Factors influencing sternal healing and comparison of different sternal closure methods: a retrospective analysis

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Abstract

Background

We determined the factors affecting sternum healing after a median sternotomy based on a retrospective analysis; additionally, we compared the stability of different sternal closure techniques.

Methods

We collected information involving patients who underwent a median sternotomy in Changzhou First People's Hospital from 2014–2019 and who had chest CT examinations at 1–24 months post-operation. The main outcome included the average sternal healing score at the five specific anatomic levels and adverse events of transverse displacement of the sternum.

Results

In the short-term healing group, the sternal score was only correlated with postoperative time (HR = 0.18, 95% CI: 0.135–0.225, $p < 0.001$). In the long-term healing group, older people had a higher risk of poor sternal healing than young people (age, HR=-0.028, 95% CI: -0.05–0.006, $p = 0.013$). Patients with left internal mammary artery dissociation (LIMA-d) had a high risk of poor sternal healing (HR=-0.444, 95% CI: -0.869-0.019, $p = 0.045$). The binary logistic regression showed that steel wire fixation was a favorable factor for preventing transverse displacement of the sternum (HR = 0.122, 95% CI: 0.007–0.651, $p = 0.047$).

Conclusion

In summary, advanced age and internal mammary artery interception are risk factors that affect sternal healing, based on the imaging findings. This new method of sternal closure provides an effective way of ensuring sternal stability of both sternal plates and reduces the risk for complications after cardiac surgery in high-risk patients.

Introduction

Median sternotomy is one of the most common incision methods in heart surgery[1]. It provides excellent exposure of the heart, which is helpful for surgeons when they operate[2]. Currently, the main focus of research involves complications from median sternotomy, whereas sternum healing has not attracted widespread attention. Unlike the significant morbidity and mortality of postoperative sternal complications[3–5], poor sternal healing is more common in elderly patients[6]; however, most cardiothoracic surgeons overlook this problem because of its low risk. The morbidity of chronic pain after cardiac surgery, which has an adverse impact on health-related quality of life, has increased to 56%[7].

Moreover, a prospective study conducted by H. K. Gjeilo[8] showed that 3.8% of patients had chronic pain after 5 years. Additionally, the prophase of sternal healing is related to sternal complications. One of the causes of postoperative deep sternal wound infections is the malabsorption of sternal hematoma, which leads to failure to form an effective dead space[9–10]. Through the analysis of the factors affecting sternum healing, it is helpful to enact appropriate surgical methods and postoperative care that accelerate the prophase of sternal healing and that reduce the incidence of complications for the high-risk groups with poor sternum healing. The purpose of the study was to investigate the determinants of sternal healing and to estimate the effect of titanium plates (compared to the effect of wire cerclage) on sternal motion after cardiac surgery.

Methods

Study design

This retrospective study enrolled 122 patients who were examined with chest CT at one to twenty-four months after cardiac surgery at the Third Affiliated Hospital of Soochow University, Changzhou, China. Chest CT imaging that includes the whole sternum allows us to evaluate sternal healing after surgery. The inclusion criteria included patients aged 18–80 years undergoing elective cardiac surgery via a median sternotomy. The exclusion criteria included severe chronic obstructive pulmonary disease, histories of taking immunosuppressive drugs or autoimmune disease, histories of osteoporosis and bone dysplasia, histories of second thoracotomy, hemodialysis and placement of an aortic balloon regurgitation device during the perioperative period, and history of renal insufficiency. All of the patients were re-examined via chest CT scans one week after cardiac surgery, and sternal therapy was reduced well.

The examined baseline characteristics of the patients were as follows: sex, EF, history of hypertension, history of pulmonary hypertension, internal mammary artery injury, history of diabetes, body mass index (BMI), age, operative time, postoperative time, fixation method, cortical thickness (the average thickness of the anterior and posterior sternal cortex at the midline of the five specific anatomic levels), and sternal thickness (the average thickness of the sternum at the midline of the five specific anatomic levels). The main outcome included the average sternal healing score at the five specific anatomic levels and adverse events of transverse displacement of the sternum.

