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Mechanism of sternotomy dehiscence

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Abstract

OBJECTIVES: Biomechanical modelling of the forces acting on a median sternotomy can explain the mechanism of sternotomy dehiscence, leading to improved closure techniques.

METHODS: Chest wall forces on 40 kPa coughing were measured using a novel finite element analysis (FEA) ellipsoid chest model, based on average measurements of eight adult male thoracic computerized tomography (CT) scans, with Pearson's correlation coefficient used to assess the anatomical accuracy. Another FEA model was constructed representing the barrel chest of chronic obstructive pulmonary disease (COPD) patients. Six, seven and eight trans-sternal and figure-of-eight closures were tested against both FEA models.

RESULTS: Comparison between chest wall measurements from CT data and the normal ellipsoid FEA model showed an accurate fit ($P < 0.001$, correlation coefficients: coronal $r = 0.998$, sagittal $r = 0.991$). Coughing caused rotational moments of 92 Nm, pivoting at the suprasternal notch for the normal FEA model, rising to 118 Nm in the COPD model (*t*-test, $P < 0.001$). The threshold for dehiscence was 84 Nm with a six-sternal-wire closure, 107 Nm with seven wires, 127 Nm with eight wires and 71 Nm for three figure-of-eights.

CONCLUSIONS: The normal rib cage closely fits the ellipsoid FEA model. Lateral chest wall forces were significantly higher in the barrel-shaped chest. Rotational moments generated by forces acting on a six-sternal-wire closure at the suprasternal notch were sufficient to cause lateral distraction pivoting at the top of the manubrium. The six-sternal-wire closure may be successfully enhanced by the addition of one or two extra wires at the lower end of the sternotomy, depending on chest wall shape.

Keywords: Median sternotomy • Biomechanics • Dehiscence

INTRODUCTION

Median sternotomy is a common cardiac surgical approach. Dehiscence is a rare complication (0.5–5%) [1], but carries a significant morbidity and mortality rate of 10 to 40% [2]. Sternal separation mainly results from lateral distraction [3]. There remains no ideal method of sternal closure and new methods of sternotomy closure are regularly reported in the literature. Robicsek stated that there is a need to 'design a biomechanical model, in which forces acting upon the reunited sternal halves may be reproduced and measured' [4] in order to test these new techniques.

Experimental data on forces acting on a sternotomy is difficult to obtain [4] due to the variation in anatomical structural properties of fresh human cadaveric specimens and the high degree of interspecimen variability [5]. Modelling the chest wall can be used to simulate forces acting on a sternotomy [6]. The chest wall is a complex structure that can be simulated by computer modelling using finite element analysis (FEA) techniques. The thorax resembles a pressure vessel and coughing generates a pressure that differs substantially from the ambient pressure. FEA modelling is an ideal solution for calculating wall stress in pressure vessels with a complex shape.

The subject of sternotomy dehiscence has already been studied in a number of very important and pioneering studies. For example previous FEA modelling of the chest by Bruhin *et al.* has compared the relative stability of different wiring techniques, including simple wiring and figure-of-eight [7]. However, this work by Bruhin *et al.* did not elucidate a mechanism leading to sternotomy dehiscence as testing was not performed with a distending pressure simulating coughing. This present work attempts to address this lacuna by performing FEA simulations with the aim of studying how sternotomy dehiscence develops and suggest a practical technique to prevent it. In particular, in this article, we describe and validate a novel ellipsoid pressure vessel model of the thorax and calculate the forces acting on the sternum during coughing. The forces acting on the sternum at different rib levels were assessed and the mechanism of sternotomy dehiscence of a conventional six-wire-sternal closure was investigated. Accurate calculation of chest wall forces can lead to a better understanding of the mechanism of sternotomy dehiscence and possible biomechanical solutions to prevent dehiscence.

