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ORIGINAL ARTICLE

Efficacy of robotic versus open transversus abdominis release in a porcine model

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Abstract

Purpose Transversus abdominis muscle release (TAR) combines retromuscular mesh placement with posterior component separation and muscle release. TAR is usually an open technique for abdominal wall reconstruction; however, several centers have performed this operation robotically and claim better clinical outcomes when compared to open surgery. We sought to compare robotic versus open TAR utilizing a porcine model.

Methods Animals were randomized to open versus robotic TAR with mesh placement, survived for 4 weeks, then underwent diagnostic laparoscopy to assess adhesive burden and adhesion tenacity. T-peel testing was utilized to assess mesh ingrowth. The primary outcome was adhesive burden; secondary outcomes included mesh incorporation, contraction, and operative time.

Results Nine robotic and eight open TARs were performed. Mean operative time was significantly shorter for the open cases compared to robotic cases (88.6 ± 12.9 min versus 228.3 ± 46.2, $p < 0.01$). Operative time in the robotic arm of the study decreased over time, from 300 to 165 min. No difference was seen in the mean adhesion area between the two groups. Adhesion tenacity and mesh flatness were similar. The work required to peel the mesh off surrounding tissue was significantly higher in the open TAR than in the robotic TAR group: 52.6 ± 15.5 and 32.9 ± 10.6 mJ/cm^2, respectively ($p < 0.01$).

Conclusions There were no differences in adhesions between the robotic and open approaches, but greater mesh contraction and ingrowth was observed in the open TAR group. Though operative time was longer in the robotic group, time dropped by about 40% from the first case to the last.

Keywords Hernia · Transversus abdominis release · Robotic surgery

Introduction

The transversus abdominis release (TAR) method of abdominal wall reconstruction is a novel technique that entails placing mesh in the retrorectus plane, much like the Rives-Stoppa method, and performing a posterior component separation (PCR) with release of the transversus abdominis muscle. This method was first introduced in 2012 by Novitsky and colleagues and has gained popularity since. It combines placement of uncoated mesh extraperitoneally with the ability to repair massive abdominal wall defects and reapproximate the rectus muscles in the midline. When Novitsky et al. originally described the TAR method, they found that of 42 patients who underwent open PCS with TAR, ten (23.8%) developed wound complications but only two (4.7%) developed hernia recurrences at a median follow-up time of 26.1 months [1]. In their follow-up paper in 2016, of 428 patients who underwent TAR, 39 (9.1%) developed surgical site infections and there were 13 (3.7%) recurrences [2].

There is clearly a dearth of literature detailing outcomes following robotic TAR and we were unable to find any studies prospectively comparing open or laparoscopic to robotic PCS and TAR. Though there are retrospective analyses available, there is no literature comparing mesh incorporation, mesh contraction, and adhesive burden following open, laparoscopic, or robotic PCS and TAR.

In this study, we compared robotic and open TAR in a porcine model. This approach allows for isolation of the

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differences between the open and robotic approaches and examination of tissue 4 weeks post-repair, which is not possible in human subjects. This approach also allows the exclusion of confounding factors that are found in human subjects, such as widely differing hernia size and hernia location. In addition, studying robotic and open TAR in an animal model helps better delineate how the mesh ultimately is positioned in either approach. We hypothesized that robotic TAR has several clinical benefits when compared with open TAR. This includes a decreases in adhesion formation, mesh contraction, and mesh incorporation when compared to the open operation.

Methods

After obtaining institutional approval from the Animal Studies Committee, seventeen 40 kg female domestic pigs were utilized in this survival study. Pigs were randomized to undergo a robotic or an open TAR. All animals were acclimated to their housing facilities for 72 h prior to their procedures. During the index operation, total operative time, estimated blood loss, and incidence of intraoperative complications was recorded. The procedures in this study were performed by surgery residents with some prior experience in robotic surgery, mentored by a faculty member with extensive experience in both open and robotic abdominal wall reconstruction.

Open TAR

The technique for an open TAR is described by Novitsky et al. 2012 and is briefly summarized as follows [1]. A midline laparotomy incision was made and the posterior rectus sheath incised about 0.5–1 cm from its medial edge. The retromuscular space was developed using both blunt dissection and electrocautery. Dissection continued towards the linea semilunaris, with care to preserve perforators to the rectus muscle. The transversus abdominis muscle was exposed by incising the lateral edge of the posterior rectus sheath, and the exposed muscle was then divided along its medial edge. The space between the transversus abdominis muscle and transversalis fascia was developed. These steps were repeated on the contralateral side of the abdominal wall. The medialized posterior rectus sheaths were reapproximated in the midline with an absorbable braided suture. A 20 × 20 cm piece of midweight macroporous polypropylene mesh was then placed in the retromuscular space and secured with suture in each corner, and the anterior rectus sheaths were reapproximated with absorbable monofilament suture. The skin and subcutaneous tissue was closed in the standard fashion.

