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FAILURE ANALYSIS OF STERNOTOMY

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Abstract: *Median sternotomy is a surgical procedure allowing direct access to the hearth via sternum dissection. The post-operative complications – infection and dehiscence – are associated with high morbidity and mortality rate. Out of the available techniques used to re-approximate the two sternum halves the wiring technique is preferred. This approach has specific problems demonstrated by the rupture of the wire or cutting through the bone. There is a limited knowledge about the biomechanical chest behaviour and the interaction at the interface between bone and sutures. These data are very difficult if not impossible to obtain via direct measurement 'in vivo' and even experimentally 'in vitro', due to complexity of the whole system and number of not well defined parameters that might play important role in the process. This paper will try to bring more information, by means of computational simulation, about the bone response to the presented suturing technique, the magnitude of stresses developed within the sutures, analysis of the relative displacement of the two halves, their behaviour, and the possibility of bone failure at the bone-wire interface.*

Keywords: Sternotomy, finite element, failure.

1. Introduction

Median sternotomy is a surgical procedure that provides direct access to the vital organs, which are protected by a chest wall. Thus the sternum is dissected along the midline and after the surgery the two halves of sterna bone are re-approached and secured in the position by a sternotomy technique. The postoperative complications, infection and dehiscence, although they have relatively low occurrence, are associated with a high mortality and morbidity rate once they occur (Schimmer et al., 2008). There are two commonly used closing methods – plating and wiring technique used by the majority of cardiac surgeons at the local Mater Dei hospital as it is easier to manage, and provides better opportunity to level the two halves, even though this approach represents very specific problems of postoperative complications such as the wire rupture or cutting through the bone. The failures, as reported by the surgeons, are mainly associated with convulsive cough that generates a high pressure within the chest reaching up to 40kPa. Due to the fact that the sternotomy attracted very little attention there is a limited number of papers discussing the sternotomy failure. Most of the papers are reporting mainly clinical observation (Pai, 2005), few present the results of an experimental testing using cadavers, foam models or animals (Casha et al., 2011; Dasika, 2003). In this paper we'll try to expand the available knowledge about the chest behaviour, the possibility of failure due to wire cutting bone, and identify the key factors affecting the mechanical response by using computational modelling.

2. Methods

Modelling of the failure scenario required three-dimensional sternum geometry that was obtained by manual segmentation of CT scan data. Following the segmentation an incision along the midline of the sternum has divided the bone into two halves. The suturing configuration shown in Fig.1 corresponds to the rehearsed thus preferred technique by the collaborating surgeon. The surgical suture is passed through the sternum at approximately 1cm from each side of the joined halves while the peristernal wires are

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sutures that wrap the wire around the whole sternum at the spaces between the ribs. The wire technique provides the possibility to make tighter closures while reducing the risk of the wires cutting through the cortical bone. Wire locking system is based on the twisting of the two ends of wire. This particular feature was omitted from our model as it does not contribute to the reported failure mechanism. Most wires were modelled via extruding the wire circular profile along the suture direction thus creating 3D wire volume. The sterna cortical bone covering the surface area of the sternum was assumed to have a uniform thickness of 1.38 mm as a result of CT scan analysis done during the manual segmentation. We were not able to compute an average density of cortical bone from CT scan as the image of 'phantom' was missing thus had to rely on evaluated guess based on the Hounsfield units (HU) and estimated the Young's modulus of cortical bone to be 5 GPa while the cancellous bone being of 50 MPa. Both tissue's were then modelled as an isotropic continuum. The suturing wire, normally used at Mater Dei Hospital, Malta is ETHICON® no.5 circular profile wire, made of stainless steel 316L with measured diameter of 0.79 ± 0.005 mm, had to be tested to obtain the corresponding mechanical properties. The material properties were obtained experimentally using Hounsfield Tensometer but the results turned out to be unreliable due to faulty gripping system, therefore the material model was created based on the data available in materials library that gives Young's modulus of 193.05 GPa for steel SS-316L, yield and ultimate strength of 290 MPa and 620 MPa respectively, with Poisson's ratio of 0.25 (SS-316L, www.hpmetals.com).

