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Numerical Analysis of the Sternal Closure in the Open Heart Surgery for the Finite element model of a Complete Human Chest

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ABSTRACT

Sternal closure is the last step of median sternotomy in an open heart surgery. Different techniques of sternal closure have been described. The objective of this study was to analyze the structural response of the wires and separated sternum during this procedure using finite element methods. Two-dimensional thoracic computer tomography scans were segmented and analyzed by image processing techniques and transferred into a three-dimensional finite element model of a complete chest. Linear elastic law models were used for several regions. Then, the sternal closure process on the sternum was modeled and a basic model of the lungs was used for applying intrathoracic loads. Nonlinear contact conditions were applied .The structural response of this model was investigated under normal breathing and a severe cough by means of lung model. The results show that the lower regions of the sternum and also lateral sides of sternum in contact with wires are the regions which have maximum stress values therefor the risk of failure or damage in these areas is high. The maximum stress for a severe cough load case is 243 N/mm^2 for the wires and 65.6 N/mm^2 for sternum bone that can lead to failure in this region for more severe cases.

KEYWORDS: sternal closure, finite element, chest model, biomechanics sternotomy, wire.

INTRODUCTION

Median sternotomy has been extensively used by cardiothoracic surgeons since 1957 in order to gain access to the heart since it provides an excellent exposure. The last stage of this operation is sternal closure. The complications of this operation is reported between 0.3% and 5% but is associated with high mortality rate (14% - 47%)[1] .This complications consist of infection, wire failure and separation of the sternal segments due to bone cutting[2]. Many studies have been conducted to introduce new techniques and devices for decreasing the failure rate [3-9].

The first biomechanical study in this field measured the suitable applied forces for closing fixation wires, according to the maximum load on the chest which is because of a severe cough [1]. Most of the studies have compared different techniques (single loop, figure of eight, peristernal and etc.) and devices (titanium plates, steel cables, sterna-band, talons and etc.) [3-8]. One of the latest studies is about the effect of using bone glue on the stability of the sternal closure [6].

The application of numerical discretization techniques, especially finite element method (FEM), enables us to investigate stress and displacement distribution on the separated sternum. There is only one research which has studied the sternotomy closure for a chest with numerical methods. In this study, structural response of the FEM model of chest (consist of sternum halves, cartilages and the ribs) was investigated under normal breathing and dorsal bending [9].

The objective of our study was to analyze a FEM model of a complete human chest during a sternotomy closure procedure with 5-row simple technique, to find the stress and displacement distribution in two load cases: breathing and a severe cough. Pre-stressing forces were considered and for applying the load cases we used an approximated lungs model in the ribcage. The results were compared with available results of previous studies to ensure that results are accurate. As a result of such numerical studies we are able to find the regions which have the greatest risk for failure so we can design new techniques and devices to prevent complications.

MATERIALS AND METHODS

For calculating structural response of a sternum closed by wires, we must have the finite element model of the whole chest .For this reason, two dimensional thoracic computer tomographic scans (CT scans), which were grabbed in 1.5-mm slices for a 37-year man, were segmented and analyzed by image processing techniques. We distinguished various areas consist of Sternum bone, ribs, cartilages and spinal column by a manual procedure in each scan slice. This step is important because the mechanical properties of these regions are different and it is possible to assign different material properties to them with separating the regions. An automated procedure transferred these 2-D areas into a three-dimensional computer aided design model (CAD).These steps were done in MIMICS software [10]. By using this procedure we have the regions with real geometries in addition to varying thickness of the ribs and sternum which are tubular in reality. Fig1 shows the final CAD model with different regions.

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The second step is transferring this CAD model to a finite element (FEM) model .With an automated meshing procedure we transferred this geometrical information into the FEM model. All the imported sub regions were modeled by solid elements and were rigidity connected to their neighbor parts to form the whole chest model. We used linear elastic material law for the sub regions with properties taken from previous studies [11, 12].