MATERIALS AND METHODS

Thoracic computerized tomography (CT) Digital Imaging and Communications in Medicine (DICOM) data from eight adult males, randomly chosen and anonymized, were collected and measurements of the chest height and both chest diameters were taken at various rib levels in order to construct an ellipsoid model based on average measurements. The novel FEA ellipsoid model was constructed as an ideal ellipsoid with coronal diameter of 24 cm, sagittal diameter of 22 cm and an apex to equator vertical height of 21 cm. Another FEA model with a coronal diameter of 31 cm, sagittal diameter of 28 cm and identical height was constructed to simulate chronic obstructive pulmonary disease (COPD) patients, since both chest diameters increase in COPD [8].

FEA was performed using Ansys software (Ansys, Inc., Canonsburg, PA, USA). Modelling was performed in ADPL (ANSYS Parametric Design Language). The model of an ellipsoid shell was constrained vertically at its base but allowed freedom in the transverse and anteroposterior dimensions, and subjected to a 40-kPa internal distending pressure [9–11] on all sides. Circumferential forces on the surface of the shell were measured at all levels tangentially to the surface. The rib level was measured at the mid-axillary line.

Various assumptions were made—it was assumed that the chest wall forces were transmitted through bones only and that the chest wall was of uniform thickness. The weight of the head, neck and arms were assumed to be passing solely through the spinal column.

A simulation of the lateral distraction of the sternum was performed and the circumferential rib cage forces and the moments of these forces pivoting at the manubrium were calculated and compared with the known wire cut-through forces [12] and wire untwisting forces of conventional six-wire sternal closures [13]. Since excess wire twisting does not increase closure strength [14], wire twisting was optimized to three twists. The threshold for sternotomy dehiscence was measured using six, seven and eight trans-sternal, and trans-sternal figure-of-eight closures.

A comparison was also performed with two previously described models:

firstly with the cylinder model [13] with the formula:

$$T = Prl, \tag{1}$$

where T is circumferential stress, P is the distending pressure, r is the radius of the chest as a cylinder and l is the length of the chest as a cylinder; and secondly with the spheroidal model [6] with the formula:

$$\sigma = \frac{Pb}{h}\left[1 - \frac{b^3}{a^2(2b+h)}\right], \tag{2}$$

where σ is circumferential stress, P is the transmural distending pressure, h is the wall thickness at the equator, b is the geometric average of semi-transverse diameters and a is the height from the apex to the equator.

The strength of the relationship between the FEA model's ellipsoid shape and the average of the eight CT rib cage measurements was tested by Pearson's correlation coefficient, assuming a 0.05 level of significance. The paired-samples t-test was used to

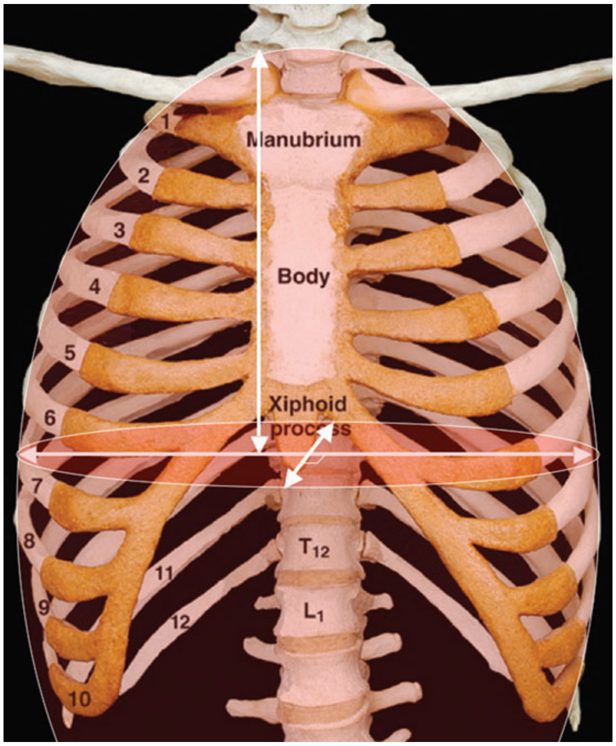

Figure 1: Diagram of triaxial ellipsoid superimposed on a human skeleton showing the close fit, $P < 0.001$.

