

Novel mesh suture may resist bone cutting seen with wire-based sternal closures



Sandeep N. Bharadwaj, MD,^a Connor H. Raikar, BA,^a Gregory A. Dumanian, MD,^b and S. Christopher Malaisrie, MD^a

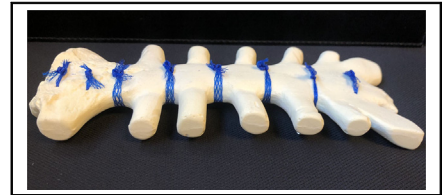
ABSTRACT

Objective: Sternal dehiscence is frequently associated with wire-based closures cutting through fragile bone, allowing sternal motion, separation, and infection. We investigated whether bone cutting could be limited by using a newly available mesh suture with improved force distribution.

Methods: Five sternal models were closed using 8 interrupted single sternal wires, double sternal wires, braided poly(ethylene terephthalate) sutures, single-wrapped mesh sutures, or double-wrapped mesh sutures. To simulate chest-wall forces, closed sternal models were pulled apart using 1020 N of axial force applied incrementally. Double sternal wire and double-wrapped mesh suture were further compared by closing 3 new models with each material and subjecting these models to cyclic loading cycles, simulating breathing and coughing. Image analysis of needle hole size measured “bone cutting” by each closure material and sternal distraction as a function of force.

Results: All models exhibited maximal separation at the xiphoid. During axial loading, needle hole size increased 7.2% in the double-wrapped mesh suture model and 9.2% in the double-wire model. Single-wrapped mesh suture, single wires, and braided poly(ethylene terephthalate) extended needle hole size by 6.7%, 47.0%, and 168.3% of original size, respectively. The double-wire model resisted sternal distraction best, separating 0.285 cm at the xiphoid. During cyclic loading, mesh suture exhibited significantly less bone cutting ($P = .02$) than double wire, with comparable levels of sternal separation ($P = .07$).

Conclusions: Mesh suture may resist bone cutting seen in sternal wire closure in bone models with comparable distraction to currently used sternal closure methods. (*JTCVS Techniques* 2023;20:130-7)



A novel mesh suture may decrease sternal bone cutting.

CENTRAL MESSAGE

A novel mesh suture demonstrates decreased bone cutting and may decrease sternal dehiscence when used for closure in comparison with standard wire fixation.

PERSPECTIVE

Sternal wound dehiscence carries high rates of morbidity and mortality. Wire-based closures fail due to bone cutting, which leads to sternal separation, instability, and infection. We tested a novel mesh suture that flattens orthogonal to the line of force. Less bone cutting was observed than with wire closures. Use of mesh suture-based sternal closures may decrease the risk of sternal dehiscence.

Median sternotomy dehiscence has reported incidence rates of up to 5% and associated morbidity/mortality rates of 10% to 40% due to elevated risk for deep sternal wound

infections and mediastinitis.^{1,2} Previous reports demonstrate separation after sternal closure with wires occurs mostly due to lateral separation forces and wire cutting through bone. This allows substantial motion, sternal separation, and infection risk (Figure 1).^{3,4}

Studies of a novel mesh suture have demonstrated greater strength and resistance to pull-through than standard suture for abdominal wall closure in a cadaveric porcine model. The increased diameter of the mesh suture (4.1 mm that can flatten to 6 mm) in comparison with a standard 1 polypropylene suture (0.5 mm diameter suture that does not deform to lateral stress) is responsible for its superior force distribution.⁵ An in vivo porcine model using mesh suture also demonstrated numerically fewer hernias and improved outcomes in comparison with standard polypropylene

From the Divisions of ^aCardiac Surgery, and ^bPlastic Surgery, Department of Surgery, Northwestern University Feinberg School of Medicine, Chicago, Ill.

Funding for sternal models was provided by Northwestern University Feinberg School of Medicine Division of Cardiac Surgery and the Bluhm Cardiovascular Institute.

Mesh suture was provided gratis by the MSI.

Received for publication March 16, 2023; revisions received May 26, 2023; accepted for publication June 7, 2023; available ahead of print June 20, 2023.

Address for reprints: S. Christopher Malaisrie, MD, Northwestern Memorial Hospital, Arkes Family Pavilion Suite 730, 676 N. Saint Clair St, Chicago, IL 60611 (E-mail: chris.malaisrie@nm.org).

2666-2507

Copyright © 2023 The Author(s). Published by Elsevier Inc. on behalf of The American Association for Thoracic Surgery. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

<https://doi.org/10.1016/j.jtc.2023.06.002>

Abbreviations and Acronyms

DWM = double-wrapped mesh suture
SWM = single-wrapped mesh suture

suture.⁶ Given these properties, we investigated, in an *in vitro* model, whether sternal closure with mesh suture could resist the bone cutting seen with standard wire closures.