Surgical methods

The sternum was closed by one of the two following methods: titanium plates (Sternal Fixation System; Was-ton Medical Appliance Co. Ltd.), in which four plates are used in the first, second, third, and fourth or fifth intercostal spaces, and closure of the sternum with 5–7 metal wires (Surgical Stainless Steel Suture; Ethicon, LLC) in the form of a single interrupted suture or a figure-eight suture. Concerning the method of closure, the patients were divided into three groups (sternum plate groups, wire groups, and mixed fixation groups). The surface of the sternum was smeared with nonabsorbable bone wax to stop bleeding. A few patients received a new fixation method. Specifically, one half of the titanium plate was placed on one

side only where the region had been fixed with a 8-shaped steel wire; subsequently, the titanium plate around the 8-shaped steel wire allowed for a firm approximation of the two sternal halves, followed by the placement of the other half of the plate. The configuration of the plate around the wire prevented the wire from cutting through the bone and provided a 360-degree stabilization. After all of the plates and wires were secured, the soft tissue was closed with a 2 – 0 polybutylate-coated braided polyester suture, and the skin was closed with 4 – 0 polybutylate-coated braided polyester suture (ETHIBOND EXCEL, Shanghai, China).

Outcome measures

The endpoint of the study was sternal healing, which was determined by independent radiologists by using CT scans and a validated evaluation method. Five specific anatomic levels (☐: the manubrium, ☐: top of the aortic arch, ☐: aortopulmonary window, ☐: main pulmonary artery, ☐: aortic root) were selected for evaluation by two different radiologists with senior titles. Radiologists independently scored each location by using a 6-point scale (0: no sign of healing, 1: minimal healing, 2: mild healing, 3: moderate healing, 4: partial synthesis, and 5: complete synthesis). Sternal union was defined as a mean score of ≥ 3 . After the Kapper test, the average value of the scores from two radiologists was taken as the final result. Cortical thickness and sternal thickness were also manually measured by the two radiologists through the CT scan results.

Statistical analysis

To assess the risk factors for poor sternal healing, we divided the patients into two groups: a short-term healing group (1–6 months: the S group) and a long-term healing group (12–24 months: the L group). A multiple linear regression was performed to identify the risk factors for poor sternal healing in the S group and the L group. Continuous data are presented as the mean $\pm$ standard deviation and were evaluated with a t-test. Categorical data, which are summarized as a number (%), were evaluated with the chi square test and the Fisher's test. Although a significance level of 0.1 was used in the univariate linear regression analysis to select the variables for the multiple linear regression, p-values less than 0.05 were considered to indicate statistical significance. We performed propensity score matching (PSM)[11] to control for bias by using the "MatchIt" R package[12]. Age was the adjusted variable that was used to propensity score match for patients by the nearest methods with a case–control ratio of 1:3 (Fig. 1). All of the statistical analyses were performed by using R software (version 3.6.3).

Results

Participants and characteristics

A total of 122 patients were enrolled, including 77 males and 45 females, with an average age of 57.83 ± 11.80 years. The mean BMI was 61.6 ± 11.3 kg. Sixty-four patients underwent off-pump coronary artery bypass grafting. Additionally, isolated valve procedures were performed in 58 patients. The mean CT examination time after surgery was 12.53 ± 8.43 months. The two radiologists determined the healing

score based on the sternal CT scan (Fig. 2). The results were analyzed via a Kapper-test. The results showed that the scoring method was reliable and repeatable (Table 1). Moreover, there was a significant bias in the research data because surgeons always chose an appropriate sternal closure method according to the specific situations of the patients (Table 2). To control for bias, we performed PSM, and 102 patients were selected for the subsequent analyses. Table 3 displays a summary of the demographic and clinical characteristics of the patients after PSM.

Table 1
Consistency test of sternal healing score

	Kapper value
□	0.852
□	0.831
□	0.798
□	0.882
□	0.799
□: Manubrium □: Top of aortic arch □: Aortopulmonary window □: Main pulmonary artery □: Aortic root. Kapper value > 0.6: The two groups were significantly similar.	

