qualitative demonstration of translation was shown using the current prototype, materials and staples.

Absorbable Staples

Qualitative polymer testing of PLA/PCL

Polymer formations of PLA/PCL cross-linked with DCP in varying ratios provided different properties summarized in Table 1. 50/50, 70/30 and 90/10 PLA/PCL ratios were fabricated and were qualitatively assessed on their tensile strength, compressive strength and brittleness. A 50/50 ratio with 10phr DCP and 70/30 with 10phr DCP gave brittle staples with fair tensile and compressive strength. With no DCP, the staples were extremely brittle. The 90/10 ratio with 10phr DCP exhibited less brittleness with fair compressive strength and good tensile strength. These qualitative assessments were taken immediately after staple formation and after 24 hours degenerated to mostly brittle properties.

Table 1 Qualitative assessment of material properties

PLA %	PCL %	DCP (PHR)	Brittle?	Tensile	Compressive
50	50	10	Yes	Fair	Fair
70	30	0	VERY	Crumbles to touch	
70	30	0.1	Yes	Bad	Fair
70	30	10	Yes	Fair	Fair
70	30	20	No	Stretchy	Poor
90	10	0	Very	Crumbles to touch	
90	10	0.1	Yes	Fair	Good
90	10	10	No	Good	Fair
90	10	20	NO(bendy)	Poor	Poor

Quantitative tensile testing of PLA/PCL

Young's modulus of elasticity was calculated using the stress-strain data collected from the tensile test machine (Figure 3). For a 50/50 ratio E= 103MPa. For 90/10 ratios, the Young's modulus of elasticity varied from 49MPa (90:10 Day 2, large radius) to 377MPa (90:10 Day 2).

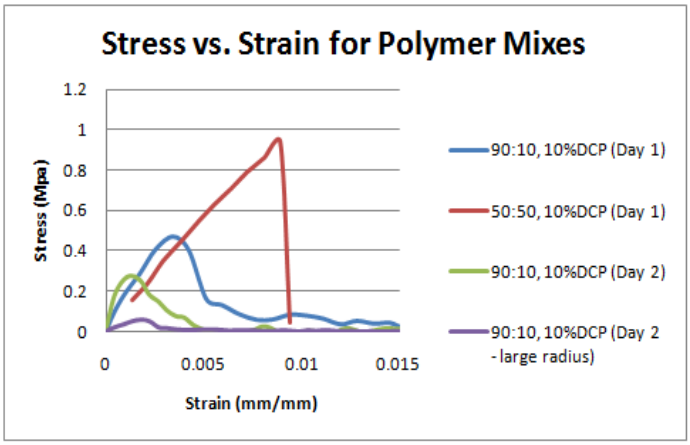

Figure 3 Tensile testing of polymers

Quantitative tensile testing of sutures

Young's modulus of elasticity was calculated using stress-strain data collected from the tensile test machine (Figure 4). For three trials of two gloves sutured together to form a water tight seal the modulus of elasticity ranged from 0.008MPa to 0.013MPa.

