Investigating Potential Role of Surgeons in Sternal Wire Failure by Biomechanical Tests

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Abstract

Background: Stainless steel wires are commonly used to close the sternum after cardiac-related operative procedures. However, complications have been reported associated with fracture of wires and subsequent migration into the chest cavity. The objective of this study was to biomechanically evaluate the role of surgeons in contributing to wire failure. We hypothesized that surgeons may impose damage to the sternal wire, which may be exacerbated by postoperative wire degradation and patient movement.

Methods: A biomimetic sternal model and custom test fixture simulated a median sternotomy. The sternum was closed by a fellowship-trained cardiothoracic surgeon using figure-of-eight and simple closure techniques. Closures were completed using No. 7 gauge wires made of 316 L stainless steel. Force data were collected at each costal cartilage level (six or eight levels), at each closure stage (three or two stages), for all 10 figure-of-eight and simple closures (n = 20 bones), respectively. Post hoc analysis of ultimate tensile stress in the wires determined potential for failure.

Results: The mean (SD) force for all tests was 220.5 N (59.4 N) using the figure-of-eight technique and 182.8 N (79.5 N) using the simple technique. The mean ultimate stress in the wires was 346 MPa and 286 MPa for figure-of-eight and simple techniques, respectively. We found that a significant number of observed forces exceeded the yield strength of the wire during closure (figure-of-eight, 126 of 178; simple, 73 of 160).

Conclusions: Weakened areas of the wire likely define the locations of wire fracture, initiated by the surgeon, but exacerbated by wire degradation or patient movement.

Introduction

Median sternotomy is the most common procedure performed for open-heart cardiac operations. The sternum is cut longitudinally and the sternal halves are separated to allow access to the chest cavity. After the procedure, the sternum is traditionally closed with stainless steel wires. However, numerous complications have been reported when the wires fracture, causing migration of wires into cardiac chambers, great vessels, and the abdomen.[1-10] Several studies have focused on wire degradation and corrosion or patient movement as the reason for failure of sternal wires, which has resulted in those complications.[11-18] This process may be exacerbated by wire degradation caused by long-term implantation or postoperative movement of patients.

Furthermore, during closure of the sternum, surgeons typically exert axial forces on the wire. These force-based loads may introduce mechanical stresses that exceed the yield strength of the wire material (ie, point at which the material begins to permanently deform, but not fail), thereby weakening the wire. To our knowledge, no research has examined the role of surgeons in sternal wire failure. Furthermore, no studies have quantified the axial force applied by surgeons during placement of sternal wires.

We evaluated the potential role of surgeons in contributing to wire failure by measuring axial forces applied to sternal wires. Forces were placed by a fellowship-trained cardiothoracic surgeon using figure-of-eight and simple closure techniques until appropriate approximation of sternal edges was found. We hypothesized that surgeons may impose damage to sternal wires during operative procedures.

Methods

All tests were performed using a biomimetic sternum specially designed by the manufacturer with a density of 50 pcf (Sawbones, Pacific Research Laboratories, Vashon Island, WA) and included the manubrium, xiphoid process, and costal cartilage. The model was divided midline using a bandsaw to simulate a median sternotomy.

A custom test fixture was designed to simulate sternal attachment to ribs and provide resistance to re-approximation of the bones (Figure 1). The fixture used a crossed-rail system, which allowed for lateral movement of the sternal halves during re-approximation (ie, along the y-axis) and superior-inferior positioning of the sternum for placing each closure level over the load cell during repair (ie, along the x-axis). The sternal halves were fixed to the testing apparatus through the manubrium and most distal costal cartilage. Lateral forces were applied using medium strength TheraBand, held taut before closure, to replicate the forces exerted by the pectoral muscles (The Hygenic Corporation, Akron, OH). The testing apparatus was rigidly attached to a 15-kN axial load cell for testing. An MTS FlexTest 100 controller and Basic Testware software recorded the force applied during the procedure (MTS Systems, Eden Prairie, MN).

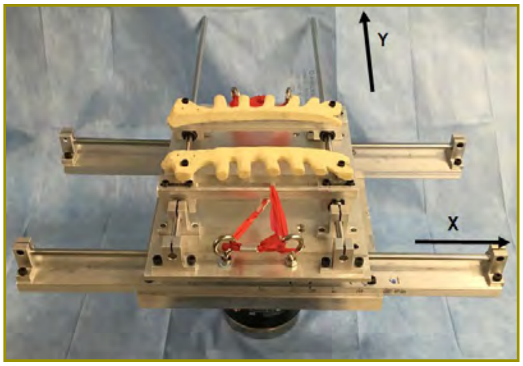

Figure 1. Experimental test setup showing sternal halves positioned in the custom designed testing fixture. A force of 15 kN is positioned under the fixture to collect data on applied axial load during closure.

