Prophylactic onlay mesh placement techniques for optimal abdominal wall closure

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Prophylactic On-Lay Mesh Placement Techniques for Optimal Abdominal Wall Closure – Randomised Controlled Trial in an Ex-Vivo Biomechanical Model

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Randomised Control Trial

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Keywords: small bite suture, on-lay mesh, abdominal wall closure, laparotomy closure, incisional hernia, wound dehiscence

Abstract

Background

Incisional hernias occur after up to 40% of laparotomies. Recent randomised control trials demonstrate the role of prophylactic mesh placement in reducing the risk of developing an incisional hernia. An on-lay approach is relatively straight forward, however a variety of techniques have been described for mesh fixation. The biomechanical properties have not been extensively interrogated to date.

Methods

This ex-vivo randomised control trial using porcine abdominal wall investigated the biomechanical properties of three techniques for prophylactic on-lay mesh placement at laparotomy closure. A Classical on-lay, Anchoring on-lay, and novel Bifid on-lay approach were compared to small bite primary closure. A biomechanical abdominal wall model and ball burst test were used to assess transverse stretch, bursting force and loading characteristics.

Results

Mesh placement took an additional 7-15minutes when compared to standard primary closure. All techniques performed similarly, with no clearly superior approach. The minimum burst force was 493N, and the maximum 1053. The classical approach had the highest mean burst force (853N+/-152N). Failure patterns fell into either suture line or tissue failures. Classical and Anchoring techniques provided a second line of defence in the event of primary suture, whereas the Bifid demonstrated a more compliant loading curve.

All mesh approaches held up at extreme quasistatic loads. Subtle differences in biomechanical properties highlight the strengths of each and suggest possible use cases. The failure mechanisms seen here support the known hypotheses for early fascial dehiscence. The influence of dynamic loading needs to be further investigated in future studies.

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Introduction

Effective closure of the abdominal wall is an essential part of general surgical practice. Despite rapid advances in minimally invasive techniques such as laparoscopy and robotics over the last 30 years, open access will continue to remain relevant in technically challenging and emergency cases. Midline laparotomy incisions carry significant long-term morbidity, with incisional hernia being the most frequent complication (1, 2). Over 4 million laparotomies are performed annually in the United States (3), with rates for incisional hernia after laparotomy ranging from 20% in unselected patient populations, to up to almost 40% in high risk patient cohorts (4, 5). Incisional hernias are symptomatic in up to 84% of patients (3) with a 5-year revision rate of over 20% (6), with many presenting as emergencies either as incarceration (6-15%) or strangulation (2%)(7, 8). Abdominal incision failure either early or late is associated with significant morbidity, mortality, and cost, both financial and personal.

Prophylactic mesh placement at time of abdominal closure significantly reduces incisional hernia rates from 20-33% to 3.9-16% (11-14). However, there appears to be a trend towards increased chronic pain (7.8%) and seroma formation (12.9% vs 6.9%) (13). Synthetic meshes have been shown to be safe for use even in the setting of peritonitis (12), and long acting resorbable biosynthetic meshes such as TIGR® matrix mesh (Novus Scientific AB, Virdings Allé, Uppsala, Sweden) have been safely used for abdominal closure (15) without significant infection or seroma, including in a cohort of high risk emergency laparotomy patients (16). A recent multicentre randomised controlled control published in the US demonstrated significantly lower rates of

Deleted: Both patient and technical factors contribute to formation of incisional hernias. Co-morbidities such as pulmonary disease, connective tissue disorders, obesity, and diabetes can predispose patients to developing incisional hernias . Whereas these patient factors are typically not modifiable, surgical techniques are. Over the last two decades, multiple randomised control trials and meta-analyses have interrogated the technical elements of laparotomy closure and their impact on incisional hernia rates . It is now understood that continuous slowly or non-absorbable sutures are superior to interrupted closure and rapidly absorbable suture materials in elective laparotomy closure . ¶
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There is compelling evidence showing a small bite fascial closure (5mm wide, 5mm separation) closure reduces incisional hernia rate at 1 year from 21% to 13% when compared to mass closure techniques using large bites (10mm wide, 10mm separation) and is now the recommended closure technique of the European and American Hernia Societies (9). The optimal suture placement is still a topic of debate, with biomechanical modelling suggesting that small separation (5mm), with wide bites (16mm) may be optimal (10), though this has not yet been tested in clinical practice. Other approaches such as the Hughes repair (also known as the far-and-near technique) have been investigated by randomised control trial but have failed to demonstrate the same improvements in incisional hernia rate when compared to mass closure (28.7% vs 31.8%) as seen in small bite closure . ¶

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incisional hernia and median mesh cost, when using a synthetic mesh (5.6%, $105) compared to a biological mesh (20.5%, $21,539) at 2 years, with no significant difference in the rates of surgical site occurrence (17).