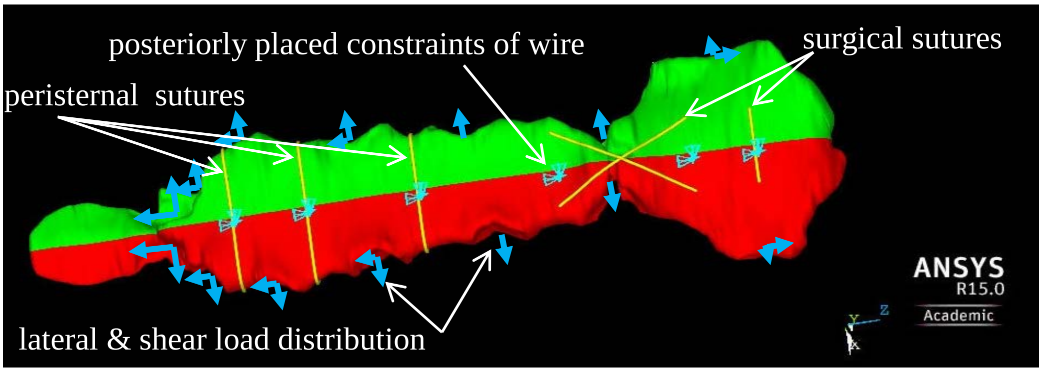

Fig.1: Model of the sterna with suturing configuration

The geometry model was segmented in Ansys 15 using SHELL181 elements with defined thickness of 1.38 mm thus mimicking the cortical bone on the 3D surface of the sterna while SOLID185 elements were assigned to 3D volume of the wire as well as to the sterna volume.

2.1. Model of the load and boundary conditions

The load of lateral force varying from 160 N to 1650 N and simulating the convulsive cough reaching a distending transmural pressure of 40 kPa was evaluated by different researcher using experimental or analytical approach (Casha, 1999; Trumble, 2002; Dasika, 2003; Pai, 2005). The load adopted for our computation is based on the reverse engineering where the chest wall is assumed to be an elliptical 'pressure vessel' while the varying thickness of the chest wall is taken into consideration (Casha et al., 2011). The force computation according to (1) takes into account the transmural pressure p, the wall thickness h at the equator, the minor semi-axis b as the geometric average of semi-transverse diameters, and the major semi-axis a as the height from apex to equator.

$$\sigma = \frac{p \cdot b}{h}\left[1 - \frac{b^3}{a^2(2b+h)}\right] \qquad (1)$$

The computed force of 449 N is comparable to the experimental results and offers the load distribution on all seven coastal notches where the first seven ribs connect to the sternum via cartilages that provides the direct transfer of the load from the chest wall and intercostals muscles to the sternum. The lateral load applied to the sternum had to be accompanied by a shear force that corresponds to direction of each particular cartilage. The forces presented in the Tab.1 record the applied force components in lateral direction along x-axis, and shear force along the z-axis, while the force Fres is the total force applied via cartilage.

Tab. 1: Distribution of lateral and shear forces among first seven ribs

Rib Level	1	2	3	4	5	6	7
Fres [N]	46	55	69	78	74	87	124
Fx [N]	43	53	68	76	62	67	80
Fz [N]	17	15	5	-18	-40	-56	-94

To simulate the behavior of a sternum after the sternotomy required to set up number of contact pairs between the two re-approached parts of the sternum and the contact regions between bone and wires. The non-linear geometry behaviour of contact pairs is controlled mainly by normal stiffness factor FKN and FTOLN being of 0.9 and 0.01 respectively. The contact algorithm was set to Penalty method with contact detection on Gauss points while contact surface behaviour was set as a perfectly rough surface with no sliding for all contacts at the bone-wire interface. The contact at mid-plane of the sterna bone was set as unilateral with possibility of sliding. To simulate the 'fixed' position of the two halves, while each is attached to the corresponding half of the rib cage, a single node was selected at the posterior side of each suture and the constrains prohibited movement in all directions. Consequently, the FE model is defined by 593301 elements with total of 189435 degrees of freedom, and 8550 constraint equations. The analysis type was set for large displacements since the equation of stress conversion is valid for incompressible engineering materials with $\varepsilon < 0.005$ which doesn't tally for biological tissues that usually undergo large deflection but relatively small strains.

3. Results

As already mentioned earlier there are three mechanical factors influencing the healing process after the sternotomy. These are the condition between the two halves of the re-approached sternum, tension in the wire, and wire cutting the bone. Thus the first analysis of both sides of sternum demonstrate the maximum displacement that varies from 0.34 to 1.25 mm according to the varying pressure inside of the chest.