Table 2
Demographic and clinical characteristics of eligible patients

Characteristic	Steel suture	Titanium plates	Mixed fixation	p
n	19	88	15	
Gender				
Female	12 (63.16)	56 (63.64)	9 (60.00)	0.964
Male	7 (36.84)	32 (36.36)	6 (40.00)	
Age	51.32 ± 14.83	60.50 ± 10.02	50.40 ± 11.64	< 0.001
High	167.63 ± 11.40	164.85 ± 7.59	167.20 ± 5.09	0.282
Weight	65.37 ± 13.04	66.34 ± 10.73	64.80 ± 11.07	0.855
BMI	23.04 ± 2.54	24.36 ± 3.37	23.07 ± 2.85	0.131
NYHA				
I	5 (26.32)	24 (27.27)	2 (13.33)	0.125
II	5 (26.32)	30 (34.09)	9 (60.00)	
III	8 (42.11)	34 (38.64)	4 (26.67)	
IV	1 (5.26)	0 (0.00)	0 (0.00)	
Pulmonary hypertension				
Yes	13 (68.42)	77 (87.50)	12 (80.00)	0.116
No	6 (31.58)	11 (12.50)	3 (20.00)	
LIMAT				
Yes	9 (47.37)	40 (45.45)	9 (60.00)	0.843
No	10 (52.63)	48 (54.55)	6 (40.00)	
EF	57.32 ± 6.26	58.52 (5.50)	61.60 (3.60)	0.065
Hypertension				
Yes	13 (68.42)	36 (40.91)	12 (80.00)	0.004
No	6 (31.58)	52 (59.09)	3 (20.00)	
Diabetes				
Yes	15 (78.95)	64 (72.73)	12 (80.00)	0.747
No	4 (21.05)	24 (27.27)	3 (20.00)	
History of MI				

Characteristic	Steel suture	Titanium plates	Mixed fixation	p
Yes	11 (57.89)	52 (59.09)	14 (93.33)	0.035
No	8 (42.11)	36 (40.91)	1 (6.67)	
Operation time	3.24 ± 0.87	3.11 ± 0.73	2.80 ± 0.92	0.246
Postoperative time	13.79 ± 6.47	12.36 ± 8.88	11.93 ± 8.17	0.769
Cortical thickness	2.44 ± 0.55	2.93 ± 0.60	2.96 ± 0.57	0.004
Sternal thickness	11.92 ± 1.48	12.32 ± 1.59	12.59 ± 0.85	0.418
Sternal score	3.04 ± 1.13	2.44 ± 0.98	2.67 ± 0.82	0.057

Table 3
Demographic and clinical characteristics of eligible patients after PSM

Characteristic	Steel suture	Titanium plates	Mixed fixation	p
n	19	68	15	
Gender				
Female	12 (63.16)	45 (66.18)	9 (60.00)	0.891
Male	7 (36.84)	23 (33.82)	6 (40.00)	
Age	51.32 ± 14.83	57.43 ± 9.20	50.40 ± 11.64	0.018
High	167.63 ± 11.40	165.66 ± 7.25	167.20 ± 5.09	0.56
Weight	65.37 ± 13.04	66.82 ± 11.01	64.80 ± 11.07	0.771
BMI	23.04 ± 2.54	24.31 ± 3.59	23.07 ± 2.85	0.201
NYHA				
I	5 (26.32)	21 (30.88)	2 (13.33)	0.147
II	5 (26.32)	22 (32.35)	9 (60.00)	
III	8 (42.11)	25 (36.76)	4 (26.67)	
IV	1 (5.26)	0 (0.00)	0 (0.00)	
Pulmonary hypertension				
Yes	13 (68.42)	59 (86.76)	12 (80.00)	0.173
No	6 (31.58)	9 (13.24)	3 (20.00)	
LIMAT				
Yes	9 (47.37)	31 (45.59)	9 (60.00)	0.836
No	10 (52.63)	37 (54.41)	6 (40.00)	
EF	57.32 (6.26)	58.87 (5.43)	61.60 (3.60)	0.072
Hypertension				
Yes	13 (68.42)	33 (48.53)	12 (80.00)	0.044
No	6 (31.58)	35 (51.47)	3 (20.00)	
Diabetes				
Yes	15 (78.95)	51 (75.00)	12 (80.00)	0.882
No	4 (21.05)	17 (25.00)	3 (20.00)	
History of MI				

Characteristic	Steel suture	Titanium plates	Mixed fixation	p
Yes	11 (57.89)	41 (60.29)	14 (93.33)	0.042
No	8 (42.11)	27 (39.71)	1 (6.67)	
Operation time	3.24 ± 0.87	3.02 ± 0.76	2.80 ± 0.92	0.291
Postoperative time	13.79 ± 6.47	11.97 ± 8.81	11.93 ± 8.17	0.692
Cortical thickness	2.44 ± 0.55	2.94 ± 0.60	2.96 ± 0.57	0.004
Sternal thickness	11.92 ± 1.48	12.26 ± 1.59	12.59 ± 0.85	0.429
Sternal score	3.04 ± 1.13	2.51 ± 0.99	2.67 ± 0.82	0.131