On-lay mesh placement is a straightforward technique when compared to complex abdominal wall reconstruction approaches such as component separation. A classical on-lay involves fixing the mesh to the anterior rectus fascia with an overlap of over 3cm after primary closure of the linea alba (14). The issue with the classic on-lay is that it does not directly buttress the fascial edge closure. It remains to be seen if incorporating the mesh into the closing fascial suture would offer a biomechanical advantage.

This study used post-mortem porcine abdominal wall specimens as an ex-vivo model to compare the biomechanical properties of standard suture primary closure, with classical on-lay technique, an augmented anchoring on-lay, and a novel bifid mesh incorporating closure.

Methods

Sample preparation, randomisation, and closure techniques

Porcine abdominal walls were collected fresh from an abattoir and frozen on arrival to the laboratory. Due to practical constraints of storage, transport and funding testing was limited to 20 abdominal walls. Samples were removed from the freezer and

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thawed prior to testing, for a minimum of 24hours. The samples were prepared by removing skin, and subcutaneous fat, leaving just the abdominal fascia, musculature, preperitoneal fat, and peritoneum. For all but the initial four samples, this preparation was performed before freezing to reduce the need for prolonged thawing periods associated with the larger unprepared samples.

Simple randomisation was used. Twenty computer generated numbers were randomly assigned to one the four closure methods – Primary Closure, Classic On-Lay, Anchoring On-Lay, or Bifid On-Lay – in a 1:1:1:1 allocation ratio. After the abdominal incision was made, a number was drawn blindly by the surgeon (IS). A second investigator (JC) checked the number against its assigned closure method. This methodology was then used for the abdominal closure. This process was repeated for each consecutive abdominal wall across four testing days until no samples remained. Two samples were discarded due to putrefaction prior to closure allocation. This left a total of eighteen abdominal walls for allocation and testing.

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A 10cm supraumbilical incision was made in the midline of each sample, through the linea alba using a template. A 2-0 polypropylene (Prolene®, Ethicon, Somerville, New Jersey, USA) was used for all suturing. A small bite (5mm separate, 5mm width) technique was used for primary midline closure. A 15cm x 6cm rectangular TIGR® matrix mesh was used for all mesh closures.

For the “Classic” group, primary closure was augmented by the placement of mesh over the anterior fascia, with a 3cm overlap on either side of the incision. The mesh was fixed in place with a running, locking suture placed circumferentially around its outer borders, tacking the mesh to the anterior fascia. In the “Anchoring” group, 3 interrupted sutures were placed through the full thickness of the linea alba and left untied prior to primary closure. These were placed at the apices and in the middle of the incision. Double ended needles were left on these sutures, which were then passed through the mesh after primary closure. The sutures were then tied and cut, providing three points of fixation between the mesh and the full thickness abdominal incision. The mesh was then fixed circumferentially in the same manner as used in the “Classic” approach. For the “Bifid” technique, the mesh was cut evenly along its length, leaving two 15cm x 3cm strips. A strip of mesh was tacked to the anterior fascia on either side of the incision using a running, locking suture in such a manner that the cut edge overlapped the abdominal incision. A small bite, primary closure was then performed, taking linea alba, and mesh on either side of the incision effectively incorporating the two strips of mesh into the closure for a buttress effect. See Figure 1.

A single, general surgery specialist registrar (IS) performed all closures. Technical and clinical training in all prophylactic mesh placement techniques used here had been provided by consultant surgeons (MS and DW). For each closure, the time for completion was recorded. The Kruskal-Wallis Test was performed using GraphPad Prism 9.4.1® to analyse statistical significance (2-sided 5%) in the differences in preparation times between groups. Time for closure completion was summarized using median and range for each group. All samples were tested on the Biomechanical Abdominal Wall Model (BAWM) and then the Modified Ball Burst Test (MBBT) immediately after preparation. Primary outcomes were time taken for completion (minutes, seconds), transverse stretch (Δ), and burst force (Newtons).