These parameters are shown in ***Table 1*** Using the spinal column in this model is for considering the influence of the backbone flexibility in results and also as a support for other parts. And because it has not a large effect in the stress distribution on the sternum, we confined to an approximate model (without considering discs). The lower and upper free ends of the backbone were taken completely fixed.

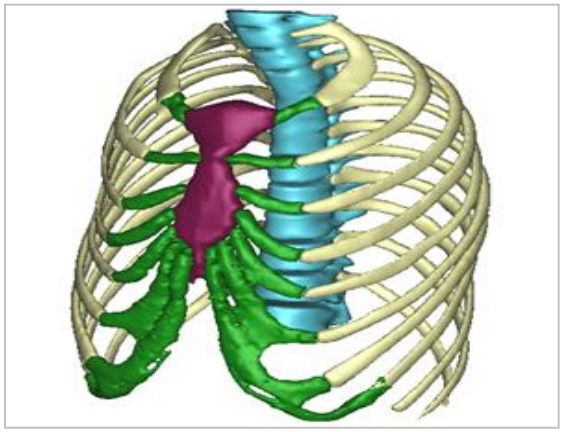

Fig 1. Computer aided design (CAD) model of the chest with different sub regions.

For the sternotomy closure simulation, we separated the sternum bone from the middle. There are many different techniques for the sternal closure process and we chose one of the most common techniques which is 5-row single loop technique.

In this technique, sternum segments are kept together by fixation stainless-steel wires in 5 specific places (the areas between each pair of the ribs) .These wires with diameters of 1mm and linear elastic law parameters with Young modulus of 2×10^5 N/mm^2 and Poisson ratio of 0.3 were considered[13].

It has been estimated that total load across a sternotomy, during a large cough, is 1500 N (<150 kg) [13].Therefor for 5 rows of wires, each fixation wire must sustain approximately 300 N. So we applied 300 N for closing each wire. In the contact zones, between two sternum segments and also between the fixation wires and sternum, nonlinear contact conditions were chosen. These conditions consist of a hard normal contact condition and a tangential contact with Coulomb friction coefficient of 0.2, which describe stiff contact under pressure and zero cohesive forces under tension contact.

Table 1. Linear elastic material parameters for different regions of chest [11, 12]

	Young's modulus (N/MM2)	Poisson ratio (-)	Density (Kg/M3)
sternum	11500	0.3	2000
ribs	5000	0.3	2000
cartilages	24.5	0.45	1500
spinal column	1500	0.3	1900

In this study, two different load cases were applied to analyze the structural response of the model .First load case was the normal breathing which cause a permanent cyclic force on the chest. And the second one was a severe cough which generates the maximum load on the sternum. There are several mechanisms to simulate these load cases .In some experimental studies, direct forces were applied on the sternum segments for finding the maximum sustainable force for wires and other devices [3-8]. In the numerical study, load cases were described by prescribed rotations at the spinal ends of the ribs [9].For a more accurate simulation, we used a basic model of lungs in the ribcage for applying the load cases .Using this model enables us to have a more realistic distribution of loads from the lungs on the whole chest regions (sternum, cartilages and ribs). This basic model was based on human lung dimensions and due to the complexity of the lung shape, was integrated. Different load cases can be simulate by applying a suitable internal pressure. For mentione0d load cases, the internal region of lung model with wall thickness of 10mm was applied to two pressure loads proportional to the load cases**.** The suitable internal pressure for breathing load case is 10^{-3} N/mm^2 [14].

And according to previous studies we could consider an average pressure of 5×10^{-3} N/mm^2 for large cough load case. The elements of this model were considered solid and mesh elements were triangular. The properties which we used for lung model were according to study and consisted of 10 N/mm^2 for Young's modulus and 0.47 for Poisson ratio [15].