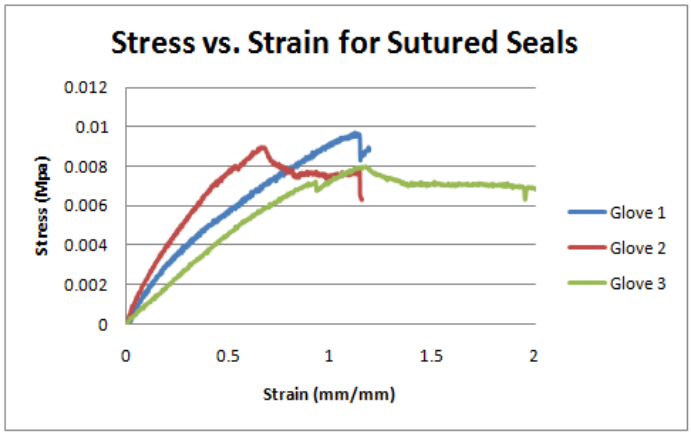

Figure 4 Tensile testing of sutured glove constructs

Discussion

Automated Uretero-intestinal Anastomosis Device

The device described in this manuscript is currently in the prototype phase – as such, it is not yet able to perform a uretero-intestinal anastomosis. The parts of the device are functional, but due to the material choice for the staple-forming teeth, the force required to drive staples into the ring clamp would damage the device. That said, the device and its components are novel in that no other surgical device exists for this application. It opens up the possibility of surgery involving the anastomosis of small-diameter lumenal organs, such as the ureters. The parts of the device are intricate, and no commercial staple will function with the stapler due to size issues. While this was an obstacle to performing proper testing of the prototype, this simultaneously supports its innovation and necessitates the development of small staples for the device.

The testing of the sutures was performed to serve as a comparison of tensile strength with a stapled construct. Had this type of testing been performed using a stapled construct, we would expect the tensile strengths of the two tests to be similar. The results of this test can be extrapolated to the suturing of the ureters to the neobladder during a uretero-intestinal anastomosis; if the stapled construct has an ultimate tensile strength at least as high as the sutured construct with a similar elastic modulus, we assume that a stapled uretero-intestinal seal would hold up well.

During testing we observed that in some cases the rubber ripped before the suture; future testing methods would employ a tougher and more biologically relevant material (such as animal tissue) to more accurately compare sutured and stapled constructs. An additional qualitative leak test, which is modeled after procedures followed during surgery, would also assess the legitimacy of the stapled construct. Since no staples sized for our stapler existed, only the mechanics of the device were assessed.

Absorbable Staples

The creation of staples made from biodegradable polymers for surgical applications is necessary for this procedure due to the stone-forming properties of metal staples. Additionally, while biodegradable sutures exist, staples made from these materials do not. Developing a formulation that exhibits good mechanical properties would be a significant achievement in the surgical field. Therefore, qualitative and quantitative tests were performed on polymer samples for a small staple application. We saw that the mechanical properties were very dependent upon the ratio of PLA to PCL and especially the amount of DCP used. This mirrors the findings from the Semba et al. publication which works with PLA-PCL co-polymers[5]. Surprisingly, we found the ratio of 90/10 PLA/PCL to consistently exhibit the best mechanical properties in terms of balancing tensile strength, plasticity, and compressive strength. This runs counter to the Semba paper[5], which finds a 70/30 ratio of PLA/PCL to have the best plastic properties of all formulations tested. Additionally, the DCP cross-linking agent used in our experiments was 10-fold higher than in the Semba paper[5]. This is not unwarranted, as lower DCP values we tested were not amenable to desired mechanical properties.

The disparity in results may be attributed to a variety of factors. Importantly, the processing method we employed was crude while Semba et al.[5] used polymer extrusion machines to produce the test subjects. We observed extensive brittleness in the polymers after creation, which is likely due to our fabrication methods. Our test polymers were also much smaller (1-2 mm in thickness as compared to 4 mm in the Semba paper[5]), and thus more reflective of their potential application. This small thickness may have benefitted from a higher concentration of PLA, which imparts more strength as opposed to plasticity.

The Young's moduli we found for the polymer constructs indicates that they have high strength, but this number is misleading because they fracture at such low strain values. These staples are still too brittle to be used in surgical applications. A more ideal material for this application would have material properties closer to metal, with a similarly high young's modulus but better ductility.

Conclusion

In short, by qualitatively and quantitatively assessing these polymers for their mechanical properties, we lay the groundwork for further experimentation using better fabrication methods. The properties that the polymers exhibited immediately after molding could be maintained via polymer extrusion and injection molding of the test subjects. While keeping the ratio and the size of the test subjects constant, these new methods may improve the quality of the polymers, making them suitable for the small staple application. The creation of small, bio-absorbable staples could impact every type of surgery which currently uses staples, such as bowel re-sectioning and gastric bypass. As opposed to permanent metal staples, absorbable polymeric staples will improve healing during surgery by promoting complete tissue ingrowth of the wound, leading to a better recovery among patients.

