The Heart Surgery Forum #2001-83468
5 (1):69–74, 2002 Online address: www.hsforum.com/vol5/issue1/2001-83468.html

# Sternum Screw: Analysis of a Novel Approach to the Closure of the Chest After Surgery

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(2001-83468 ... September 9, 2001)

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## ABSTRACT

**Background:** To show the benefits of using a novel approach to closure of the median sternotomy through a mechanical model and mechanical testing. Simple cannulated screws are placed on either side of the sternotomy. Conventional stainless steel wire is passed through the cannula of each screw and the sternotomy is closed in the usual manner.

**Methods:** Hertzian contact analysis was used to estimate the stress between the wire and the sternum. Mechanical testing was used to compare using wire on its own with a sternum screw plus wire. Ten samples of balsa wood (sternum substitute) had wire placed through a hole in them, while a further ten samples were fitted with a cannulated screw and had wire passed through the screw cannula. The wire was connected to a materials testing machine, which applied tension to the wire until the wire or screw cut through the wood.

**Results:** The analysis showed that the mean stress between the wire and the sternum decreases with increasing wire diameter. At low diameters of wire the stress in the sternum can be comparable to the failure stress of bone. Using a cannulated screw reduces the stresses in the sternum. The mechanical testing showed that the wire cut through the wood at a mean load of 104 N, whereas the sternum screw cut through the wood at a mean load of 209 N ($p = 0.007$, Mann-Whitney Test).

**Conclusions:** Closing a median sternotomy with cannulated screws plus wire should reduce the occurrence of sternal dehiscence.

## INTRODUCTION

The median sternotomy is the most widely accepted incision used to gain access to the heart and great vessels. The use of sternal wires fixation to close the median sternotomy was first described by Milton over a hundred years ago [Milton 1897]. The method, which involves the apposition of the sternal edges by twisting six or more stainless steel wires, still remains the most widely accepted technique [Julian 1957]. Some surgeons choose to place the wires around the body of the sternum believing that the lateral cortex of the bone provides additional support to the wires [Robiscek 2000]. Most surgeons, however, place the wires through the sternum at manubrium level. Despite its widespread use, sternal wire fixation is not without its morbidity and mortality. Serious complications include sternal dehiscence occurring at up to 2.4% incidence and mediastinitis at 0.25% [Sirivella 1987, Baskett 1999]. In addition, sternal malunion and nonunion contributing to excessive sternotomy site movement worsens postoperative pain leading to decreased inspiratory effort. This predisposes to postoperative lung collapse due to inadequate clearance of pooled mucus leading to infection.

With recent rapid advances in cardiac techniques, an increasing number of patients with coexisting disease are being offered surgery. The older population with osteoporosis and patients with chronic obstructive pulmonary disease are now routinely being operated on. This increase in the range of patients for cardiac surgery also suggests a greater proportion of candidates on steroids and with diabetes, both recognised risk factors for impaired wound and bone healing.

The prevention of sternal dehiscence and sternal infection remains a challenge to the cardiac surgeon. Several authors have investigated alternative and more rigid methods of sternal fixation following median sternotomy. Reinforced sternal struts, complex wiring techniques, flat sutures of plastic, polyester and steel, and metal plates have all been described in the literature [LeVeen 1968, Taber 1969, Sirivella 1987, Scovotti 1991, Soroff 1996, Ozaki 1998]. However, the optimal method eliminating the problems of sternal closure remains extant.

This paper describes a novel approach to closure of the median sternotomy using simple cannulated screws placed on either side of the sternotomy. The concept is to use cannulated screws and wire to close a median sternotomy rather than wire on its own. Sternum screws would be inserted into the sternum, as shown in Figure 1 (◎), on either side of the sternotomy. Conventional stainless steel wire, currently used on its own to close the sternotomy, would be passed through the cannula of each screw. The sternum can then be closed and the wire twisted in the usual manner. The benefits of this approach will be demonstrated through a simple mathematical