Factors influencing sternal healing

Figure 3 shows the rate of good sternal healing over time from 1 to 24 months. The average total sternal healing score in the S group was 2.56 ± 1.52 ; in addition, 56% of the patients showed good healing. In the L group, the mean total sternal healing score was 2.63 ± 1.12 , and good healing was observed in 62.5% of the patients. Poor healing was more frequently found in the lower sternum than in other areas. Table 4 shows the results of the analyses of the influencing factors for the sternal healing score. In the S group, the sternal score was only correlated with postoperative time (HR = 0.18, 95% CI: 0.135–0.225, $p < 0.001$). In the L group, older people had a higher risk of poor sternal healing than young people (age, HR=-0.028, 95% CI: -0.05-0.006, $p = 0.013$). Patients with left internal mammary artery grafting (LIMAG) had a high risk of poor sternal healing (HR=-0.444, 95% CI: -0.869-0.019, $p = 0.045$). It should be noted that BMI was not statistically significant. The Q-Q plot was used to verify the normality and linear relationship of linear regression (Fig. 4).

Table 4
Influence factors for sternal healing score

	Group of short term	p	Group of long term	p
Age	-0.003 [-0.011,0.005]	0.387	-0.028 [-0.05,-0.006]	0.013*
BMI	-0.002 [-0.029,0.025]	0.889	-0.01 [-0.077,0.057]	0.765
LIMAT	-0.104 [-0.288,0.08]	0.276	-0.444 [-0.869,-0.019]	0.045*
EF	0.017 [-0.003,0.037]	0.084	0.021 [-0.014,0.056]	0.242
Postoperative time	0.18 [0.135,0.225]	< 0.001***	0.008 [-0.029,0.045]	0.655
Cortical thickness	-0.021 [-0.172,0.13]	0.783	-0.043 [-0.462,0.376]	0.840
Sternal thickness	-0.024 [-0.089,0.041]	0.471	0.001 [-0.138,0.14]	0.995
Titanium plates	-0.162 [-0.497,0.173]	0.35	-0.076 [-0.556,0.404]	0.758
Mixed fixation	-0.036 [-0.442,0.37]	0.863	-0.336 [-1.006,0.334]	0.333

Transverse displacement

In this study, we identified transverse separation of the sternum in 17 patients. This problem existed in 16 patients with titanium plate fixation and 1 patient with steel wire fixation, whereas there was no problem with mixed fixation. Transverse displacement mainly occurred in the lower sternum (in the levels of the main pulmonary artery and aortic root). Only one patient's sternum had a score of 2 at the level of transverse deviation, and the rest of the patients had a score of 0.

Figure 5 shows the sternum model after median sternotomy. The case group included patients with a closed sternum via steel wire fixation and patients with mixed fixation. Patients who used titanium plate fixation were selected as the control group. A binary logistic regression showed that steel wire fixation was a favorable factor for preventing transverse displacement of the sternum (HR = 0.122, 95% CI: 0.007–0.651, $p = 0.047$).

Discussion

Bone healing is mainly affected by macroscopic factors (biomechanics and blood supply), as well as microscopic factors (such as molecular biological factors)[13]. Bit Kover found that there was no sternal healing 3 months after median sternotomy in a prospective computed tomography scan study[14]. As an independent risk factor, advanced age is not only related to sternal postoperative complications, but it also affects sternum healing. Studies have confirmed the importance of immune mechanisms and the inflammatory response in bone healing[15]. Cells that are important in inflammatory responses (macrophages, T cells, and mesenchymal stem cells) are related to age. The number and activity of osteochondrocytes and their progenitor cells in the bone marrow of elderly individuals are lower than

those in young individuals. In addition, advanced age is a high-risk factor for vascular diseases, which is closely related to the ability of blood vessels to transport blood flow and leads to poor blood perfusion of the sternum. Furthermore, the choice of bypass vessels is important during coronary artery bypass surgery. Puskas[16] confirmed that the transplantation of the internal mammary artery as a bypass vessel significantly improved the long-term survival rate. In clinical practice, almost all cardiothoracic surgeons choose the internal mammary artery as the first choice for transplantation. The interception of the internal mammary artery will not only increase the chance of sternal complications (such as mediastinal infections and sternal opening), but will also affect sternum healing[17]. As an independent risk factor influencing sternum scores, BMI > 35 kg/m² has been reported in the previous literature[18]; however, the BMI of Asians is generally lower than that of Europeans[19]. In this study, only five patients had a BMI greater than 30 kg/m². All of the patients were fixed with sternum plates; thus, this study failed to obtain positive results related to BMI. During the follow-up, we found that a small number of patients with dysplasia of the lower sternal segment had difficulty achieving sternal healing based on imaging scans after surgery. The cortical bone and the thickness of the sternum were used as indicators for measuring sternum development. We found that either the thickness of the sternum or the cortical bone thickness was not related to the sternal healing score.