METHODS

Median sternotomies were performed on 5 sternal bone models (Sawbones USA, SKU 1025-2) with densities of 320 kg/m³; literature reports average sternal densities of women and men in their 60s to be 160 kg/m³ and 227 kg/m³, respectively. Each sternotomy was then closed using 8 interrupted (1) single stainless-steel wires (A&E Medical Corporation), (2) double stainless-steel wires (A&E Medical Corporation), (3) braided poly(ethylene terephthalate) sutures (#5 MERSILENE; Ethicon, LLC), (4) number 2 single-wrapped mesh sutures (SWM), or (5) number 2 double-wrapped mesh sutures (DWM). All sternal wire used was #6 (8 metric) sternal wire.

Number 2 Duramesh Mesh Suture (Mesh Suture Inc) is made of 18 polypropylene filaments that are braided and bonded to create a single device. Each polypropylene filament is the size of a 4-0 standard polypropylene suture. Nonsterilized mesh suture was provided gratis by the company; no representative from the company was involved in testing or generation/interpretation of results.

All models were closed according to our institutional practice, using 2 wires/sutures in the manubrium, 5 around the interrib spaces, and 1 in the xiphoid. All manubrial and xiphoid needle holes were made using a 48-mm conventional cutting needle (double-wire needle) (Sternum Suture Kit; A&E Medical Corporation) to standardize bone-cutting measurements, with the implants threaded through these holes. Each sternal model was used to test one closure configuration; models were not reused.

Before testing, pictures were taken of the models and image analysis (ImageJ 1.53; National Institutes of Health) was used to quantify needle hole size. Markings were made on each hemisternum approximately every 1 cm apart to facilitate ease of measurement of sternal distraction.



FIGURE 1. Representative image of a dehiscenced sternal closure with double wire, demonstrating how double wire had cut through bone to allow sternal separation. Note that the location of bone cutting in this image does not necessarily reflect locations of measurement in our experimental model.

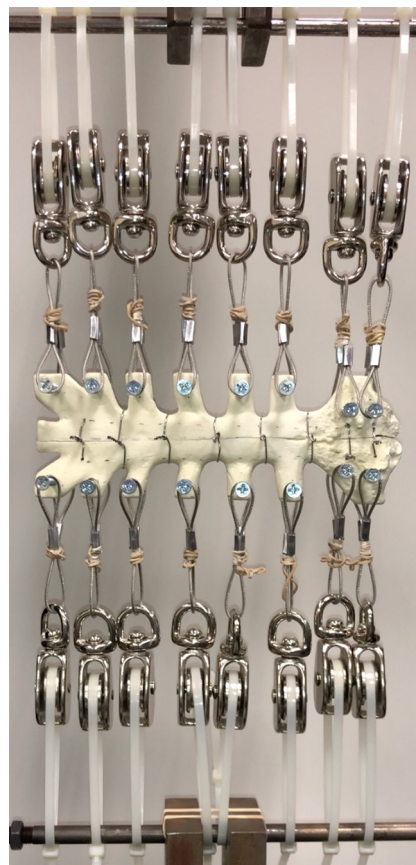


FIGURE 2. Experimental set-up used to laterally distract sternal models. Each model was distracted using 1020-N separation force applied in 60-N increments.

Each sternal model was then attached to an MTS Criterion 100 kN load cell at Northwestern University using a series of pulleys and zip ties (Figure 2). Our experimental model was based on sternal biomechanical testing setups used by other groups to gauge efficacy of sternal closure.⁷ Under live force monitoring, each zip-tie was tightened until the point where further tightening would result in force traversing the sternal model. This was done to ensure all force applied by the load cell would be translated directly to the sternal model and closure mechanism. Eight anchoring pegs in each hemisternum were used to distribute force evenly across the length of each model.

To simulate chest wall forces acting on the sternum, the MTS Criterion 100 kN load cell was used to pull apart each model using 1020 N (104 kg) of force applied in 60-N increments (Figure 2). A 1020-N cutoff was chosen as an approximation of distending pressure applied on the sternum during a moderately-sized cough, based on current literature.⁸ The load cell separated models at a rate of 0.21 mm/s and paused for 10 seconds at each 60-N interval to allow settling of the model. The set-up was designed such that the load-cell exerted only linear force across the sternal closure. Any oscillation and movement of the model was allowed to subside over the 10-second pause at each force interval. Images of the sternal model were taken at each 60-N mark, and post-hoc image analysis was used to measure primary outcomes of needle hole size expansion (2-dimensional area of needle hole after wire/suture removal) and sternal separation (distance between pre-made marks on each hemisternum) versus force. Separation was measured at the manubrium, between the fourth and fifth rib, and at the xiphoid process where possible.