*Submitted September 4, 2001; accepted September 9, 2001.*

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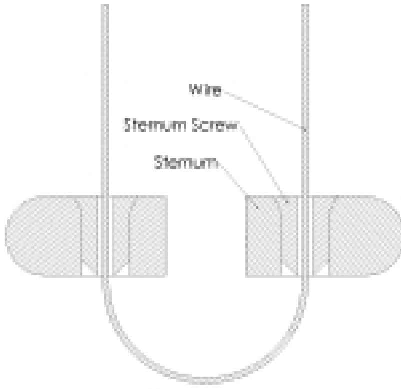


Figure 1. Schematic diagram of two sternum screws fitted into the sternum with a wire passed through the cannula of each screw.

model and mechanical testing of prototype screws. The next section presents a mechanical model and mechanical testing of prototype screws to demonstrate why using a screw plus wire is a preferred method to using wire on its own for preventing sternal dehiscence.

## MATERIALS AND METHODS

### *Mechanical model*

**Principles:** The interaction between the stainless steel wire and the sternum was modelled as a cylinder in contact with a planar surface, as shown in Figure 2 (◎). Cylinder 1 is the wire with a radius $R_{wire}$, Young's modulus $E_{wire}$ and Poisson's ratio $\nu_{wire}$. Cylinder 2 is the sternum with a radius $R_{sternum}$, Young's modulus $E_{sternum}$ and Poisson's ratio $\nu_{sternum}$. Mathematically, a planar surface has a radius equal to infinity, hence $R_{sternum = \infty}$. The mean pressure between the wire and the sternum can be determined from Hertzian contact analysis [Johnson 1995] by the equation:

$$P_{mean} = \frac{\pi}{4}\left[\frac{FE^*}{\pi R}\right]^{1/2} \quad (1)$$

where F is the applied force per unit length and E* is the combined elastic constant given by:

$$\frac{1}{E^*} = \frac{1-\nu^2_{wire}}{E_{wire}} + \frac{1-\nu^2_{sternum}}{E_{sternum}} \quad (2)$$

The relative radius R is defined by:

$$\frac{1}{R} = \frac{1}{R_{wire}} + \frac{1}{R_{sternum}} \quad (3)$$

In order to calculate the mean pressure acting between the wire and the sternum it was necessary to determine the unknown variables in equation 1, namely F, $E^*$ and R. The values used are described in the next sections.

**Combined elastic constant ($E^*$):** No information was found in the literature about the material properties of the human sternum and, therefore, the material properties of other bone were considered. The material properties of bone can vary considerably and no absolute values can be quoted [Reilly 1975, Rho 1997, Zioupos 1998, Zysset 1999]. Indeed, Zioupos & Currey [Zioupos 1998] have shown that the Young's modulus of cortical bone decreases with age. However, for this analysis some average values determined by Reilly and Burstein [Reilly 1975] for human femoral bone were used: a Young's modulus ($E_{sternum}$) of 17 GPa and a Poisson's ratio ($\nu_{sternum}$) of 0.46. The stainless steel wire had a Young's modulus ($E_{wire}$) of 200 GPa and a Poisson's ratio ($\nu_{wire}$) of 0.29 [Gere 1987]. Substituting the material properties for bone and steel wire into equation (2) we get:

$$\frac{1}{E^*} = \frac{1-\nu^2_{wire}}{E_{wire}} + \frac{1-\nu^2_{sternum}}{E_{sternum}} = \frac{1-0.29^2}{200\times10^9} + \frac{1-0.46^2}{17\times10^9}$$

giving a value for $E^*$ of $2 \times 10^{10}$ Pa.

**Relative radius of curvature (R):** If the wire is considered to rest on a flat bone surface, the radius of the sternum is infinite. Substituting into equation (3) we get:

$$\frac{1}{R} = \frac{1}{R_{wire}} + \frac{1}{R_{sternum}} = \frac{1}{R_{wire}} + \frac{1}{\infty}$$

so that $R = R_{wire}$, since $1/\infty$ is equal to zero.

It was decided to vary the radius of the wire to see how the pressure between the wire and sternum varied. By increasing R to a sufficiently large value, it can also represent contact between a screw and the sternum.

**Force per unit length (F):** The force, T, to maintain closure of a sternotomy was calculated by Casha et al. [Casha 1999] by modelling the thorax as a cylindrical pressure vessel, and is given by the equation:

$$T = rLP \quad (4)$$

where r is the radius of the chest, L is the height of the thoracic cavity and P is the distending pressure.