The sternum was closed by a fellowship-trained cardiothoracic surgeon using six or eight wires for the figure-of-eight and simple closure techniques, respectively. All closures were completed using No. 7 surgical steel wires made of 316 L stainless steel, with ultimate tensile strength and yield strength at 515 MPa and 205 MPa, respectively (ASM Aerospace Specification Metals, Inc, Pompano Beach, FL). Placement of wires for the figure-of-eight closure began near the xiphoid process and ended at the manubrium. Placement of wires for the simple closure began at the manubrium, ending near the xiphoid process.

During testing, the data collection was segmented by stages of closure. The figure-of-eight closures had three stages: approximation, initial twist, and slack. The approximation stage involved the positioning of the wires into their appropriate locations and crossing the wires over the sternum to secure positions. The initial-twist stage included wire tensioning and an initial twist was placed in each individual wire. The slack stage involved the twisting of the wires until the sternotomy had been appropriately re-approximated. Two stages composed the simple closures: initial twist and slack. Ten full sternal closures (ie, experiments) were performed using each closure technique. Force data were collected at each level of costal cartilage (six or eight levels) and closure stage (there or two stages) for all 10 figure-of-eight and simple closures (n = 20 bones), respectively. Maximum applied axial force for each test was recorded. A one-way analysis of variance (commonly known as ANOVA) with the Tukey honestly significant difference (HSD) post hoc test was used to compare all experiments, wires, and stages for each closure type.

Results

The data for two wires in the approximation stage of a single sternum (experiment) fixed with figure-of-eight wire were not collected because of controller error, and 344 of 346 independent maximum force observations were collected for analysis (178 figure-of-eight, 160 simple). Owing to large sample size, only relevant post hoc significances were reported.

Figure-of-Eight Technique

The force (SD) for all combined tests was 220.5 N (59.4 N). Results of ANOVA testing showed statistically significant differences in force between experiments (P = 0.0001), wires (P = 0.01), and stages (P = 0.0001). Applied forces in experiments one, two, and three were lower than in all other experiments except five (Figures 2A and 2B). Applied forces for placement of wires one and two were lower than required for placement of wire six (Figures 3A and 3B). Forces applied in the initial twist stage were lower than those applied in the approximation and slack stages (Figures 4A and 4B).

Simple Technique

The force (SD) for all combined tests was 182.8 N (79.5 N). Results of ANOVA testing showed statistically significant differences in applied force between experiments (P = 0.01) and stages (P = 0.0001). Force in experiment one was lower than the measured force in experiment two. Additionally, the forces applied in the initial-twist stage were lower than those applied in the slack stage.

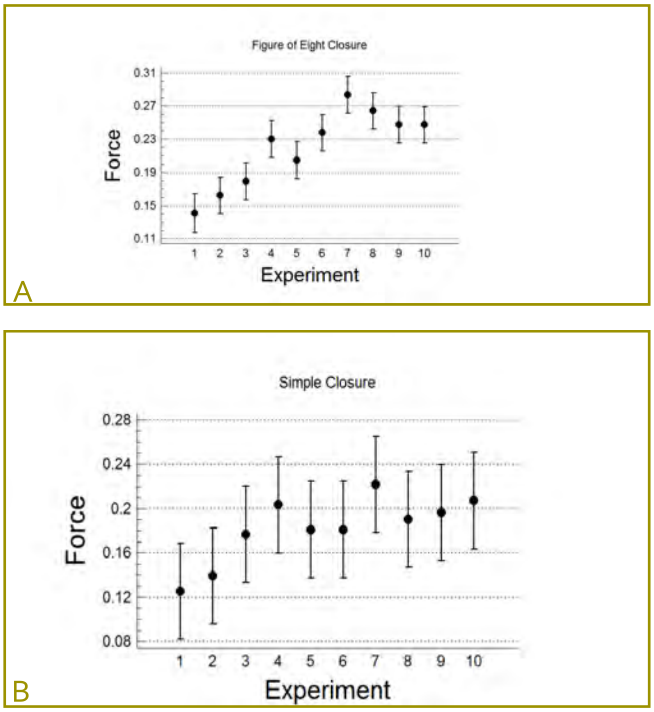

Figure 2. Means and 95.0% Tukey honest significant difference intervals of force (kN) by experiment for (A) figure-of-eight and (B) simple closures. Results include data for all wires and stages for each experiment.