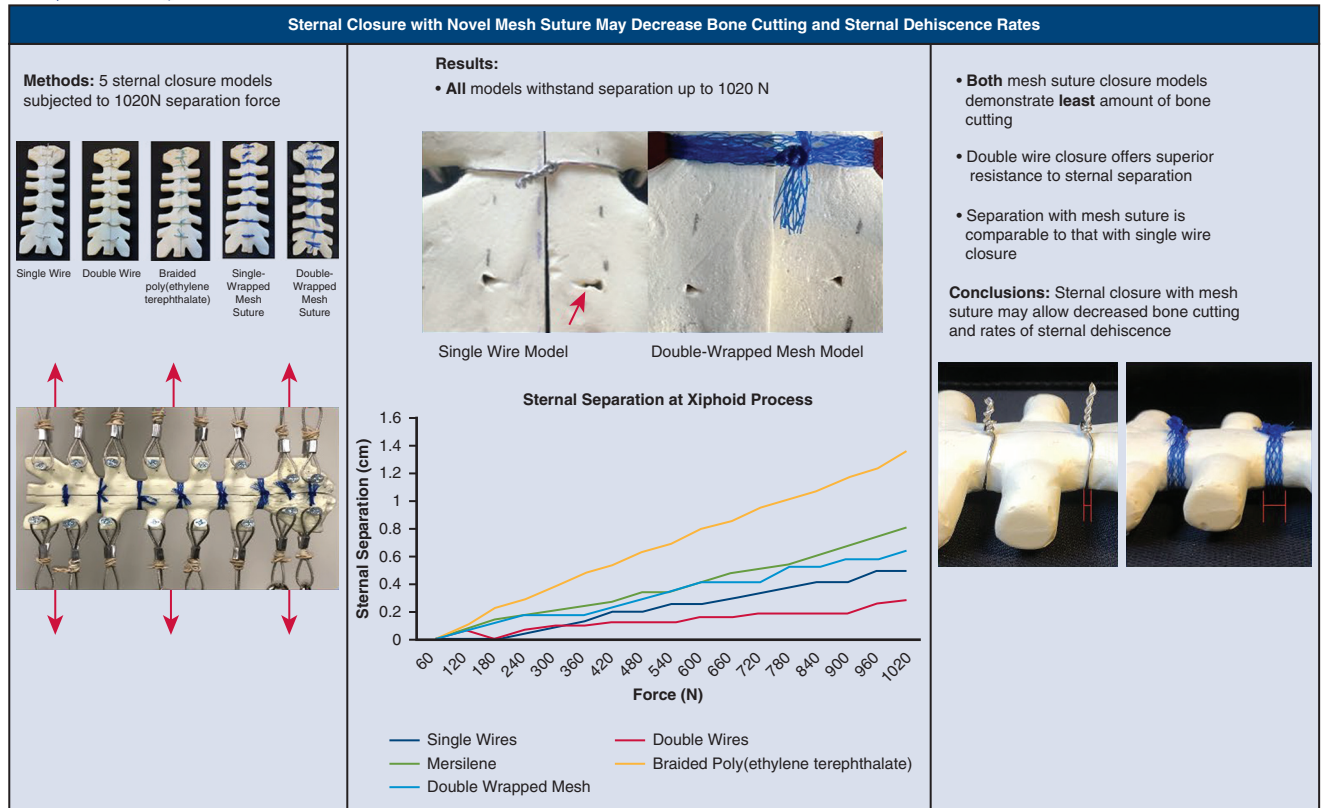


FIGURE 3. Five sternal models—each closed with single wires, double wires, braided poly(ethylene terephthalate), or double-wrapped mesh sutures—were subjected to 1020 N of separation force in increments of 60 N (left panel). Although all sternal models were able to sustain the force, both mesh suture models demonstrated the least amount of bone cutting under load. The double-wire closure demonstrated the least amount of sternal separation at a 1020-N load.

To increase reliability of results, a second round of testing was performed directly comparing closures with double wires and DWM. Six new sternal models of lower-density 240 kg/m³ (SKU: 1025-26), modeling weaker/osteoporotic bone, were closed using the same configuration. Three double sternal wire models and 3 DWM models were subjected to 5 rounds of cyclic loading between 10 and 400 N to simulate breathing followed by 3 rounds of cyclic loading between 10 and 1650 N to simulate maximal distension during coughing. These parameters were chosen based on published reviews quantifying forces applied on the sternal midline during breathing and coughing.⁸ Needle hole size expansion and sternal separation were measured as described previously.