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Biomechanical Abdominal Wall Model

The surrogate abdominal wall model has been previously described in multiple studies (10, 18). A porcine abdominal wall is stretched over a box-shaped rig. This represents the abdominal wall and cavity. An oversized balloon contained within the box is inflated with a controlled compressed air supply to standardised pressures, designed to represent physiological intra-abdominal pressures. Pressures within the rig were increased at 2kPa (15mmHg) increments to a maximum of 24kPa (180mmHg). Each increment was held for 10 seconds ensuring quasistatic conditions.

Transverse stretch was measured using dot-tracking video analysis (GoPro Hero® 7 and 8 cameras) of the anterior abdominal wall captured during testing. Dot-pairs were painted onto the abdominal wall with black acryl paint (see Figure 2). These were placed 4cm lateral to the incision, at 2cm intervals beginning at the top of the mesh. Still images were extracted from the video footage at the end of each 10seconds interval. A custom MATLAB® script was used to measure transverse stretch by comparing dot-pair distances at 0kPa to each pressure increment. Transverse stretch was expressed in terms of dot-pair distance at a given pressure, divided by original length at 0kPa. Mean stretch for each pressure value was calculated within each group by averaging values across all dot pairs for that closure method, allowing for comparison between groups as opposed to between individual samples. Outcomes were summarised numerically and graphically.

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Modified Ball Burst Test

A custom Ball Burst rig was developed using a 3D-printed rectangular polylactic acid (PLA) mounting-frame with a metallic mounting vice and a 7cm diameter steel ball loaded on a Zwick Proline Twin Column testing machine. Samples were mounted such that the ball applied its load through the posterior abdominal wall. The ball head was placed with its centre over the middle of the incision. The ball advanced at a rate of 5mm/min until a preload of 0.1N was reached. From this point, a standard rate of travel of 10mm/min was set to provide quasistatic loading, with the ball head applying load to the sample until a 20% drop off in force compared to the maximum recorded was observed. The maximum force observed was denoted the burst force. Data for time, travel distance, and force were collected at 0.6-0.7 second intervals throughout each test. Observations regarding tissue tearing, and suture and mesh failure were recorded for each sample.

Study protocol is available on request from the corresponding author (IS).

Results

Sample Randomization and Preparation

A total of eighteen samples were randomly assigned to the test groups – four to the Primary Closure, and four to Classic On-lay. Five samples were assigned to each of the Anchoring and Bifid groups. Early testing required defrosting periods greater than 24 hours due to tissue bulk and inconsistent thawing. This resulted in three samples – two from the Anchoring and one from the Bifid groups – having early evidence of putrefaction.

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Preparation times varied between groups. Primary was fastest (mean 9mins, 51seconds,±1min, 54seconds) and Anchoring the slowest (mean 24mins, 1second,

±2mins, 21seconds). Classic and Bifid groups took similar times to complete, taking an average of 16mins, 54seconds and 18mins, 7seconds respectively, with significant overlap between sample preparation times (Figure 3). The Kruskal-Wallis Test confirmed a statistically significant difference in completion times when comparing the closure methods(p<0.0001), but does not tell us which is stochastically dominant. Simple comparison of means suggests it is the primary closure group.

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Biomechanical Abdominal Wall Model

All eighteen samples were placed tested on the Abdominal Wall Model immediately after closure was performed. For comparison between groups, the mean transverse stretch was calculated using all dot pairs (n) across samples within a given group for all pressure values. n=26 for Primary, n=28 for Classic, n=32 for Anchoring and n=32 for Bifid. The total number of dot pairs across all groups was 118. At 24kPa, mean transverse stretch (Δ±standard deviation) for Primary was 1.23 (±0.034), Classic was 1.23 (±0.035), Anchoring was 1.24 (±0.034), and Bifid was 1.23 (±0.067)(Figure 4).

Modified Ball Burst Test

After testing on the Abdominal Wall Model, each sample was then mounted on the Modified Ball Burst platform. The mean bursting force (mean, ±standard deviation) for Primary Closure (702N ±87N), Anchoring On-Lay (706N ±145N), and Bifid On-Lay (710N ±245N) was similar, however there was significant variation within each group. The Classic On-Lay (853N ±152N) performed best on average. The best performing and worst performing samples were from the Bifid group. These failed at 1053N, and 493N respectively.