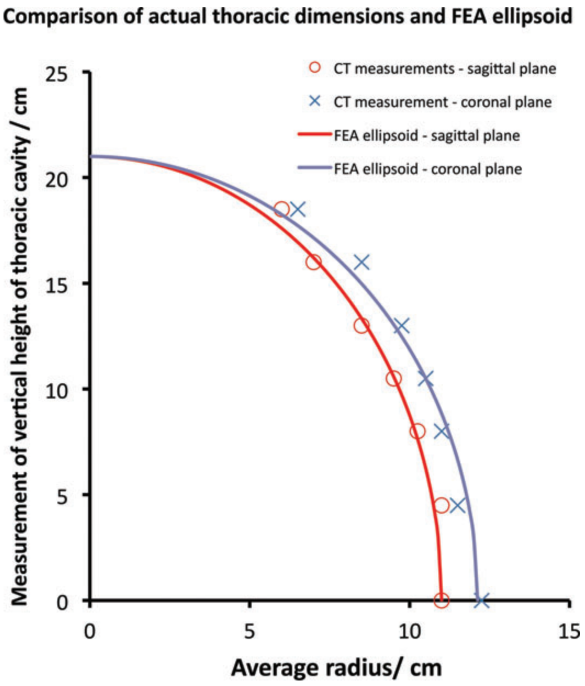

Figure 2: Graph showing the ovoid or ellipsoid FEA model compared with actual average rib cage measurements in both coronal and sagittal planes (correlation coefficients: coronal section $r = 0.998$, sagittal section $r = 0.991$, with $P < 0.001$ in both planes). FEA: finite element analysis; CT: computerized tomography.

compare mean lateral chest wall forces between the spheroidal model and the FEA model, with significance accepted at *P*-values <0.05. Statistics were performed using the IBM SPSS software package (Armonk, New York, NY, USA). The study was approved by the University of Malta's ethics committee on human research.

RESULTS

Single-factor analysis of variance between the eight sets of thoracic CT measurements used to construct the model showed no statistical difference. The comparison between the average chest CT measurements and the ellipsoid model (Fig. 1) showed a significantly close fit, *t*-test, $P < 0.001$ (correlation coefficients: coronal section $r = 0.998$, sagittal section $r = 0.991$), as shown in Fig. 2.

Chest wall forces in the circumferential plane were calculated directly from the FEA model. The comparison between three different methodologies, namely the cylinder model [13], the mathematical spherical based ellipsoid [6] and the anatomically more accurate novel FEA ellipsoid model, showed substantially lower (*t*-test, $P < 0.001$) chest wall forces in the ellipsoid model when compared with the two mathematical models, as well as the COPD model; see Fig. 3.

Results of circumferential rib load and rib level are shown in Fig. 4. There was a significant relationship between circumferential rib load and rib level in the ellipsoid FEA model of the chest loaded with a maximal cough of 40 kPa. The Pearson product–moment correlation (0.993, with a 95% confidence interval of 0.948–0.998) was significant ($P < 0.001$).

The total lateral force acting on the sternum, in the normal ellipsoid model, was 660 N on 40 kPa maximal coughing, with the rotational moment of forces pivoting at the suprasternal notch of 92 Nm. In the FEA COPD model, the lateral forces on coughing rose to 827 N, with a moment of 118 Nm. The threshold necessary for a conventional six-wire sternal closure to dehisce by pivoting at the upper part of the sternum was 84 Nm. The addition of just one extra sternal wire at the lower end of the sternum to the model increased the rotational moments necessary to dehisce the conventional wired sternal closure to 107 m, while the addition of an eighth sternal wire also at the lower end of the sternotomy would increase the moments to 127 Nm. Three transsternal figure-of-eight closures had a threshold of 71 Nm for dehiscence.