For simulating the cough load, we must consider its impact .However, all our calculations were static and we considered an average internal pressure for cough load case. According to lungs anatomy, their costal surface have

contact with most of the ribs and all cartilages but there is not any contact between them and sternum and also spinal column .so we restricted lung model motions in these regions (sternum and backbone) in addition to some areas in the lower and upper model sections .The contact conditions were similar to wires and sternum contact conditions. The meshing and FEM calculations were done in ABAQUS/standard FEM software [16].

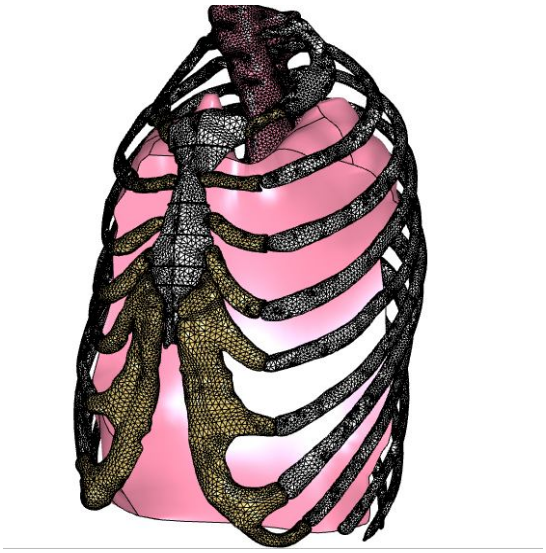

Fig 2. Meshed parts of FEM model of chest and fixation wires and the lung model (unmeshed region).

RESULTS AND DISCUSSION

Fig3 demonstrates the stress distribution for the sternum bone segments after the wire closure and without any load application. It can be seen that the fixation techniques lead to stress concentrations along the contact zones between sternum and wires. In this condition the maximum amount of the vos-Mises stress on the bone is 24.7 N/mm^2 .This maximum Occurs in the lateral region of the bone so these regions have the greatest risk of failure .However; this amount is less than the acceptable maximum stress for sternum bone which is 150 N/mm^2 . Furthermore the maximum stress for steel wires in this case is 103 N/mm^2 while the yield stress for wires are 360 N/mm^2 so there is not any plastic deformations in wires.

For the breathing load case, Fig4 illustrates stress distribution on the sternum segments .In this case, stress distribution on the sternum segments is due to two types of load .First, the loads from wires which are bigger than the non-load condition, and second, the load which is applied by the cartilage parts as a result of movements of the ribcage different parts in breathing mechanism. The regions with high values of von-Mises stress are on the lower regions of the sternum segments, because in this regions 4 ribs joint together to the sternum through cartilages .therefor, the applied tensile forces from cartilage increases in these regions. For the severe cough load case, the forces from cartilages are more; therefore the distribution is different with the breathing.

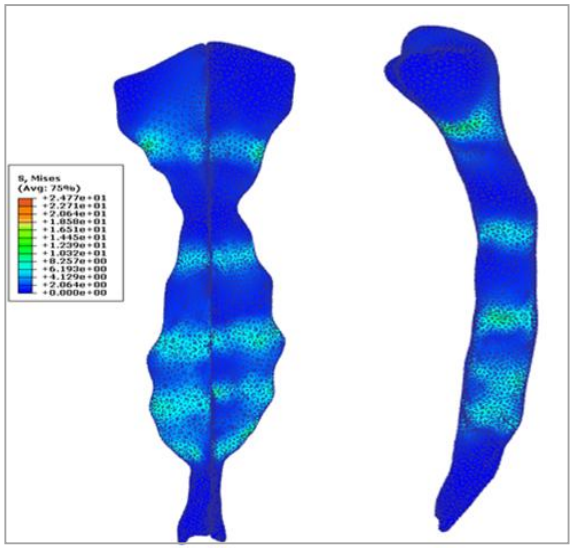

Fig3. Illustration of von-Mises stress distribution for 5 rows of wires without load, in front and side views.

In Fig5 we can see the areas with maximum stresses near the cartilage zones which show that maximum stress is because of the tensile load .The maximum stress on the bone is 65.5 N/mm^2 which shows that the failure risk in the bone is still low.