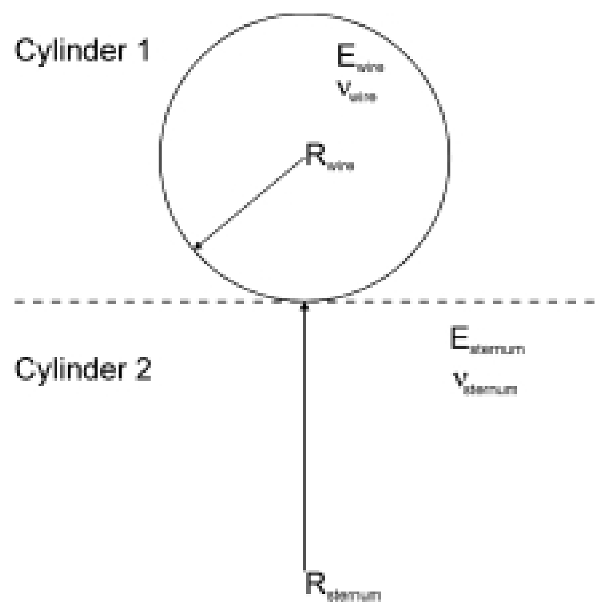


Figure 2. Schematic drawing of the sternum and wire modelled as two cylinders. (Cylinder 2 has an infinite radius).

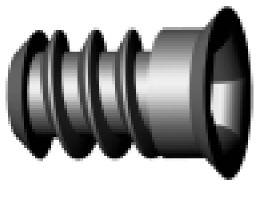

Figure 3. Rendered image of the prototype sternum screw.

Values suggested by Casha et al. for the radius of the chest (r) and the height of the thoracic cavity (L) were 0.15 m and 0.25 m, respectively. During coughing, the distending pressure can reach 300 mmHg (40 kPa) [Sackner 1988]. Substituting these values into equation (4) we get:

$$T = rLP = 0.15 \times 0.25 \times 40000 = 1500\ \text{N}$$

Thus, the total force required to keep the sternum closed is 1500 N. Since it is common to close the sternum with six wires, the force acting on each individual wire would be 250 N. For this analysis we need to know the force per unit length (F), i.e., dividing the force by the length it acts over. From surgical experience, the sternum has a thickness of approximately 0.01 m. Therefore, the force per unit length acting between the wire and the sternum will be 25 kN/m.

The value of pressure given by Casha et al. is likely for subjects with a large chest and a strong cough. Other authors suggest other values of pressure during coughing as 50 to 100 mmHg (6.7 to 13.3 kPa) or more [Sackner 1988]. Therefore, the force per unit length for these pressures would be 4.2 and 8.3 kN/m, respectively.

**Implementing the model:** The above values of the combined elastic constant ($E^*$), relative radius of curvature ($R_{wire}$) and force per unit length (F) were substituted into equation (1) to give the mean pressure between the wire and the sternum at pressures of 6.7, 13.3 and 40 kPa (corresponding to 50, 100 and 300 mmHg respectively). The radius of the wire ($R_{wire}$) was varied between 0.05 and 5 mm to see how the pressure varied. It should be noted that the magnitude of the stress is equal to the local pressure [Johnson 1985]. Hence, pressure and stress are interchangeable terms in the context of this paper.

### *Mechanical testing*

**Prototype screw:** A prototype sternum screw was manufactured and a rendered image is shown in Figure 3 (◎). It has an outer thread diameter of 6 mm, which surgical experience and previous anatomical studies have shown could be fitted into the human sternum [Ashley 1956]. The cannula down the centre of the sternum screw has a diameter of 2 mm to allow for a No. 5 stainless steel wire of 0.7 mm diameter (Ethicon Ltd, Edinburgh, UK) to easily pass through. It may be preferred that a range of screw diameters would be available to the surgeon.