All reported data were from direct measurements or averages of available measurements. Statistical analyses were performed using paired *t*-tests to compare means of continuous variables of needle hole size and sternal separation.

RESULTS

During axial loading of the 320 kg/m³ models, all sternal models withstood 1020 N of separation force without failure. Both mesh suture models demonstrated the least amount of needle hole size expansion, only increasing 6.7% from baseline in the SWM model and 7.2% in the

DWM model (Figure 3). The double wires extended needle hole size by 9.2%, single wires by 47.0%, and braided poly(ethylene terephthalate) by 168.3% of original size (Figure 4). The inter-rib spaces had mild indentations noted for all groups. As there was no circular “hole” as a starting point for measurement, we were unable to quantify these indentations.

For all models, the point of maximal distraction was at the xiphoid process and the point of least distraction was at the manubrium. The double-wire model resisted sternal distraction the most, separating only 0.285 cm at the xiphoid under 1020 N of force. The next strongest closures, in order, were the single wires, DWM, braided poly(ethylene terephthalate), and SWM with maximal xiphoid separations at 1020N of 0.495 cm, 0.639 cm, 0.814 cm, and 1.361 cm, respectively (Figure 5).

Sternal distraction was least at the manubrium for the double-wire model. For all other models, distraction was least at the midpoint of the sternal body (between the fourth and fifth rib). Distraction at manubrium, from least to most,

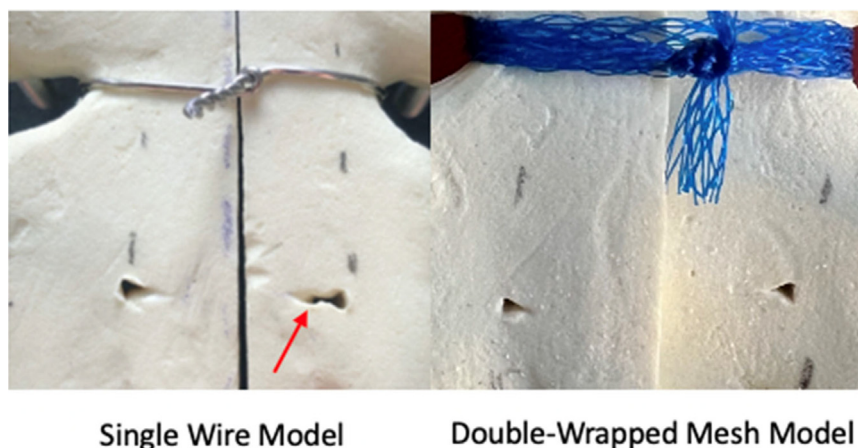


FIGURE 4. Visible bone cutting in single-wire closure model (*left, red arrow*) compared with minimal visible bone cutting in double-wrapped mesh suture model (*right*).

was 0.032 cm, 0.165 cm, 0.581 cm, 0.645 cm, and 1.013 cm for the double-wire, single-wire, DWM, braided poly(ethylene terephthalate), and SWM models, respectively. Distraction at midpoint of the sternal body, from least to most, was 0.083 cm, 0.095 cm, 0.523 cm, 0.543 cm, and 0.950 cm for the single-wire, double-wire, DWM, braided poly(ethylene terephthalate), and SWM models, respectively. Overall, the DWM models demonstrated less sternal distraction with slightly greater bone cutting (7.2% vs 6.7%) as compared with the SWM models.

During cyclic loading of the lower density (240 kg/m³) models, all models were tested until model failure. All models failed from tearing of the bone away from the load cell attachment rather than failure of the sternal closure method. Failure occurred near 600 N of force. On average, double-wire model needle hole size increased by 17.0% following testing. This was significantly greater than the 7.4% average needle hole size expansion noted across the DWM models ($P < .01$). During breathing simulations, the double-wire models noted average maximal separations of 0.007 and 0.009 cm at the midpoint and xiphoid, respectively. This increased to 0.031 and 0.029 cm, respectively, during coughing simulations. Likewise, the DWM models demonstrated average maximal separations of 0.068 and 0.036 cm during breathing simulations and 0.322 and 0.116 cm during coughing simulations. We were unable to quantify sternal separation at the manubrium, given failure of the model attachment mechanism. There was no significant difference in measured sternal separation between the 2 closure methods ($P = .07$).