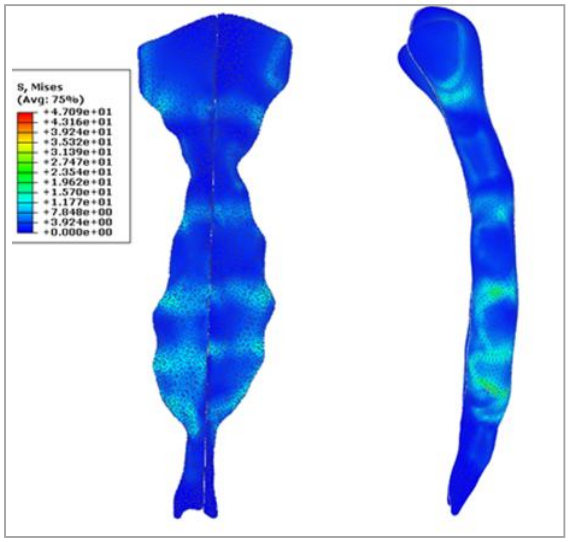

Fig4. Illustration of Von-Mises stress distribution of the sternum for load case breathing in front and side views.

However the stresses in steel wires are high . This maximum value is 243 N/mm^2 in the regions which are in contact with side regions of sternum segments. Although this value in compare with steel yield stress (360 N/mm^2) is still low, in more severe cough conditions can cause damage and even failure in the wires.

So we must use the wires that have bigger contact surfaces with the sternum. There are some polymer wires thar their cross sections is rectangle and so they have more contact regions with the bone. This can lead to less stress both in bone and wire and increase the failure risk in these regions.

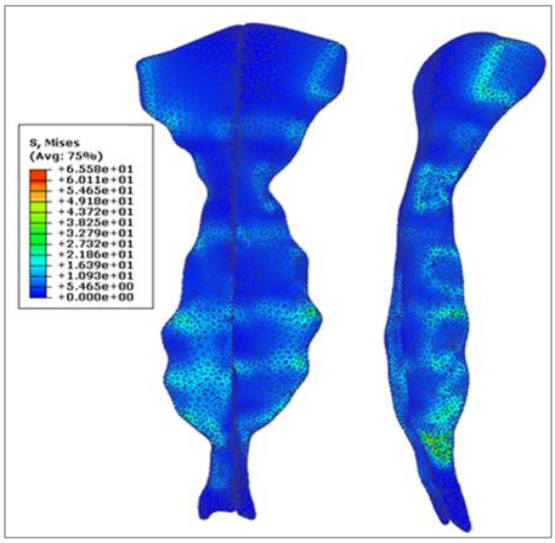

Fig5.Illustration of Von-Mises stress distribution of the sternum for severe cough the load case, in front and side views.

DISCUSSION

In this study we simulated the sternotomy closure procedure which is done in open heart surgeries. For this purpose, we created a numerical mechanical model based on FEM and investigated the structural response of this model to important load cases. As a result, digital 2D information of the chest (CT scan) was converted into a 3D model (CAD volume model) with the final transformation of the geometrical information into a FEM of the complete chest. We also provided a basic model of lungs for applying the breathing and cough loads. The suitable elements and material were chosen for the different regions and contacts between them were considered.

As a first quantitative outcome of the proposed approach, it was shown that the lower region of the sternum (xiphoed) is the region which has high values of stress .The lateral sides of sternum segments in contact zones also have more values of stress. Therefor the risks of failure or damage in these regions are high. This result can lead to making special devises or techniques for closing these regions. The results also demonstrate that a severe cough load as the biggest load on chest, leads to a maximum stress in steel wires model equal to 243 N/mm^2 that is a risky value and can reach the yield stress in larger coughs.