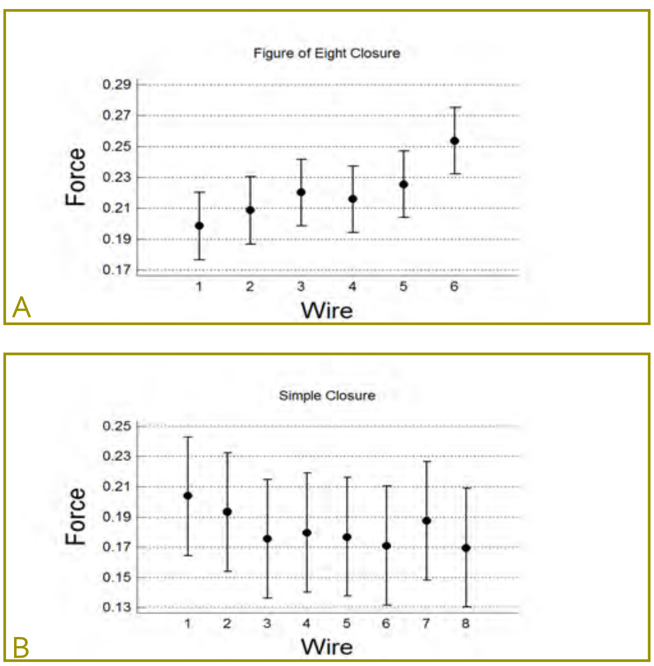

Figure 3. Means and 95.0% Tukey honest significant difference intervals of force (kN) by wire for (A) figure-of-eight and (B) simple closures. Results include data from all stages and experiments.

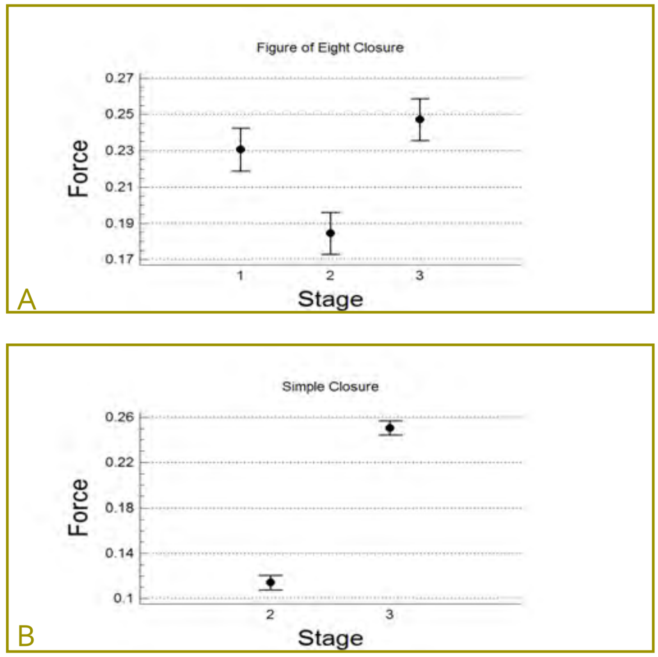

Figure 4. Means and 95.0% Tukey honest significant difference intervals of force (kN) by stage for (A) figure-of-eight and (B) simple closures. Results include all wires across all experiments at each stage.

Ultimate Stress in Wires

Knowing the maximum loads of each observation (n = 344) and the cross-sectional area of the No. 7 surgical steel wire (0.9 mm), the ultimate tensile stress applied to each wire was calculated using the following equation for uniaxial loads:

$$\sigma = \frac{F}{A}$$

$$\text{where } \sigma = \text{tensile stress}, F = \text{instantaneous ultimate force, and}$$

$$A = \text{instantaneous cross sectional area}$$

The mean ultimate tensile stress applied was 346 MPa and 286 MPa for figure-of-eight and simple wires, respectively.

Discussion

Significant difference was minimal in applied force by wire between techniques. Notably, wires that experienced the highest applied force were placed in the region of the manubrium. The wires placed in the manubrium passed through the bone and experienced greater resistance when being pulled tightly to approximate the sternal halves during stage three of closure. Sternal wires placed around the sternal body were subject to less friction when pulled.

In comparing stages of each technique, the slack stage required the greatest amount of force because it was the last stage of the procedure and tight approximation of sternal halves was required to prevent sternal dehiscence. The 95% Tukey HSD tests within each stage in the data collected were narrow, indicating a very consistent determination of re-approximation by the surgeon. The consistency is further demonstrated by the fact that the experiments were performed on different weeks.