DISCUSSION

The use of polypropylene mesh as a tissue approximation device has recently exhibited considerable success in closing high tension abdominal wall defects.⁹ These successes are attributed to superior force distribution at the suture/

tissue interface that limits tissue tearing and suture pull-through (Figure 6).⁵ Our experimental results demonstrate the least amount of bone cutting when using mesh suture sternal closures, consistent with this force-distribution theory. In abdominal models, histologic examination of porcine models reveals the individual filaments to flatten orthogonal to the direction of force—a visual explanation for resistance to pull-through (Figure 7). In our sternal model, the mesh suture clearly flattens in each of the rib interspaces (Figure 6). Preclinical animal experiments for mesh suture demonstrate fibrovascular incorporation of the mesh at 8 and 90 days.¹⁰ This forms a scar scaffold that both increases the strength of repair over time and contributes to tolerance against bacterial contamination.¹¹ Meanwhile, there is no comparable scar magnification achieved by solid wires and suture tapes that encapsulate rather than incorporate bone elements. For sternal wiring, the increase in bone strength occurs over months as opposed to days.¹² Further, the inflammatory response from encapsulated foreign bodies may be a cause of local pain after median sternotomy. These advantages highlight why this porous mesh suture may be favored in sternal closure, where considerable morbidity, mortality, and resource use may occur if sternal wires pull through bone.⁸

The main limiting factor in adoption of mesh suture in sternal closure may be its ability to resist sternal distraction. Casha and colleagues¹³ report that any suitable sternal closure technique must be able to withstand twice the maximum potential stresses applied on the sternum. At both breathing-level and maximal forces, SWM and DWM models exhibited greater distraction in high-density models than either wire-based closure. In contrast, low density models, though limited by model failure, demonstrated indifferent maximal distraction ($P = .07$) for wire and mesh closures with significantly less bone cutting in the DWM closure. Replication of these results with