Several forces, such as breathing and coughing, act on the sternum and load the sternum through a combination of lateral shear and transverse shear. Losanoff et al.[20] confirmed that the lateral tension of the thorax is mainly concentrated in the lower part of the sternum. This is due to the confluence of multiple ribs in the lower sternum and the greater mobility of the chest wall in the area during breathing and exercise[21]. Therefore, healing of the lower sternum is poor. Minimal anteroposterior movement of the sternal halves will lead to the cortical bone on one side of the sternum entering the cancellous bone of the other side of the sternum. This can affect bone fusion even without frank dissociation[22]. Therefore, sternal closure seems to be important for long-term sternal healing. Mechanical studies have demonstrated that rigid plate fixation of the sternum results in superior mechanical properties compared with wire fixation[23]. COL David J. Cohen[24] compared the biomechanics of different sternal closure techniques and found that the plates were stiffer than the figure-eight wire constructs used in the transverse shear direction.

The main reasons for the differences between the results of this study and the conclusion of COL David J. Cohen include the fact that the sternum plates that were used in the two experiments were different. The failure of the wire system usually involves wire cutting into the bone under loads. Within the maximum shear force that steel wires can bear, the stability of the eight-shaped steel wire fixation sternum may be stronger than that of the sternum plate. In vitro experiments have difficulty in completely imitating the complex biomechanics of the human body by the force of a simple direction.

Titanium plates provide more stability than wire cerclage alone, but they lack posterior sternal stabilization. The 360-degree rigid sternal fixation (with a combination of plates and wire cerclage described in this study) has been performed in 2 patients to date, with good sternal healing being observed (with a sternal healing score ≥ 3). Taylor M. James once proposed a similar method for fixing

the sternum, and this method was employed in 40 patients, with a zero incidence of deep sternal wound infection[25]. The use of wire cerclage in combination with rigid sternal plates that helps to stabilize the sternum both in the posterior plane and in the lateral plane may reduce the amount of mechanical stress that is placed on the plate. Due to the complications of this method, we recommend considering this technique for especially high-risk patients who are older or those patients with morbid obesity. According to biomechanics, we can use this method to fix the lower part of the sternum, whereas the upper part of the sternum can be fixed with a titanium plate or with the sole use of an eight-shape wire (Fig. 5).

The inherent limitations of this study include its retrospective nature. There was an obvious selection bias regarding whether a patient received titanium plate reinforcement because this technique is usually used in older people or those individuals with morbid obesity. We attempted to control for this bias by using PSM. Lastly, due to the small number of patients with fixed sternums with this new method, our ability to examine its stiffness was limited.

In summary, advanced age and internal mammary artery interception are risk factors that affect sternal healing, based on imaging findings. This new method of sternal closure provides an effective way of ensuring the sternal stability of both sternal plates and reduces the risk for complications after cardiac surgery in high-risk patients.

Abbreviations

M: Manubrium T: Top of aortic arch A: Aortopulmonary window P: Main pulmonary artery R: Aortic root.

PSM: propensity score matching

LIMA-d: Internal mammary artery dissociation

*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$

Declarations

Ethics approval and consent to participate

This study was approved by the Committee of Ethics of the Third Affiliated Hospital of Soochow University: Changzhou First People's Hospital, Changzhou, China.

Consent for publication

Not applicable.

Availability of data and materials

The datasets that were used during the current study are available from the corresponding author upon reasonable request.

Conflicts of interest statement

The authors declare that they have no competing interests.

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Figures

Figure 1

Flow chart for the data screening.

Figure 2

Axial computed tomography scan images representative of each score on a 6-point scale. Each score was defined as follows: (0) no sign of healing (clear lack of healing, nonunion, and sternal separation); (1) minimal healing (sternal separation and lack of bridging bone); (2) mild healing (sternal separation with hazy, immature bone formation); (3) moderate healing (partial bridging bone indicative of sternal

stability); (4) partial synthesis (significant bridging bone); (5) complete synthesis (complete bridging bone).

Figure 3
Rate of good sternal healing over time from 1-24 months.

Figure 4
If the two distributions are similar, the Q-Q diagram tends to fall on y = X-ray. If the two distributions are linearly correlated, the points tend to fall on a straight line on the Q-Q graph.

Figure 5

(M): model of the sternum after median sternotomy; (S): sternum closed with the new method; (P): sternum closed using titanium plates; (W): sternum closed using wires. Transverse displacement of the sternum occurred in the P and W images.