Robotic TAR

Pneumoperitoneum was achieved using a Veress needle. Three 8-mm ports were then placed in the right side of the abdomen lateral to the linea semilunaris. Then working in a trans-abdominal approach, the posterior rectus sheath was opened similarly to the open approach. After extending this laterally to the neurovascular perforators to the rectus muscle, the posterior sheath and transversus abdominis muscle was divided. This plane was then extended out laterally for 15 cm. Three additional robotic trocars were then placed along the left abdominal wall and an identical mesh to what was used in the open approach was introduced into the abdomen and secured along the left abdominal wall in two places with absorbable suture. The robot re-docked to the left side of the abdomen and these steps were repeated on the contralateral side. The posterior sheath was then closed with an absorbable barbed suture. The mesh was unrolled and secured to the opposite side of the abdomen with an absorbable suture.

Sacrifice and re-exploration

After a 4 week survival period animals were sacrificed for mesh examination. At this time, a diagnostic laparoscopy was performed to quantify adhesive burden and grade adhesion tenacity (Table 1), based on a five-point scale from Deeken et al. [3]. Visual observations were made regarding the health of the animal, and the abdominal wall and mesh samples were harvested en bloc. The length and width of the mesh was measured and the total area compared to the

Table 1 Adhesion tenacity grading scale

Grade	Description
0	No adhesions observed
1	Loose adhesions requiring blunt dissection only
2	Firm adhesions requiring sharp dissection (without extensive vascularity)
3	Firm adhesions requiring sharp dissection (with extensive vascularity)
4	Firm adhesions requiring sharp dissection, with extensive fibrotic ingrowth and vascularity
5	Grade 4, with firm attachment to visceral organs (bowel, liver, spleen)

original mesh area to calculate mesh contraction. Mesh flatness was graded on a qualitative 4 point scale (Table 2). Six to eight specimens measuring 4 cm × 3 cm wide were then obtained from each mesh-tissue repair site, taking care to avoid fixation points. These specimens were used in T-peel testing to determine mesh ingrowth.

Mechanical testing

Mesh ingrowth is an important parameter in determining the efficacy of hernia repairs, and poor ingrowth has been associated with hernia recurrence. Ingrowth can be quantitatively evaluated through T-Peel testing (Fig. 1), a standardized test method which pulls the mesh from the muscle layer ex vivo. While other mechanical tests analyze the strength of mesh-tissue composites, by measuring the force at which the mesh separates from the muscle, T-peel testing quantifies mesh integration into host tissue. Mesh ingrowth was evaluated via T-peel testing as described by Lake et al. [4]. Six to eight 4 cm × 3 cm specimens were procured from the mesh site and mesh was retracted 1 cm to create a 3 cm × 3 cm composite region of mesh-tissue ingrowth. The free edge of the mesh and the abdominal wall were clamped into opposing grips on a uniaxial tensile testing machine (Series 5542 Universal Testing System; Instron, Norwood, MA, USA). Displacement was applied at 0.42 mm/s (1 in/min) until the mesh fully peeled away from the tissue. Mesh ingrowth was quantified through peak force, work, and critical force. Work was computed as the area under the force–displacement curve. The critical force was defined, as per Lake et al., as the average force required to peel mesh from underlying tissue. It was calculated as the average of force values greater than 50% of the peak force observed [4].

Data analysis

Continuous outcomes were compared using *t* tests. If the data was measured on an ordinal scale, the Wilcoxon–Mann–Whitney test was employed. Chi-square analysis was used to compare categorical variables. All analyses were performed using SAS 9.4. Statistical significance was defined as $p < 0.05$.