The current study has several limitations. Statistically significant differences were observed in force by experiment between use of wires one, two, and three for figure-of-eight methods and wire one for simple techniques, which introduced a factor that was controlled for during testing. During the experiments, the surgeon was on the top step of a two-step stool but chose to step down to the first step for subsequent tests. He felt as if he would not be positioned so high above an actual patient when performing operative treatment. This height difference of 22.7 cm (9 in) resulted in a significant change in applied force by the surgeon, indicating that surgeon height may be a factor in the level of force and thereby the level of potential damage to the wire induced by use of the surgical technique. Height difference had less effect on the simple than figure-of-eight procedure.

Notably, in the currente study, post hoc calculation of the ultimate tensile stress applied to the wires. Mean ultimate tensile stress applied to figure-of-eight and simple wires was 286 MPa and 346 MPa, respectively. In comparison with ultimate tensile strength (515 MPa) and yield strength (205 MPa) of No. 7 stainless steel surgical wires, a significant number of observed forces exceeded the yield strength of the wire during closure (figure-of-eight, 126 of 178; simple, 73 of 160). Mechanically, any applied stresses that exceeded the yield strength of the wires were causing unrecoverable deformation to the material. These weakened areas of the wire likely define the locations of wire fracture, initiated by the surgeon, but exacerbated by wire degradation or patient movement. Further research may help investigatemclinical impact of the role of surgeons in sternal wire failure, with larger cohorts and alternative gauge wire commonly used for this procedure.

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Conflict of Interest

The authors report no conflicts of interest.

References

1. Imran Hamid U, Gillespie S, Lynchehaun C, Parissis H. Traumatic bilateral pneumothoraces due to sternal wire migration. Case Rep Med 2012;2012:438429.

2. Lee SH, Cho BS, Kim SJ, et al. Cardiac tamponade caused by broken sternal wire after pectus excavatum repair: a case report. Ann Thorac Cardiovasc Surg 2013;19(1):52-4.

3. Mieno S, Ozawa H, Katsumata T. Ascending aortic injury caused by a fractured sternal wire 28 years after surgical intervention of pectus excavatum. J Thorac Cardiovasc Surg 2010;140(1):e18-e20.

4: Stefani A, Morandi U, Lodi R. Migration of pectus excavatum correction metal support into the abdomen. Eur J Cardiothorac Surg 1998;14(4):434-6.

5. Rungatscher A, Morjan M, Faggian G. Sternocleidomastoid muscle hematoma due to sternal wire migration. J Card Surg 2011;26(3):296.

6. Al Halees Z, Abdoun F, Canver CC, Kharabsheh S. A right ventricle to aorta fistula caused by a fractured sternal wire. Asian Cardiovasc Thorac Ann 2007;15(5):453-4.

7. Levisman J, Shemin RJ, Robertson JM, Pelikan P, Karlsberg RP. Migrated sternal wire into the right ventricle: case report in cardiothoracic surgery. J Card Surg 2010;25(2):161-2.

8. Radich GA, Altinok D, Silva J. Marked migration of sternotomy wires: a case report. J Thorac Imaging 2004;19(2):117-9.

9. Schreffler AJ, Rumisek JD. Intravascular migration of fractured sternal wire presenting with hemoptysis. Ann Thorac Surg 2001;71(5):1682-4.

10. Hazelrigg SR, Staller B. Migration of sternal wire into ascending aorta. Ann Thorac Surg 1994;57(4):1023-4.

11. Chao J, Voces R, Peña C. Failure analysis of the fractured wires in sternal perichronal loops. J Mech Behav Biomed Mater 2011;4(7):1004-10.

12. Shih CM, Su YY, Lin SJ, Shih CC. Failure analysis of explanted sternal wires. Biomaterials 2005;26(14):2053-9.

13. Shih CC, Su YY, Chen LC, Shih CM, Lin SJ. Degradation of 316L stainless steel sternal wire by steam sterilization. Acta Biomater 2010;6(6):2322-8.

14. Tomizawa Y, Hanawa T, Kuroda D, Nishida H, Endo M. Corrosion of stainless steel sternal wire after long-term implantation. J Artif Organs 2006;9(1):61-6.

15. Wangsgard C, Cohen DJ, Griffin LV. Fatigue testing of three peristernal median sternotomy closure techniques. J Cardiothorac Surg 2008;3:52.

16. Cohen DJ, Griffin LV. A biomechanical comparison of three sternotomy closure techniques. Ann Thorac Surg 2002;73(2):563-8.

17. Losanoff JE, Collier AD, Wagner-Mann CC, et al. Biomechanical comparison of median sternotomy closures. Ann Thorac Surg 2004;77(1):203-9.

18. Losanoff JE, Basson MD, Gruber SA, Huff H, Hsieh FH. Single wire versus double wire loops for median sternotomy closure: experimental biomechanical study using a human cadaveric model. Ann Thorac Surg 2007;84(4):1288-93.