Loading patterns were interrogated during the Modified Ball Burst test by comparing force and travel distance. As there was significant variation in burst force and travel distance across samples, a cut-off of 70mm travel distance was used for intergroup analysis. No samples failed before this travel distance, allowing comparison of initial loading characteristics before failure effects. The Bifid technique demonstrated a more compliant loading curve, with lower forces recorded at equivalent travel distances compared to other methods (Figure 5). The primary closure tended towards an abrupt failure point, demonstrated by a sharp drop-off in force on the load curves. By comparison, all three mesh techniques showed a trend to more gradual failure, often without a sudden failure point. Inspection of the samples after testing demonstrated multiple modes of technical failure including suture or knot failure at the primary closure, tacking suture pull-through, and fascial pull through (Figure 6). Most samples failed when the surrounding tissues gave away, as opposed to a failure of the closure.

Discussion

The results of this study demonstrate that each approach to mesh augmented closure can be performed with minimal additional time investment (7-15minutes) when compared to primary closure. All groups demonstrated similar transverse stretch properties when placed on the abdominal wall model, with no clearly superior approach emerging. Performance on the Modified Ball Burst Model was again comparable, though the Classical approach had the highest mean burst force (853N ±152N). The Bifid approach showed the greatest variability across the samples (710N ±245N), as well as a more compliant loading curve. Failure patterns closely related to burst forces, with sudden failures typically being a consequence of primary suture line failure or fascial pull through.

Under normal anatomical conditions, average resting intra-abdominal pressures (IAP) in healthy adults is 1.6mmHg (19). With coughing, Valsalva manoeuver and jumping it can reach 107mmHg, 64.9mmHg, and 171mmHg (equivalent to 22.8kPa) respectively (19). Perioperative IAP rises to a peak of 1.74kPa on patient wakening from anaesthesia (18). The biomechanical abdominal wall model used here sequentially increases pressures on the closures to a maximum of 24kPa, far exceeding physiological IAP values. Despite this, no closure failures were seen at this stage of testing across any samples.

The minimum burst force seen during testing was 493N. This force was delivered directly onto the closure and concentrated through the spherical indenter. In lay-person’s terms, this is equivalent to a 50kg person balancing their weight directly onto the wound through only their fist. The best performing repair, at 1053N, would have held up to a 100kg weight. The stress/strain relationship which describes overall tissue elasticity (Young’s modulus) is challenging to define for soft tissue, and even more so for complex combined biological and synthetic constructs such as that created by the abdominal wall mesh interface. The success or otherwise of a given closure method is as dependent on local tissue failure properties as it is on the elasticity of the construct. The ballburst test provides a simple, robust approach to compare these complex constructs in a meaningful way. Even considering the limitations of this study, notably the small sample sizes and initial issues around sample thawing, these findings demonstrate the ability of the repairs to stand up to supraphysiological stresses.

Both these biomechanical models test the closures under quasistatic conditions, with gradual sustained increases in the forces involved. In many circumstances, such as coughing, jumping, and laughing, the abdominal wall does not experience this kind of sustained, gradually increasing loads but rather undergoes rapid, repetitive increases and decreases. Dynamic, repeated loading stimulating coughing produces distinct failures patterns in rat incisional hernia models. These failures are influenced by peak load and duration (20). The influence of dynamic loading should be tested in future.

The failure patterns seen in our test benches fall into 2 major categories – suture failure or tissue failure. Tissue failure was likely a consequence of the forces fatiguing the organic tissues whereas suture failures were either a direct result of a suture or knot breaking or cutting through the tissue into the midline wound. A similar phenomenon has been demonstrated in animal models comparing mesh and primary closure, with failures in the mesh group occurring at the wound healing interface (21). Further animal models and clinical studies have demonstrated that early fascial gaping can predict incisional hernias long before they manifest clinically. This gaping, identifiable either by CT or the serial x-ray monitoring migration of metallic clips placed on fascial edges, is likely the consequence of early clinically occult fascial dehiscence (22, 23).
The presence of a mesh across the incision may act as a “second line of defence” in the event of primary suture failure or fascial dehiscence. The Bifid group showed the

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most intragroup variability and a more compliant loading pattern. These properties may be attributable to a unique buttress effect provided to the suture line, like that sought by use of pledgets in vascular surgery. However, as it lacks the “second line of defence” in the event of a technical suture failure such as a snapped knot, it cannot compensate like the other mesh approaches.