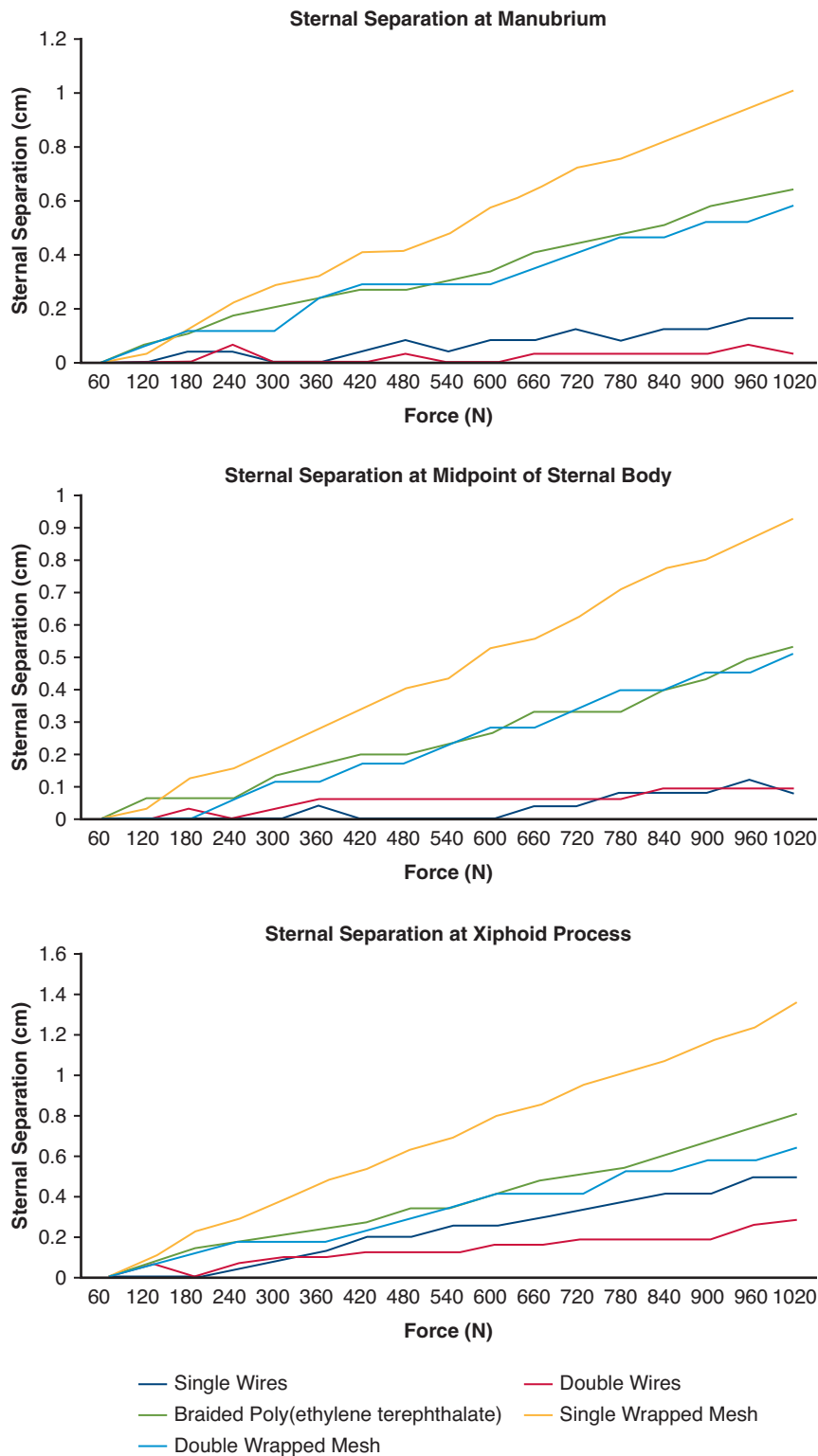


FIGURE 5. Sternal distraction (centimeters) versus force (N) for the 5 sternal closure models. Sternal distraction was greatest at the xiphoid for all models. Double-wire closure demonstrated the least sternal separation at the xiphoid at 1020-N force. Although the single-wrapped mesh suture model had a notably low resistance to distraction, the double-wrapped mesh suture model had a much greater resistance to distraction that approached results seen with braided poly(ethylene terephthalate) or single-wire closure.

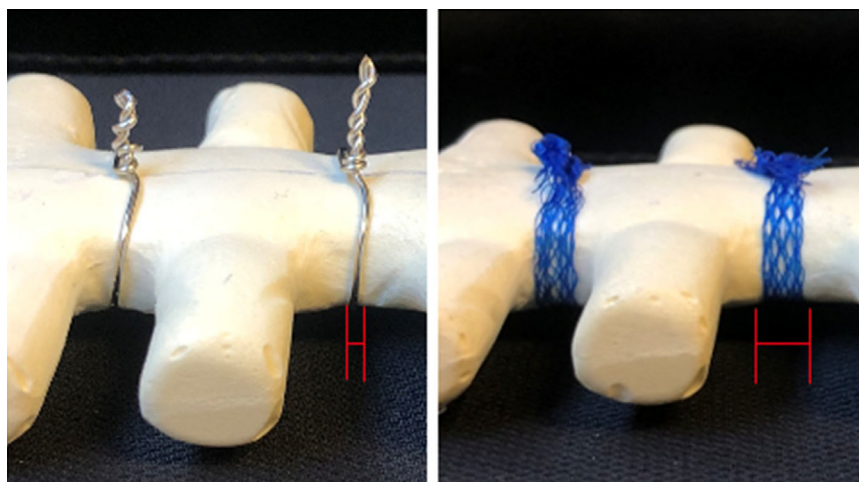


FIGURE 6. Profile view of single-wire sternal closure and single-wrapped mesh sternal closure. The highlighted increased area over which force is distributed in mesh-based closures may be what contributes to decreased bone cutting in these models.

larger sample sizes is warranted. Our results of least (best) sternal separation with wire-based closures likely reflects the rigid fixation/reduction provided by inelastic sternal wires and may be beneficial to late-stage bone healing.¹²

Compliance of the closure method must also be considered. A sternal wire closure that separates will not re-tighten when the force dissipates. The stiff wire has cut through the bone, and the bone will not remain opposed. In comparison, a sternum closed with mesh suture that separates would be expected to automatically reapproximate, as the gapping occurs with a temporary and reversible elongation of the suture. Cyclic loading of mesh suture in outside tests has not been shown to cause early

device fatigue and failure. This is especially advantageous in the setting of osteomyelitis, where infection causes prevents proliferation, induces apoptosis, and inhibits mineralization of osteoblasts in addition to causing direct bone destruction.¹⁴ Within more porous and infected bone, it is possible that this elasticity of the mesh suture, combined with flattening of the suture around the sternum (specifically in the mid-sternum), allows the sternum to expand when infected while preventing garroting seen in fractures of the mid-sternum (Figure 5).

Significant variability exists in sternal closure methods today, with many surgeons advocating for different methods based on individual technique and comfort level.¹⁵⁻¹⁷ Some