The stapler has been fabricated for the purpose of homogenizing results of uretero-intestinal anastomoses, but could be extrapolated to include other procedures that require small-diameter

seals. We have demonstrated this device to be mechanically functional, only requiring an appropriately-sized staple to be tested and verified as a fully-functional device. These innovations in tandem do not only make an impact on uretero-intestinal anastomosis procedures; given some tweaking of the stapler and the properties of the staples, they could also be used for surgical applications in different physiological systems. Ideally, the prototyping of these two novel devices will simultaneously improve patient healing and ease complexity of surgical procedures, advancing the progress of medical devices.

References

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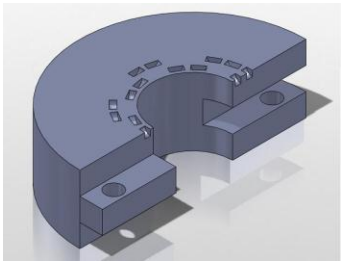
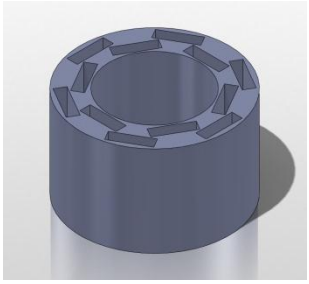
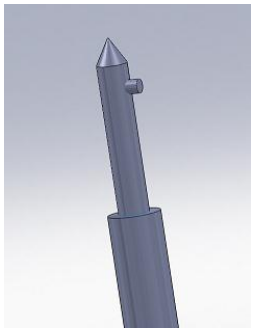
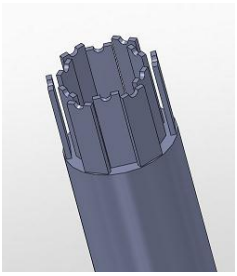
2. Lerner, S.P., Schoenberg, M.P. *Textbook of Bladder Cancer*. Florida: Taylor and Francis, 2006.

3. Proto Labs, Inc. 5540 Pioneer Creek Dr. Maple Plain, MN 55359. http://www.protolabs.com

4. Meeting with Tom Turng, UW-Madison Mechanical Engineering Professor. 2-8-11

5. Semba, T., Kitagawa, K. "The Effect of Crosslinking on the Mechanical Properties of Polylactic Acid/Polycaprolactone Blends". *Wiley InterScience*. 28 October, 2005. Published online in Wiley InterScience (www.interscience.wiley.com).

Appendix A – Part dimensions for fabricated pieces

Part picture	Description and Specifications
	Part Name: Anvil Function: Holds ureter tissue and locks onto needle Specifications: • Head diameter – 7mm • Neck diameter – 3mm • Body diameter – 6mm • Total height – 41mm • Slit height – 15mm • Slid width – 1.8mm • Internal diameter – 2.25mm
	Part Name: Ring clamp (bottom view, 1 of 2) Function: Secures ureter tissue in place, provides divets for staples being fired to bend around in. Specifications: • Internal diameter – 7mm • External diameter – 20mm • Height – 6mm • Divet dimensions – 0.5mm x 2.5mm x 1.0mm, rounded edges • Locking hole diameter – 1.5mm
	Part Name: Staple cartridge Function: Holds staples in position until they are fired. Specifications: • Internal diameter – 7mm • External diameter – 11.5mm • Height – 7mm • Slit dimensions – 2.8mm x 0.8mm • 12 holes in two overlapping rings
	Part Name: Needle and rod Function: Stationary anchor for anvil. Firing teeth slide along its length to fire staples. Specifications: • Needle diameter – 3.5mm • Rod diameter – 6mm • Needle height – 20mm • Nub diameter – 1.6mm
	Part Name: Staple firing teeth Function: Fires staples Specifications: • Inner diameter – 7mm • Outer diameter – 11mm • Teeth dimensions – 8mm x 2.5mm x 0.5mm • Groove diameter – 1.0mm • 12 teeth in two overlapping rings