This study did not investigate mesh positioning, but rather looked solely at the well-established on-lay approach. The on-lay approach is simpler to perform when compared to sublay and retrorectus approaches. The PRIMA randomised controlled trial compared on-lay and sublay approaches. Onlay (13%) outperformed the sublay (18%) approach with regards to incisional hernia formation at 2 years, though seromas were more frequent. Both approaches were superior to primary closure (30%) (14). The recently published long-term results of the PRIMAAT randomised control trial demonstrated a 0% cumulative incidence of incisional hernia at 60months when using prophylactic retrorectus mesh placement at laparotomy closure for abdominal aortic aneurysm repair, compared to 49.2% with primary closure alone (24).

We know from studies such as the STITCH and PRIMA trials (14, 25) that technical differences can result in significant variation in clinical outcomes. However, the development of incisional hernias is a complex interplay between patient, technical and disease related factors. Early occult, or clinically apparent fascial dehiscence is likely a consequence of either technical failure – either of the material used or the quality of knots – or tissue failure due to poor tissue quality. Attention to basic surgical principles, namely sound knot tying, atraumatic tissue handling, appropriate tissue apposition, and use of a laparotomy wound bundle, has a significant role to play in the prevention of these early wound failures (26) and should provide the basis on which we build more complex adjuncts such as mesh augmentation.

The approaches to prophylactic mesh placement interrogated here demonstrate comparable biomechanical properties. The placement of mesh takes additional time, up to 15 minutes extra when compared to primary closure. Suture failure patterns demonstrate the merits of each approach, with the Bifid On-Lay reinforcing poor quality surrounding tissue, and the Classic and Anchoring On-Lays providing a “second line of defence” in the event of failure of the primary closure. This may suggest different optimum use cases for each approach. The supraphysiological forces and pressures used in this study demonstrate the mesh’s ability to stand up to extreme quasistatic loads.

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References

1. Fink C, Baumann P, Wente MN, Knebel P, Bruckner T, Ulrich A, et al. Incisional hernia rate 3 years after midline laparotomy. Br J Surg. 2014;101(2):51-4.

2. Manoharan S, Liu G, Crump RT, Karimuddin AA, Scott TM, Sutherland JM. Incisional hernia repair surgery improves patient reported outcomes. Am J Surg. 2020;219(5):874-8.

3. van Ramshorst GH, Eker HH, Hop WC, Jeekel J, Lange JF. Impact of incisional hernia on health-related quality of life and body image: a prospective cohort study. Am J Surg. 2012;204(2):144-50.

4. Bevis PM, Windhaber RA, Lear PA, Poskitt KR, Earnshaw JJ, Mitchell DC. Randomized clinical trial of mesh versus sutured wound closure after open abdominal aortic aneurysm surgery. Br J Surg. 2010;97(10):1497-502.

5. Van den Dop LM, De Smet GHJ, Kleinrensink GJ, Hueting WE, Lange JF. Hybrid operation technique for incisional hernia repair: a systematic review and meta-analysis of intra- and postoperative complications. Hernia. 2021;25(6):1459-69.

6. Flum DR, Horvath K, Koepsell T. Have outcomes of incisional hernia repair improved with time? A population-based analysis. Ann Surg. 2003;237(1):129-35.

7. van 't Riet M, Steyerberg EW, Nellensteyn J, Bonjer HJ, Jeekel J. Meta-analysis of techniques for closure of midline abdominal incisions. Br J Surg. 2002;89(11):1350-6.

8. Juul N, Henriksen NA, Jensen KK. Increased risk of postoperative complications with retromuscular mesh placement in emergency incisional hernia repair: A nationwide register-based cohort study. Scand J Surg. 2021;110(2):193-8.

9. Deerenberg E, Henriksen N, Antoniou G, Antoniou S, Bramer W, Fischer J, et al. Updated guideline for closure of abdominal wall incisions from the European and American Hernia Societies. The British journal of surgery. 2022.

10. Cooney GM, Kiernan A, Winter DC, Simms CK. Optimized wound closure using a biomechanical abdominal model. Br J Surg. 2018;105(4):395-400.