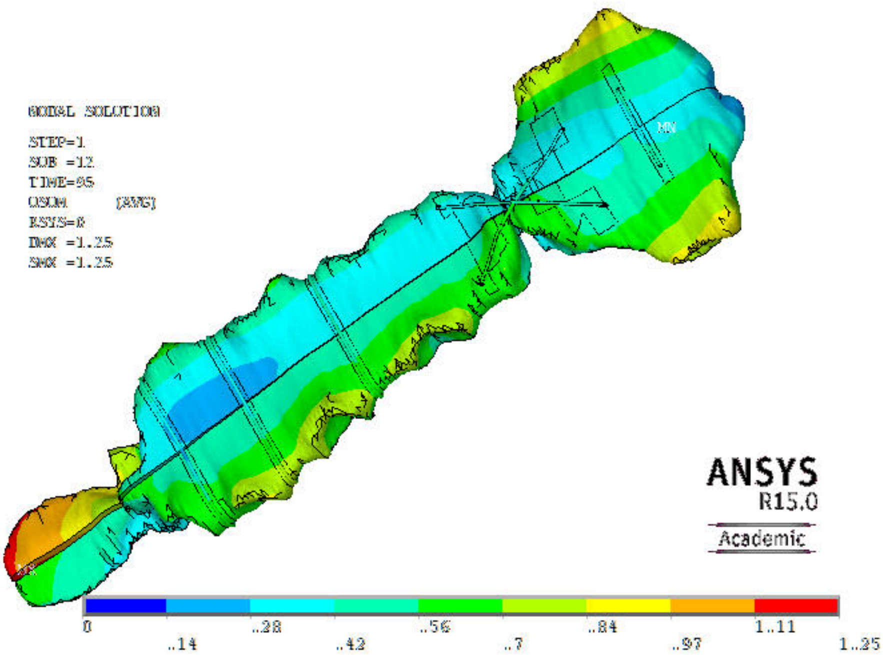

Fig. 2: Map of displacement after the sternotomy

The total maximum occurs at the attachments of the cartilages and at the caudal part of the xiphoid. The lateral gap between the two halves was computed as the difference between the displacements of left and right halve reaching its maximum of 1.87 mm at the caudal region of the xiphoid. The stress analysis within the sutures revealed very high stress reaching up to 7.98 GPa at the contact between the crossing wires while the last peristernal suture presents the highest stress of 715 MPa thus reaching beyond the level of ultimate stress though the other peristernal sutures have stresses within the yield limit. The bone – wire interface regions must be investigated for potential failure due to high contact stresses resulting in high strain. The region of the highest stress intensity corresponds with the highest strain of 0.6% developed at the contact between the suture and bone.

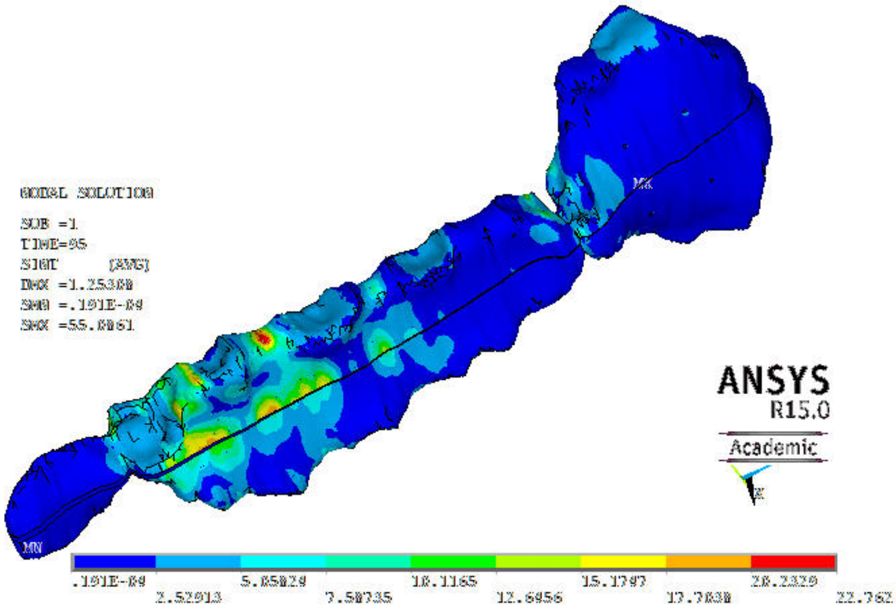

Fig. 3: Map of strain intensity

4. Conclusion

Results presented in this paper seems to be in agreement with clinical observation as the reported rupture of the wire or bone cutting occur mainly at the caudal region of peristernal sutures. Considering the reported elastic strain limit of cortical bone failure being within the limit of 2% we concluded that the wire cut through the bone would not occur but based on the results obtained from our simulation the rupture of the wire seems to be more likely the mode of failure. The maximum equivalent stress of 7.98 GPa occurs at the cross-link of the two wires at the manubrium joint where normally the real wire locking system secures the wire tension. Thus as the two wires don't cross each other in reality this stress was not considered to cause the failure. It cannot be said about the peristernal wire at the xiphoid location where the stress reached up to 715 MPA. At the same time we need to question the results at the inferior part of the sternum, which is loaded according to an elliptical analytical model of load that might not represent the real loading condition as the chest pressure represents only one component. Further research related to chest behaviour and loading condition is necessary to confirm the validity of our results.

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