Due to different objectives, it was not possible to compare our own results with reported in vitro results quantitatively. But in compare with the numerical study, it seems that the results are nearer to realistic conditions because of considering the pre-stress forces in the wires an also applying load cases with the lung model. In the future studies, the results can be better with choosing better material properties for different parts and also considering the muscles and tendons effects.

REFERENCES

1. A. R. Casha, L. Yang, P. H. Kay, M. Saleh, and G. J. Cooper, "A biomechanical study of median sternotomy closure techniques," European Journal of Cardio-Thoracic Surgery, vol. 15, pp. 365-369, 1999.
2. Satta J, Lahtinen J, Raisanen L, Salmela E, Juvonen T: Options for the management of poststernotomy mediastinitis,"Scand CardiovascJ, vol. 32, pp.29-32 ,1998.
3. J. E. Losanoff, A. D. Collier, C. C. Wagner-Mann, B. W. Richman, H. Huff, F. Hsieh, et al., "Biomechanical comparison of median sternotomy closures.," Ann Thorac Surg, vol. 77, , Jan 2004.
4. C. Wangsgard, D. J. Cohen, and L. V. Griffin, "Fatigue testing of three peristernal median sternotomy closure techniques.," J Cardiothorac Surg, vol. 3, p. 52, 2008.
5. D. R. Trumble, W. E. McGregor, and J. A. Magovern, "Validation of a bone analog model for studies of sternal closure," The Annals of Thoracic Surgery, vol. 74, pp. 739-744, 2002.
6. P. W. Fedak, E. Kolb, G. Borsato, D. E. Frohlich, A. Kasatkin, K. Narine, et al., "Kryptonite bone cement prevents pathologic sternal displacement.," Ann Thorac Surg, vol. 90, pp. 979-85, Sep 2010.
7. H. Fawzy, N. Alhodaib, C. D. Mazer, A. Harrington, D. Latter, D. Bonneau, et al., "Sternal plating for primary and secondary sternal closure; can it improve sternal stability?," J Cardiothorac Surg, vol. 4, p. 19, 2009.
8. R. S. Jutley, D. E. T. Shepherd, D. W. L. Hukins, and R. R. Jeffrey, "Calculating stress magnitude between sternotomy closures and sternum," European Journal of Cardio-Thoracic Surgery, vol. 20, p. 1071, 2001.
9. R. Bruhin, U. A. Stock, J.-P. Drücker, T. Azhari, J. Wippermann, J. M. Albes, et al., "Numerical Simulation Techniques to Study the Structural Response of the Human Chest Following Median Sternotomy," The Annals of Thoracic Surgery, vol. 80, pp. 623-630, 2005.
10. MIMICS. Materialise's Interactive Medical Image Control System. V.10.01 materillist n.v,2006.
11. K. Furusu, I. Watanabe, C. Kato, K. Miki, and J. Hasegawa, "Fundamental study of side impact analysis using the finite element model of the human thorax," JSAE Review, vol. 22, pp. 195-199, 2001.
12. B. D. Stemper, D. Board, N. Yoganandan, and C. E. Wolfla, "Biomechanical properties of human thoracic spine disc segments," J Craniovertebr Junction Spine, vol. 1, pp. 18-22, Jan 2010.
13. S. Glennie, D. E. T. Shepherd, and R. S. Jutley, "Strength of wired sternotomy closures: effect of number of wire twists," Interactive Cardiovascular and Thoracic Surgery, vol. 2, pp. 3-5, 2003.
14. A. A. COHEN, A. HEMINGWAY, and C. HEMINGWAY, "Displacement of nitrogen from normal human lungs during oxygen breathing,", vol. 37, pp. 306-14, Feb 1985.
15. N. De Geeter, C. Ionescu, and R. De Keyser, "A mechanical model of soft biological tissue--an application to lung parenchyma," Conf Proc IEEE Eng Med Biol Soc, vol. 2009, pp. 2863-6, 2009.
16. ABAQUS/CAE. Dassault systems.V 6.10, ,simulia corp ,usa 2010.