**Testing methods:** Mechanical testing was undertaken to compare using wire on its own with a sternum screw plus wire. Blocks of balsa wood 120 x 15 x 12 mm were used as a sternum substitute. As balsa wood is a low modulus material, both the wire and sternum screw would dehisce during testing. For testing the wire on its own, a hole of diameter 1.4 mm was drilled into the centre of the wood. This diameter is the size of the main part of the needle (Ethicon Ltd, Edinburgh, UK) that is currently used to insert the wire. For testing the sternum screw, a hole of diameter 5 mm was drilled into the centre of the wood. A sternum screw could then be placed in the drilled hole. Clamps were used to secure the wood to a plate, mounted on the base of an 8511 Instron materials testing machine (Instron Ltd, High Wycombe, UK).

A loop of No. 5 stainless steel wire (Ethicon Ltd, Edinburgh, UK) was passed through the hole in the wood, as shown in Figure 4a (◎), and around a bar mounted on the actuator of the testing machine. The end of the wire was then twisted to close the loop. The actuator of the testing machine was set to rise at a rate of 25 mm/min. As the actuator rose, a tension was applied to the wire. Each test continued until the wire cut through the wood. The force at failure was noted. Ten tests were undertaken using wire on its own.

The whole procedure was then repeated for the wood fitted with the sternum screw. This time the wire was passed through the screw cannula. Ten tests were carried out using wood fitted with the sternum screw, as shown in Figure 4b (◎). The force at failure, as the screw cut through the wood, was noted.

## RESULTS

Figure 5 (◎) shows a graph of mean pressure (or stress) exerted by the wire on the sternum for different diameters of wire, as predicted by Hertzian contact analysis. This analysis

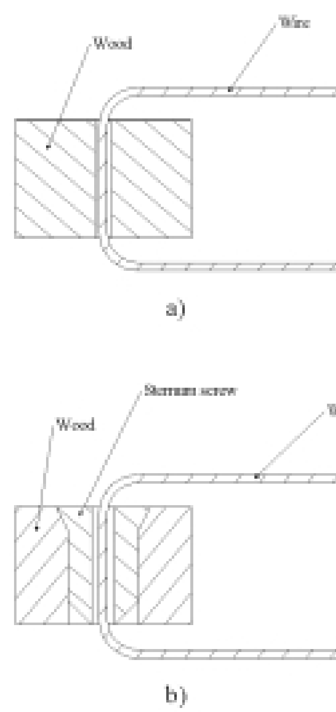


Figure 4. Schematic drawings showing (a) the wire passed through the wood; (b) the sternum screw inserted in the wood and the wire passed through the screw cannula.

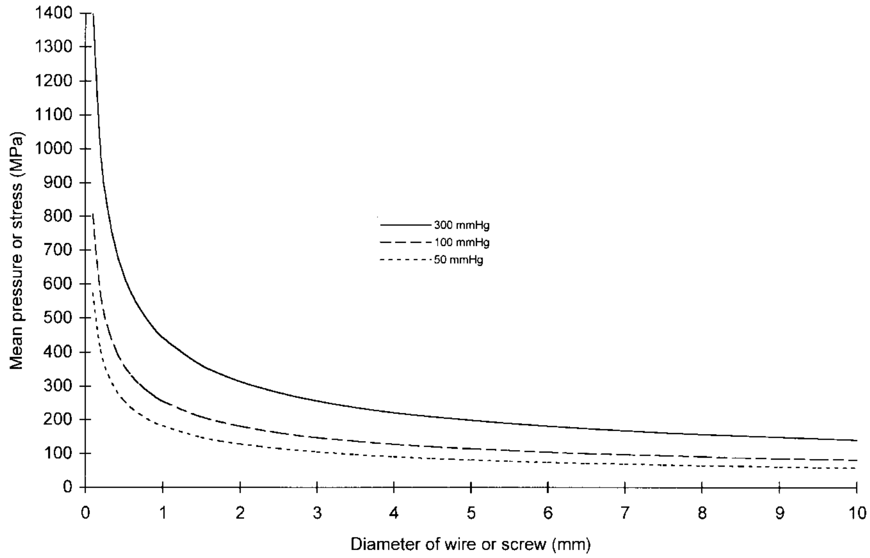


Figure 5. Variation of mean pressure (between the wire and sternum) with diameter of wire for chest pressures of 50, 100 and 300mmHg.

was performed for distending pressures of 6.7, 13.3 and 40 kPa (corresponding to 50, 100 and 300 mmHg respectively), to represent the range of values described in the literature [Sackner 1988, Casha 1999]. As expected, if the diameter of wire is small the mean pressure is high. With increasing diameter of the wire the pressure decreases.