11. Bhangu A, Nepogodiev D, Ives N, Magill L, Glasbey J, Forde C, et al. Prophylactic biological mesh reinforcement versus standard closure of stoma site

(ROCSS): a multicentre, randomised controlled trial. Lancet. 2020;395(10222):417-26.

12. Argudo N, Pereira JA, Sancho JJ, Membrilla E, Pons MJ, Grande L. Prophylactic synthetic mesh can be safely used to close emergency laparotomies, even in peritonitis. Surgery. 2014;156(5):1238-44.

13. Bhangu A, Fitzgerald JE, Singh P, Battersby N, Marriott P, Pinkney T. Systematic review and meta-analysis of prophylactic mesh placement for prevention of incisional hernia following midline laparotomy. Hernia. 2013;17(4):445-55.

14. Jairam AP, Timmermans L, Eker HH, Pierik REGJ, van Klaveren D, Steyerberg EW, et al. Prevention of incisional hernia with prophylactic onlay and sublay mesh reinforcement versus primary suture only in midline laparotomies (PRIMA): 2-year follow-up of a multicentre, double-blind, randomised controlled trial. Lancet. 2017;390(10094):567-76.

15. Söderbäck H, Mahteme H, Hellman P, Sandblom G. Prophylactic Resorbable Synthetic Mesh to Prevent Wound Dehiscence and Incisional Hernia in High High-risk Laparotomy: A Pilot Study of Using TIGR Matrix Mesh. Front Surg. 2016;3:28.

16. Alsaadi D, Stephens I, Simmons L, Bucholc M, Sugrue M. Prophylactic onlay mesh at emergency laparotomy: promising early outcomes with long-acting synthetic resorbable mesh. ANZ journal of surgery. 2022.

17. Rosen M, Krpata D, Petro C, Carbonell A, Warren J, Poulose B, et al. Biologic vs Synthetic Mesh for Single-stage Repair of Contaminated Ventral Hernias: A Randomized Clinical Trial. JAMA surgery. 2022;157(4).

18. Lyons M, Mohan H, Winter DC, Simms CK. Biomechanical abdominal wall model applied to hernia repair. Br J Surg. 2015;102(2):e133-9.

19. Cobb W, Burns J, Kercher K, Matthews B, Norton J, Heniford T. Normal intraabdominal pressure in healthy adults. The Journal of surgical research. 2005;129(2).

20. Kallinowski F, Ludwig Y, Gutjahr D, Gerhard C, Schulte-Hörmann H, Krimmel L, et al. Biomechanical Influences on Mesh-Related Complications in Incisional Hernia Repair. Front Surg. 2021;8:763957.

21. DuBay DA, Choi W, Urbanchek MG, Wang X, Adamson B, Dennis RG, et al. Incisional herniation induces decreased abdominal wall compliance via oblique muscle atrophy and fibrosis. Ann Surg. 2007;245(1):140-6.

22. Playforth M, Sauven P, Evans M, Pollock A. The prediction of incisional hernias by radio-opaque markers. Annals of the Royal College of Surgeons of England. 1986;68(2).

23. Xing L, Culbertson E, Wen Y, Franz M. Early laparotomy wound failure as the mechanism for incisional hernia formation. The Journal of surgical research. 2013;182(1).

24. Dewulf M, Muysoms F, Vierendeels T, Huyghe M, Miserez M, Ruppert M, et al. Prevention of Incisional Hernias by Prophylactic Mesh-augmented Reinforcement of Midline Laparotomies for Abdominal Aortic Aneurysm Treatment: Five-year Follow-up of a Randomized Controlled Trial. Annals of surgery. 2022;276(4).

25. Deerenberg EB, Harlaar JJ, Steyerberg EW, Lont HE, van Doorn HC, Heisterkamp J, et al. Small bites versus large bites for closure of abdominal midline incisions (STITCH): a double-blind, multicentre, randomised controlled trial. Lancet. 2015;386(10000):1254-60.

26. McGee MF, Kreutzer L, Quinn CM, Yang A, Shan Y, Halverson AL, et al. Leveraging a Comprehensive Program to Implement a Colorectal Surgical Site

Infection Reduction Bundle in a Statewide Quality Improvement Collaborative. Ann Surg. 2019;270(4):701-11.