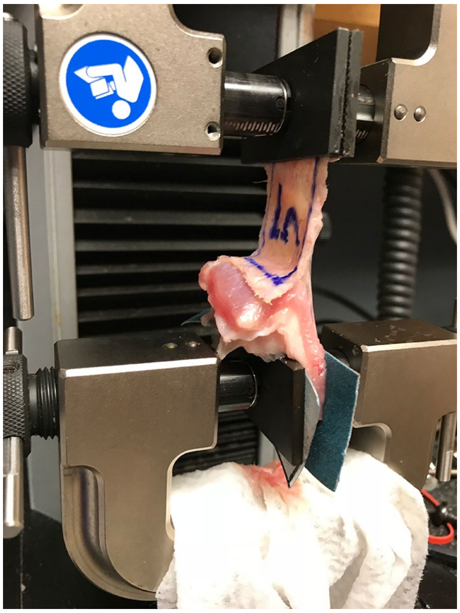

Fig. 1 T-peel test. The mesh and muscle are pulled apart at a constant rate

Results

A total of seventeen animals were included in this study: nine robotic TARs and eight open TARs. Mean operative time for the open cases was 88.6 ± 12.9 min, which was significantly shorter than the mean operative time for the robotic cases (228.3 ± 46.2, $p < 0.01$). Operative time in the robotic arm of the study decreased over time, from 270 to 300 min for the first three cases to 165–225 min for the last three cases. There were no intraoperative complications. There was one surgical site infection in the open group and zero in the robotic group ($p = 0.47$).

Mean adhesion area was 5.0 ± 8.4 cm^2 in the open group compared to 2.4 ± 3.5 cm^2 in the robotic group ($p = 0.41$). Most of the adhesions occurred in the midline, in the upper half of the abdomen (Fig. 2a, b). Adhesive burden, overall, was low (Fig. 2c). Adhesion tenacity was similar between groups ($p = 0.8$). If adhesions were observed, they were either loose adhesions requiring blunt dissection only or firm adhesions requiring sharp dissection, but without extensive vascularity (Fig. 3). Mesh flatness was also similar between

Table 2 Mesh flatness grading scale

Grade	Type	Description
0	Flat	No discernable wrinkles
1	Wavy	Mild fluctuations in mesh surface with obtuse transition angles
2	Wrinkled	Significant fluctuations in mesh surface with acute transition angles
3	Folded	Wrinkled to the point of mesh folding over on itself

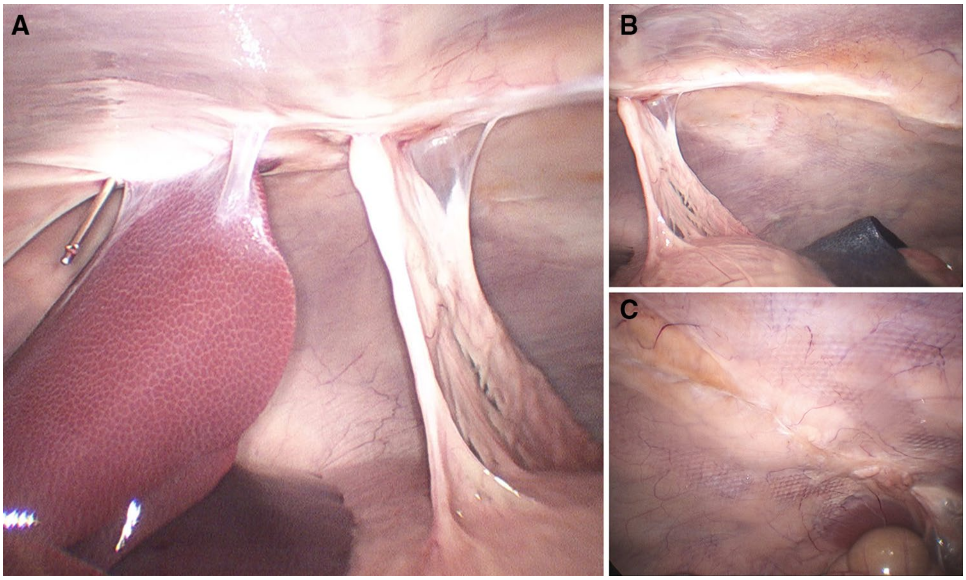

Fig. 2 Adhesive burden. Most adhesions observed were in the midline and in the upper abdomen (**a, b**), but overall, adhesive burden was low and several animals had no adhesions at all (**c**)