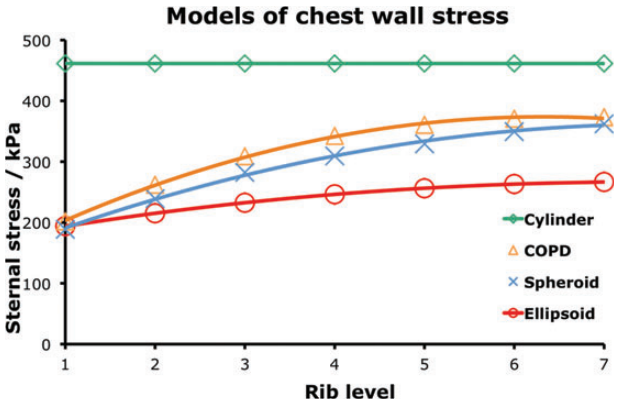

Figure 3: Chest wall stress at the sternum measured using four different models. The ellipsoid FEA model is more accurate as it follows the anatomical shape more closely. The measured ellipsoid FEA circumferential stress was significantly lower than the previously described spheroidal and cylindrical models, with the *t*-test showing statistical significance at $P < 0.001$ between the normal ellipsoid FEA model and all of the other three models. FEA: finite element analysis; COPD: chronic obstructive pulmonary disease.

DISCUSSION

Sternal dehiscence causes increased wound pain, difficulty in coughing and breathing with increased hospital stays, leading to higher costs and results in high morbidity and mortality. Complications can occur in the presternal (cellulitis, abscess, sinus tracts), sternal (osteomyelitis) or retrosternal (mediastinitis, haematoma, abscess) compartments [15].

Different methods for sternal closure continue to be reported in the literature. Many of these recommendations are based on scant clinical material or incomplete biomechanical modelling [16–20]. A biomechanical model with accurate representation of the different forces loading the sternum could lead to standardized biomechanical testing of median sternotomy closures. Sternal movement occurs mostly with lateral distraction of the sternum, rather than in the antero-posterior and supero-inferior planes [3].

FEA is particularly well suited for modelling the thorax and for computer simulations of sternotomy dehiscence. FEA is a system of solving complex structural analysis problems by the technique of mesh discretization, changing a complex surface into a mesh of nodes with differing material properties. FEA acts as a simplification of the actual extremely complex geometry. Although the FEA model fits closely only with the anterior and lateral portions of the chest wall, this is sufficient to model the chest wall forces on the sternum, as the edge of the model conforms tangentially to the actual chest wall [21].

Experimental fatigue testing on a six-wire sternotomy has shown that a lateral force of 10 kg per wire or 589 N causes the wire to cut through bone [12], while a force of 20 kg per wire or 1176 N would result in untwisting of stainless steel no. 5 wires [13], with either mode of failure leading to sternotomy dehiscence. The total lateral distracting force on the sternum in our normal ellipsoid sternotomy model was 660 N, which was just half the 1176 N

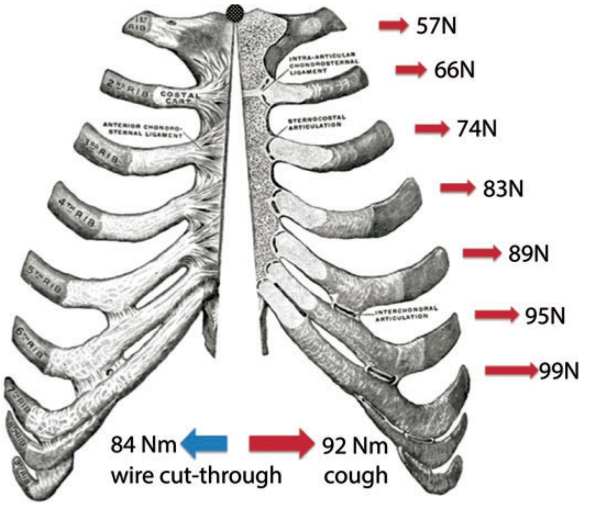

Figure 4: Diagram of a sternotomy closed with a conventional six-wire closure, showing failure resulting from the laterally distracting circumferential rib forces on a 40 kPa cough, with the resultant rotational moments from these forces pivoting at the suprasternal notch in red, and the moments necessary for wire cut-through in blue.

force for wire untwisting and marginally exceeded the 589 N cut-through strength only at the lower part of the sternum. Moreover, rotational moments pivoting at the suprasternal notch for a six-sternal-wire closure were 92 Nm compared with the threshold of 84 Nm for dehiscence by wire cutting through bone, suggesting that dehiscence would occur, starting from the xiphisternum and proceeding cranially.