In the mechanical tests, the wire cut through the wood at a mean load of 104 N. When the tests were undertaken with the sternum screw fitted to the balsa wood, the screw cut through the wood at a mean load of 209 N. The descriptive statistics for the tests are shown in Table 1 (◎). The data from the two tests were not normally distributed as assessed using the Anderson-Darling normality test. A Mann-Whitney test was, therefore, used as a significance test [Bland 1995]. It was found that there was a significant ($P = 0.007$) difference between the median values of the two tests. Thus the screw plus wire combination was stronger than wire on its own.

On closer examination of the data it was found that there was an outlier (greater than two standard deviations from the mean) in each set of data. The outliers were removed to investigate if they would influence the results. The mean failure load using wire on its own and for using the sternum screw plus wire reduced to 84 N and 183 N, respectively. The descriptive statistics are shown in Table 1. Removing the outliers led to the data being normally distributed. A two-sided two-sample t-test showed a significant ($P = 0.0003$) difference between the mean values. Therefore, these outliers did not influence the results.

## DISCUSSION

The most common and widely accepted method of sternum closure is to use No. 5 stainless steel wire (Ethicon Ltd, Edinburgh, UK) which has a diameter of 0.7 mm. Our mechanical model predicts that using this wire, with a high distending pressure in the chest, the mean stress between the wire and the sternum is high and at a magnitude comparable with the failure stress of bone. If a patient develops a cough with a distending pressure of 40 kPa (300 mmHg) the stress between the wire (diameter 0.7 mm) and the sternum is predicted to be about 500 MPa, which is likely to exceed the failure stress of the sternum. Reilly and Burstein report the mean ultimate compressive stress of human femur in the transverse and longitudinal directions to be 131 and 205 MPa, respectively [Reilly 1975]. Zioupos and Currey have shown that failure stress of cortical bone decreases from 170 MPa, for a specimen aged 35 years, by 3.7% per decade [Zioupos 1998].

The model, therefore, indicates that sternal dehiscence can occur during normal physiological loading of the chest, i.e. during coughing. This was also found in a cadaveric study when distracting forces were applied across a sternotomy that had been closed using wire [McGregor 1999]. Significant

Table 1. Descriptive statistics for the failure load in Newtons (N) for tests undertaken with wire and screw plus wire.

| | Number of tests | Mean (N) | Standard deviation (N) | Median (N) | Minimum (N) | Maximum (N) | 95% Confidence interval (N) |
|---|---|---|---|---|---|---|---|
| Wire | 10 | 104 | 74 | 77 | 39 | 279 | (51, 157) |
| Screw + wire | 10 | 209 | 93 | 188 | 108 | 439 | (143, 275) |
| Wire (outlier removed) | 9 | 84 | 43 | 63 | 39 | 166 | (52, 117) |
| Screw + wire (outlier removed) | 9 | 183 | 48 | 186 | 108 | 251 | (147, 220) |

amounts of sternal motion were detected with the application of a physiological force. It was concluded that activities of daily life could cause sternal wires to cut into the sternum.

The mechanical model in this paper indicates that the stress between the wire and the sternum decreases with increasing wire diameter. There is, therefore, the potential to prevent or reduce the occurrence of sternal dehiscence by using an increased diameter of wire. However, this would not be practical since it would be difficult to force the wire mounted on a needle through the sternum. Further, it would be strenuous to manipulate the wire and twist it in order to keep the sternum closed. The resulting knot would also be bulky and possibly palpable over the sternum. Other possibilities would be to have a sleeve or grommet around the wire in the area that contacts the sternum [McGregor 1999] or, the preferred method, to place cannulated screws through the sternum that would allow the wire to be placed through the screw cannula. The screw is the preferred method since it will be secured by the threads and may be inserted or removed easily if required.