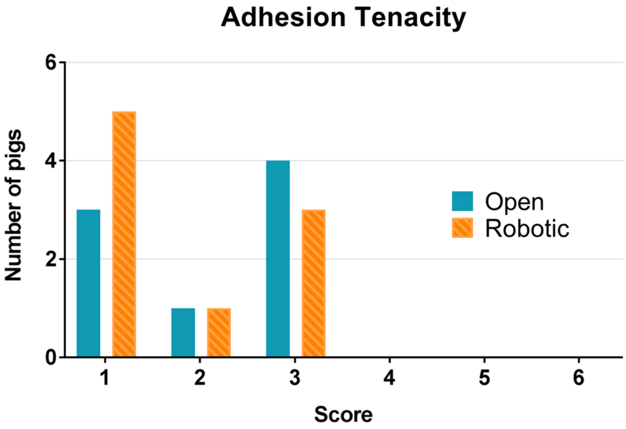

Fig. 3 Adhesion tenacity

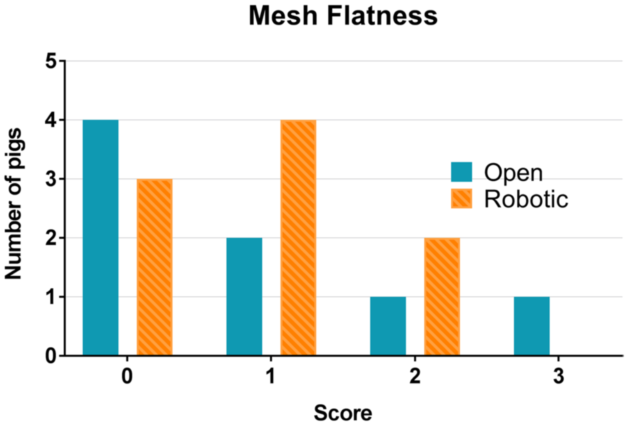

Fig. 4 Mesh flatness

the robotic and open TAR groups (Fig. 4, $p = 0.74$). Most meshes in this study were flat without discernable wrinkles or wavy with mild fluctuations in mesh surface with obtuse transition angles (Fig. 5a). Three animals had wrinkled meshes with significant fluctuations in mesh surface with acute transition angles: one in the open group and two in the robotic group. One animal in the open TAR group was found to have mesh that had folded over itself (Fig. 5b). In animals who underwent robotic TAR, we noted that the meshes were more frequently off-center (Fig. 5c), which improved as the study progressed. There was significantly greater mesh contraction in the open group compared to the robotic TAR group: 16.2 ± 4.6% versus 10.5 ± 5.4%, respectively ($p = 0.047$).

Mechanical testing demonstrated that the average critical force and work required to peel the mesh off surrounding tissue was statistically significantly higher in the open TAR group than in the robotic TAR group (Figs. 6, 7). The average critical force required to peel the mesh off underlying tissue was 8.6 ± 2.5 N in the open group compared to 5.7 ± 1.7 N in the robotic group ($p = 0.01$). The average work was 52.6 ± 15.5 mJ/cm^2 and 32.9 ± 10.6 in the open and robotic groups, respectively ($p < 0.01$).

Discussion

In this animal study, no significant differences in adhesive burden, adhesion tenacity, and mesh flatness were observed between robotic and open TAR. Operative time was significantly longer in the robotic TAR group. We observed significantly greater mesh contraction in the open

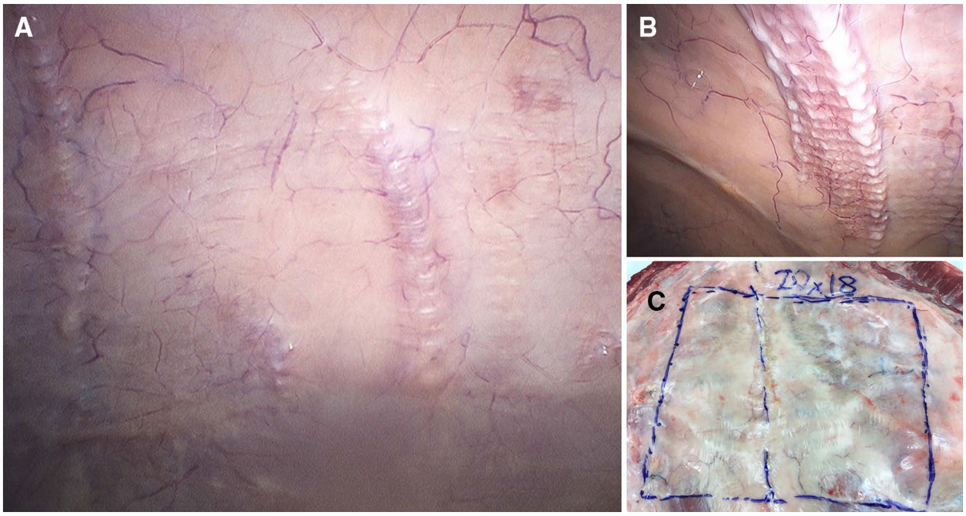

Fig. 5 Mesh flatness. Most meshes in this study were flat without discernable wrinkles or wavy with mild fluctuations in mesh surface with obtuse transition angles (**a**). One animal in the open TAR group was found to have mesh that had folded over itself (**b**). In animals who underwent robotic TAR, we noted that the meshes were more frequently off-center (**c**), which improved as the study progressed