Our model suggests three mechanisms leading to the greater distraction at the lower end of the sternum. Firstly, the circumferential forces of distraction are greater at this level as the model predicts that chest wall tension is proportional to the tangential radius at the relative chest level. Secondly, there is a concentration of forces in the lower part of the sternum due to the proximity of the attachment of the 5th, 6th and 7th ribs on the sternum. Thirdly, the 7th rib carries additional forces from the 8th, 9th and 10th ribs through the coastal margin. These three mechanisms concur with clinical evidence that sternum dehiscence often starts at the inferior aspect of the sternotomy wound [3].

Sternal instability, wound infection, osteomyelitis and dehiscence are related since each one of these conditions can trigger the other. This cascade results in an initial instability in the lower part of the sternum leading to wound bursitis and leakage of post-operative pericardial fluid through the lower part of the sternotomy wound. This scenario further leads to a sucking wound, with contamination and eventually deep-seated infection and osteomyelitis. Our model suggests that, in effect, the sternotomy unzips from the bottom upwards.

This mechanism of dehiscence does, however, suggest possible methodologies to strengthen sternotomy closures. Analysis of the ellipsoid FEA model showed that reinforcing a standard six-wire sternal closure with the addition of at least one additional sternal wire 'at the lower end of the sternum' was sufficient to significantly reduce the risk of sternal dehiscence by increasing the rotational moments required for dehiscence to 107 Nm, when compared with 84 Nm required for dehiscence of a standard six-wire sternotomy closure. In the COPD patient, the FEA model dehisced with a moment of 118 Nm, and would require an eight-wire closure to raise the resistance to dehiscence to 127 Nm. This fits in with previous empirical suggestions for use of an increase in the number of sternal wires, for example eight [12] or nine [22] sternal wires or one sternal wire for every 10 kg of body weight [23]. However, increasing the number of wires at the 'lower' end of the sternum would be the more effective location to prevent dehiscence because of the greater effect on the distracting forces and rotational moments. Three figure-of-eight closures had the lowest threshold for dehiscence at 71 Nm, confirming that this closure should be used sparingly [24].

The Robicsek weave, a lateral parasternal reinforcement with conventional peristernal wires joining the two sets of weaves, would have the same lateral distracting closure strength as a conventional closure [25]. However, this closure may be enhanced simply by twisting the ends of both weaves into a four-wire twist at the lower end of the sternum, thus strengthening the closure at the lower end of the sternotomy.

Limitations of the model include the fact that it does not include bone density or quality as a variable, and that the model disregards the effect of the lower ribs on the sternum through the costal margin. The ellipsoid model has also not been validated for COPD, which causes a relative increase in the size of upper and middle parts of the chest [8].

Future work could include adaptation of the model to other major contributory factors of sternotomy dehiscence, such as osteoporosis. Such an improved model would allow a more rigorous approach to sternotomy dehiscence required in today's era of evidence-based medicine. The suggested changes in sternal closure described here, with the addition of one extra wire in the lower part of the sternotomy, may lead to increased sternal stability and a decrease in the considerable morbidity and mortality associated with sternal dehiscence.

CONCLUSION

The human antero-lateral chest wall closely fits the ellipsoid model. Moments generated by coughing forces acting on a six-sternal-wire closure were sufficient to cause lateral distraction pivoting at the top of the manubrium due to the increased stress in the lower part of the sternum, especially in barrel-chested COPD patients, resulting from the close vicinity of the fifth to seventh ribs on the sternum. The six-sternal-wire closure may be successfully enhanced by the addition of one or two extra wires at the lower end of the sternotomy in biomechanical models of the chest, depending on chest wall shape.

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