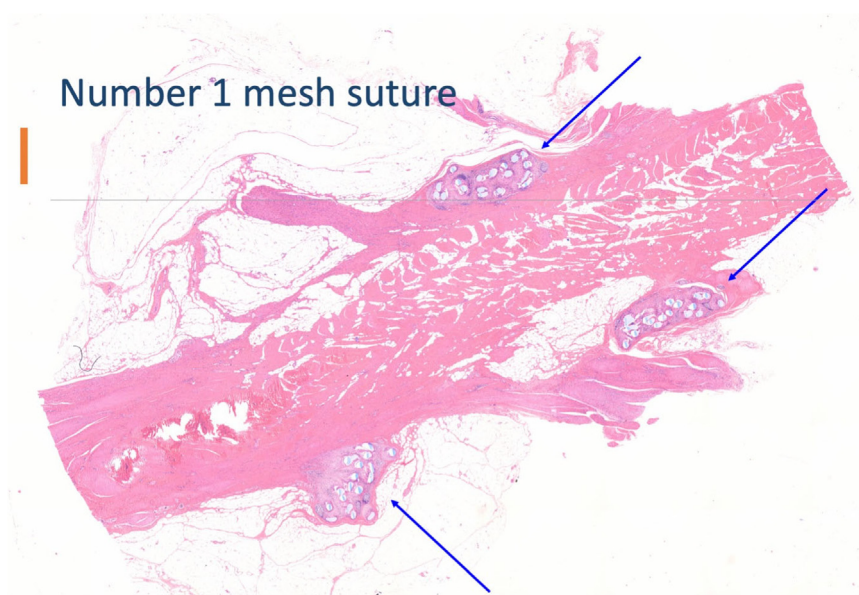


FIGURE 7. Histologic examination of abdominal closure in porcine models reveals the mesh suture flattening orthogonal to the direction of force and mesh suture incorporation into tissue scaffold.

surgeons favor figure-of-8 and interlocking multitwisted wire closures for better strength and decreased bone cutting, whereas others cite no advantage over simple interrupted closures.¹⁸⁻²¹ Certain groups also claim “increasing the number of wires is the answer to the problem of sternal dehiscence.”¹³ Conceptually, this approach aims to better distribute forces to reduce individual wires from cutting through bone.²² Recent closure methods that have capitalized on improved force distribution include the sternal Zip-Fix (Synthes GmbH) and Sternal Talon (KLS Martin Group) systems, which use zip-ties and hooks, respectively, to further improve force distribution²² and produce minimal rates of sternal instability/dehiscence.^{23,24} Other closure options include combinations of closure materials to individually tailor closure methods to high-risk patient groups. For example, a Japanese group recently supplemented wire closure in patients with osteoporosis with mesh placed over and under the sternum, which they report reduces sternal instability.²⁵ If mesh suture is used for sternal closure, all of these variables (wire configuration, number of sutures, and combinations of closure methods) may affect the performance of the mesh and would warrant testing before application in patients. For example, a combination sternal closure with DWM and double wires may capitalize on the advantages of each material.

Our study includes limitations inherent to a small sample size. The experimental model itself is limited in how accurately it replicates the distribution of forces placed on actual sternums, as only uniplanar motion was assessed in this study. Although our model was designed to distribute force equally along the entire length of the sternum, it is possible that actual force distribution along the length of the sternum is nonuniform. In addition, the model used in this pilot study was not designed to quantify bone cutting in the mid-sternum, a common location for bone cutting and dehiscence. Further, healthy and infected osteoporotic bone may behave differently. While elasticity of sternal closure may be beneficial in infected bone,²⁶ it may slow healing in healthy bone, given permissance of increased distraction.¹⁸ Delineating these effects would require in vivo analyses that permit tissue incorporation of the suture and will allow evaluations of bone healing. In addition, the model failure exhibited by lower-density models may introduce variability in our finite measurements of sternal separation; one would expect these variations, however, to be consistent across all the low-density models. Further studies should involve redesigning of the experimental set-up to better secure sternal models while selectively directing applied force across the closure element. Combinations of sternal closure devices (ie, wires and mesh suture) in addition to comparisons of wire cerclage methods to newer zip tie/plating-based closures may also be included.

The ideal sternal closure method has yet to be determined. Our results show potential for mesh suture-based

sternal closure to reduce bone cutting and thus potentially reduce rates of sternal dehiscence. However, further testing of mesh-based closures and improvement in resistance to sternal distraction are warranted before incorporation of mesh suture into the armamentarium of sternal closure options today.

Conflict of Interest Statement

Dr Dumanian is the founder of MSi, the manufacturer of mesh suture, and stands to gain from this line of inquiry. All other authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