Previous research on human sternum dimensions suggests that it would be possible to place a cannulated screw with an outside thread diameter of 6 mm through the sternum [Ashley 1956]. It is preferred that screws of varying length are available to the surgeon to accommodate various sternal depths. A screw of selected length would be placed on either side of the incision into a drilled hole so there is minimal protrusion into the chest cavity thereby eliminating the risk of iatrogenic injury. Once the screws are in place the conventional wires could then be placed through each screw cannula and twisted in the usual manner to close the sternum. Figure 5 (◎) shows the potential benefit of placing a cannulated screw into the sternum rather than using conventional wire on its own. The axis for wire diameter can now be read as outside thread diameter of a cannulated screw. For example, the mean stress between the wire (diameter 0.7 mm) and the sternum with a distending pressure of 40 kPa (100 mmHg) would be 305 MPa. If the wire was replaced with a cannulated screw (outside diameter 6 mm) and wire combination, the mean pressure between the screw and the sternum would be 104 MPa. Using a cannulated screw would reduce the contact stresses to below the fracture stress of bone and prevent sternal dehiscence.

The sternum screw has considerable advantages over other sternum reinforcing devices such as sleeves or grommets. Bone screw insertion practice is currently well developed and in extensive use by orthopaedic surgeons. Therefore, most hospitals practising the median sternotomy approach will have the necessary equipment for cannulated screw insertion. Moreover, the practice can be easily taught and adapted to the flat sternum. Insertion is simple and possibly more controlled that forcing a wire mounted on a stout cutting needle through a stiff sternum. The removal of the screw, for example in infection, is also simpler than for sleeves or grommets which have no threads to facilitate their removal. Another important advantage of the sternum screw is that, unlike conventional steel wires, the patient does not require reinsertion of wires through the sternum in the immediate post-operative recovery period in cases of re-exploration for mediastinal bleeding. The screws are left in situ and the wires re-threaded through the cannula for closure. This ensures no further weakening of the sternum. In cases of re-do sternotomy, currently on the increase, the original screws can be employed as markers to facilitate bone sawing and for rewiring after surgery. A further advantage is that the twisted wire ends may be bent back into the cannula instead of being buried beneath the sternal fascia to prevent potential damage to surrounding tissue. The results of the contact analysis show that significantly less contact stress is generated between the screw and bone than between wire and bone.

## ACKNOWLEDGMENTS

The authors wish to acknowledge the technical assistance provided by Mr. Edward Stevenson, Department of Bio-Medical Physics and Bio-Engineering, Aberdeen University, in manufacturing the sternum screws used in this study.

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## REVIEW AND COMMENTARY

***1. Editorial Board Member AN153 writes:***

Have the authors performed any cadaveric study?

***Authors' Response by Rajwinder S. Jutley:***

This paper is a theoretical paper backed up with simple mechanical testing to look at the feasibility of the sternum screw idea. In the United Kingdom, following a major scandal involving retained children's organs, human cadaveric material is not possible to obtain. However, following the encouraging results of the theoretical analysis and mechanical testing, cadaveric sheep sterna were used to evaluate the efficacy of the sternum screw. Sheep sterna have been used by study groups for biomechanical testing of sternal closures (Casha et al., European Journal of Cardiothoracic Surgery, 19:249-253, 2001). These results will be the subject of separate papers.

***2. Editorial Board Member GX21 writes:***

The paper has two complementary parts - the theoretical equations and the physical model. The results of the former are given in Figure 5 and the latter in Table 1, but the correspondence between these two approaches is not clear. Could the 20 values achieved in the model be superimposed on Figure 5 to demonstrate the agreement?

***Authors' Response by Rajwinder S. Jutley:***

Superimposing the 20 values onto Figure 5 is not possible since different things are being measured and calculated. For the theoretical model we were calculating mean pressure (or stress) between the wire and the sternum for increasing diameter of wire or screw. For the physical model we were comparing the failure force between using a standard sternal closure wire and a manufactured sternum screw. The theoretical model shows that the stress is reduced if you use a sternum screw with a greater diameter. This observation is backed up by the physical model, which shows that the force to failure is greater when a sternum screw is used.