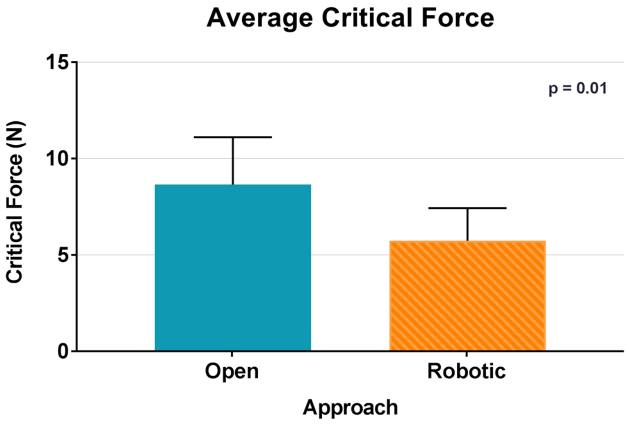

Fig. 6 Average critical force

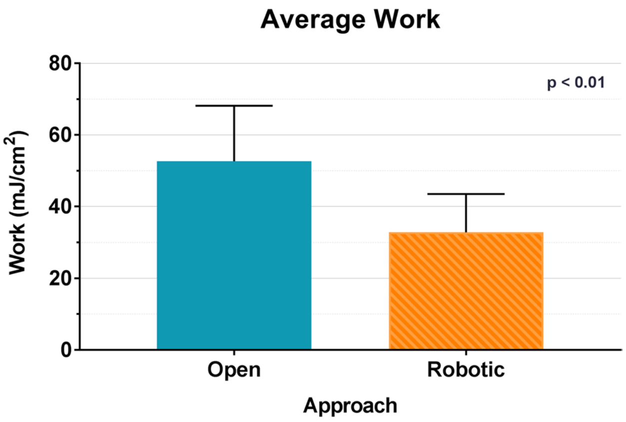

Fig. 7 Average work

TAR group. Mechanical testing demonstrated significantly greater average critical force and work in the open group compared to those animals that underwent robotic TAR.

Most of the adhesions observed in this study were to the midline and in the upper abdomen. In the robotic group, barbed suture was utilized to close the posterior rectus sheath. There is some concern that barbed suture is adhesiogenic based largely on case reports and anecdotal evidence, though this is not necessarily reflected in other animal studies, including ours [5, 6]. There was no statistically significant difference in adhesive burden between the robotic and open TAR groups and overall adhesive burden was low. This may not be a surprising result, as mesh was placed in the retromuscular space, rather than intraperitoneally. Additionally, animals were sacrificed after 4 weeks.

In our study, there was significantly greater mesh contraction in the open group compared the robotic TAR group: 16.2 ± 4.6% versus 10.5 ± 5.4%, respectively. As mesh contracts, tension is created at its anchoring point, and could lead to potential hernia recurrence [7]. Interestingly, the amount of mesh contraction observed in this study exceeded what is typically reported in recent in human studies. In a study of mesh contraction in 37 patients (20 laparoscopic and 17 open hernia repairs), there was no significant difference in mesh contraction between operative approaches. In this study, a midweight polypropylene mesh with large pores was utilized in the laparoscopic repair, fixated with metal tackers. For the retromuscular repairs, a small pore heavyweight mesh made of oxidized regenerated cellulose and polypropylene, encapsulated by polydioxanone was utilized in the open repair, with metal clip markers placed around the mesh border. Abdominal X-rays and measurement of distance between metal markers were used to determine mesh contraction. At 1 year, the mesh area decreased by 4.4% and 0.5% in LHR and OHR, respectively ($p < 0.063$) [8]. Another human study of patients undergoing laparoscopic ventral hernia repair with Parietene (Medtronic) composite mesh observed a 3.1 ± 3.9% decrease in mesh area in meshes fixated with tacks versus a 0.1 ± 2.3% decrease when fixated with sutures ($p = 0.018$) at 6 months after surgery [9]. When comparing different mesh weights, a study of 30 patients who underwent open inguinal hernia repair (15 with heavyweight and 15 with lightweight polypropylene mesh) found a 7.8% shrinkage for the heavyweight and 4.2% shrinkage for the lightweight meshes at 90 days [7]. In contrast, there are some early reports of up to 20% mesh contraction in humans, and up to 66% mesh contraction in various animal models [10–14]. It is possible that pigs have a more robust inflammatory response during the healing process than humans do, and as a result, greater mesh contraction is observed. Mesh contraction was significantly greater in the open arm of the study (perhaps again, due to the possibility that an open approach provokes a greater inflammatory response). However, the difference in means was only 5.7%.