References

- Casha AR, Manche A, Gatt R, Duca E, Gauci M, Schembri-Wismayer P, et al. Mechanism of sternotomy dehiscence. *Interact Cardiovasc Thorac Surg.* 2014;19:617-21.
- Kaul P. Sternal reconstruction after post-sternotomy mediastinitis. *J Cardiothorac Surg.* 2017;12:94.
- Sargent LA, Seyfer AE, Hollinger J, Hinson RM, Graeber GM. The healing sternum: a comparison of osseous healing with wire versus rigid fixation. *Ann Thorac Surg.* 1991;52:490-4.
- McGregor WE, Trumble DR, Magovern JA. Mechanical analysis of midline sternotomy wound closure. *J Thorac Cardiovasc Surg.* 1999;117:1144-50.
- Scheiber CJ, Kurapaty SS, Goldman SM, Dearth CL, Liacouras PC, Souza JM. Sutureable mesh better resists early laparotomy failure in a cyclic ball-burst model. *Hernia.* 2020;24:559-65.
- Dumanian GA. Sutureable mesh demonstrates improved outcomes over standard suture in a porcine laparotomy closure model. *Plast Reconstr Surg Glob Open.* 2021;9:e3879.
- Pai S, Gunja NJ, Dupak EL, McMahon NL, Coburn JC, Lalikos JF, et al. A mechanical study of rigid plate configurations for sternal fixation. *Ann Biomed Eng.* 2007;35:808-16.
- Alhalawani AM, Towler MR. A review of sternal closure techniques. *J Biomater Appl.* 2013;28:483-97.
- Kearney AM, Dumanian GA. Simplified repair of traumatic iliac crest flank hernias with mesh strips. *Plast Reconstr Surg Glob Open.* 2020;8:e2970.
- Lanier ST, Dumanian GA, Jordan SW, Miller KR, Ali NA, Stock SR. Mesh sutured repairs of abdominal wall defects. *Plast Reconstr Surg Glob Open.* 2016;4:e1060.
- Dumanian GA, Tulaimat A, Dumanian ZP. Experimental study of the characteristics of a novel mesh suture. *Br J Surg.* 2015;102:1285-92.
- Raman J, Lehmann S, Zehr K, De Guzman BJ, Aklog L, Garrett HE, et al. Sternal closure with rigid plate fixation versus wire closure: a randomized controlled multicenter trial. *Ann Thorac Surg.* 2012;94:1854-61.
- Casha AR, Yang L, Kay PH, Saleh M, Cooper GJ. A biomechanical study of median sternotomy closure techniques. *Eur J Cardiothorac Surg.* 1999;15:365-9.
- Lio P, Paoletti N, Moni MA, Atwell K, Merelli E, Viceconti M. Modelling osteomyelitis. *BMC Bioinf.* 2012;13:S12.
- Sharma R, Puri D, Panigrahi BP, Virdi IS. A modified parasternal wire technique for prevention and treatment of sternal dehiscence. *Ann Thorac Surg.* 2004;77:210-3.
- Roux D, Fournial G, Glock Y, Nottin R. New technique for sternal osteosynthesis. *Ann Thorac Surg.* 1995;60:1132.
- Allen KB, Thourani VH, Naka Y. The right wiring configuration for sternal closure: science or mythology? *J Thorac Cardiovasc Surg.* 2017;154:2004-5.
- Krejca M, Szmagała P, Skarysz J, Bochenek K, Ulczok R, Bis J, et al. Force distribution in wire sternum sutures: the consequences for sternal closure rigidity. *Med Sci Monit.* 2003;9:BR134-44.
- Shafi AMA, Abuelgasim E, Abuelgasim B, Iddawala S, Harky A. Sternal closure with single compared with double or figure of 8 wires in obese patients following cardiac surgery: a systematic review and meta-analysis. *J Card Surg.* 2021;36:1072-82.

20. Khasati N, Sivaprakasam R, Dunning J. Is the figure-of-eight superior to the simple wire technique for closure of the sternum? *Interact Cardiovasc Thorac Surg*. 2004;3:191-4.
21. Ramzisham AR, Rafliis AR, Khairulasri MG, Ooi Su Min J, Fikri AM, Zamrin MD. Figure-of-eight vs. interrupted sternal wire closure of median sternotomy. *Asian Cardiovasc Thorac Ann*. 2009;17:587-91.
22. Cataneo DC, Dos Reis TA, Felisberto G, Rodrigues OR, Cataneo AJM. New sternal closure methods versus the standard closure method: systematic review and meta-analysis. *Interact Cardiovasc Thorac Surg*. 2019;28:432-40.
23. Grapow MT, Melly LF, Eckstein FS, Reuthebuch OT. A new cable-tie based sternal closure system: description of the device, technique of implantation and first clinical evaluation. *J Cardiothorac Surg*. 2012;7:59.
24. Levin LS, Miller AS, Gajjar AH, Bremer KD, Spann J, Milano CA, et al. An innovative approach for sternal closure. *Ann Thorac Surg*. 2010;89:1995-9.
25. Morimoto K, Matsushita T, Masuda S, Kurata A. The novel technique of sternal closure with absorbable mesh for osteoporotic patients. *Heart Lung Circ*. 2021;30:e65-7.
26. Price J, Rubens F, Bell M. Elastic device facilitating delayed primary closure of sternal wound infection. *Ann Thorac Surg*. 2007;83:1162-5.

Key Words: sternal closure, sternal dehiscence, sternal wound, mesh suture, deep sternal wound infection