The mesh ingrowth observed in this study mirrors the degree of mesh ingrowth reported in other animal studies. Bayon et al. implanted monofilament polyester mesh retromuscularly in twenty minipigs and found that the average work at 3 weeks postoperative to peel the mesh off the underlying muscle ranged from about 50–75 mJ/cm^2, depending on pore size and weight [15]. Deeken et al. implanted various barrier coated meshes intraperitoneally in a porcine model and observed at four weeks average T-peel forces between 1.0 and 1.4 N/cm (10–14 mJ/cm^2) [3]. On explant, meshes in both the open and robotic arms of the study were visually inspected and looked well-incorporated. However, on mechanical testing, the work needed to peel mesh off underlying tissue was significantly greater in open animals. As hypothesized above, perhaps open surgery provokes a greater inflammatory response during wound healing than the robotic approach, leading to greater mesh contraction and ingrowth. What the clinical implication of these values remains to be determined.

Over the study period, robotic operative time dropped by 45% from the first case to the ninth. Longer operative times are a common criticism of robotic surgery, but there have been multiple studies demonstrating that it is possible to achieve great reductions in robotic operative times and even parity with laparoscopic operative times. The procedures in this study were performed by surgery residents with some prior experience in robotic surgery, under the tutelage of a faculty member with extensive experience in both open and robotic abdominal wall reconstruction. Because these procedures were performed by surgery residents there was a learning curve, which is evident from the improved operative times throughout the study. A prospective study of robotic-assisted laparoscopic ventral mesh rectopexy for pelvic floor disorders found a 23% decrease in total operative time over 51 patients. Operative time was further divided into robot set-up time and surgeon console time. Reduction in times were seen in both: 60% in robot set-up time and 36% in surgeon console time. The authors explain that a dedicated team of robot-trained nurses and support staff, a dedicated robot operating room, and a standardized surgical technique contributed to a reduced learning curve in this study [16]. A colorectal surgery study of 185 patients undergoing laparoscopic colorectal surgery and 70 undergoing robotic colorectal surgery found no significant difference in operative times for right colectomies (median = 137 versus 130.5 min, $p = 0.9$) and left colectomies (median = 162.0 versus 170.5 min, $p = 0.6$) [17]. In two human studies comparing robotic and open TAR, the average operative time for robotic TAR was significantly longer by approximately 80 min [18, 19]. However, in one study, the robotic TARs represented were the first 26 performed by the author, and that average operative time may fall with subsequent cases [18].

Our study has a number of limitations. Because we utilized an animal model in this study, we are unable to report on other clinical outcomes of potential interest in comparing a robotic and open approach to the TAR, such as postoperative pain, opioid consumption, length of stay, or postoperative complications. Because there was no hernia defect in this model, operative times in this study are likely lower than would be observed in humans. However, utilization of an animal model allows us to examine outcomes such as adhesive burden and mesh positioning and exclude confounding factors such as prior surgeries or comorbidities, which would not be possible in human subjects. Another limitation is that the animals were only survived for 30 days, but a longer survival time may impact outcomes such as adhesive burden and adhesion tenacity.

Conclusion

There were no differences in adhesions between the robotic and open approaches, but more mesh contraction and better ingrowth was observed in the open TAR group. Though operative time was statistically significantly longer in the robotic group, the operative time dropped by about 40% from the first case to the last.

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Compliance with ethical standards

Conflict of interest Dr. Blatnik is a consultant and receives an honorarium from Intuitive Surgical.

Ethical approval All applicable international, national, and institutional guidelines for the care and use of animals were followed. All procedures performed in this study involving animals were in accordance with the ethical standards of the institution at which the studies were conducted.

Human and animal rights Procedures performed received institutional approval from the Washington University in St. Louis School of Medicine Animal Studies Committee and were in accordance with standards set forth by the Association for Assessment and Accreditation of Laboratory Animal Care International (AAALAC).

Informed consent For this type of study, formal consent was not necessary.

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