Fatigue testing median sternotomy closures

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Abstract

Objective: Sternal dehiscence is commonly due to wire cutting through bone. With a biological model, we measured the rate of cutting through bone, of standard steel wire closure, peristernal steel wire, figure-of-eight closure, polyester and sternal bands sternotomy closure techniques.

Methods: Polyester, figure-of-eight, peristernal and sternal band closures were tested against standard closure eight times using adjacent paired samples, to eliminate biological variables. Fatigue testing was performed by a computerized materials-testing machine, cycling between loads of 1 and 10 kg. The displacements at maximum and minimum loads were measured during each cycle. Cutting through, manifested by the displacement at the maximum load between the 1st and 150th cycles was measured. The percentage cut-through of each closure method versus standard closure was calculated.

Results: The differences in the displacement between each of the polyester (1.01 mm), figure-of-eight (0.52 mm), peristernal (0.72 mm) and sternal band (0.66 mm) groups versus standard closure (0.22, 0.22, 2.1, 3.2 mm) in the paired samples were statistically significant (Student’s paired t-test; \( p < 0.01 \)). There were statistically significant differences in the percentage cut-through of polyester, figure-of-eight, peristernal and sternal bands (ANOVA, \( p < 0.001 \)), versus standard closure.

Conclusions: In our sheep sternum model, we have quantified the differing rate of cutting through bone of five types of median sternotomy closure techniques. We have controlled for bone variables by testing each closure versus standard closure using paired adjacent bone samples. Peristernal and sternal band closure techniques are significantly superior to standard closure. The use of polyester and figure-of-eight closures requires caution. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Sternotomy; Biomechanics; Fatigue

1. Introduction

Median sternotomy is the incision of choice by cardiac surgeons for access to the heart because it provides an excellent mediastinal exposure [1,2], is relatively pain free and heals well. However, there is a risk of sternal separation or dehiscence of between 0.5 and 2.5% [3], with a mortality rate of between 10 and 40% [4]. About two thirds of sternal dehiscences are associated with infection [5], and the other third due to mechanical breakdown.

The most important factor in preventing sternal dehiscence and mediastinitis is a stable sternal approximation [6]. Dehiscence often occurs within the first 2 weeks postoperatively [7], before bone healing is clinically significant. We have previously compared the biomechanical characteristics of median sternotomy closure techniques using a mechanical model [8]. The aim of our study was to assess and quantify the rates of wire cutting through bone, of various common median sternotomy closures, by fatigue testing a biological model, since it has been shown that fixation techniques which ensure a secure, rigid fixation of the sternum result in earlier union with primary osseous healing or osteosynthesis [9].

2. Materials and methods

A biological model of the sternum was developed, and tested over a range of loads and displacement velocities. Sheep sternum was used, as the use of bovine bone was not permitted in the UK due to the CJD crisis, and pig sternum differs from the human in being keel shaped [10].

Sheep sternums were divided using a band saw. The sternal halves were cleaned down to periosteum and 2.5 cm samples were cut. Bone thickness and cortex/medulla ratios were measured. One of a pair of adjacent samples of sheep sternum was randomly assigned to the standard stainless steel closure method. The other sternal half of the pair was randomly assigned to one of the five other closure methods.
steel closure group. The other sample of the pair of adjacent bone samples was assigned to no. 5 gauge polyester (Ethibond, Ethicon Ltd., Edinburgh, UK), figure-of-eight, peristernal or sternal band (Sterna-band, Stony Brook Surgical Innovations, Inc., New York, USA) groups. Each closure technique was tested in eight pairs of experiments. The sternal portions were held in place in a purpose-built jig with serrated edges. No. 5 gauge stainless steel wire (Ethicon Ltd.) was used in the standard steel wire, figure-of-eight and peristernal groups. Fatigue testing was performed by a computerized materials-testing machine (Autograph ASG-10KN, Shimadzu Corporation, Japan), cycling between loads of 1 and 10 kg, using a displacement velocity of 100 mm/min. Three cycles were performed prior to each experiment in order to ‘take up slack’ in the wire. Displacement data were recorded every quarter-second using a data capture card (Amplicon PC 20G, Amplicon Ltd., UK). Signal analysis was performed using software (DashConv, Lucent Solutions, Bradford, UK). The data analysis was performed using Excel (Microsoft, Richmond, USA).

Using a mathematical model [9,11] that describes the force placed across a sternotomy closure, \( T = rlP \), where \( P \) is the distending pressure, \( r \) is the radius, \( l \) is the height of the chest, and \( T \) is the force across the sternotomy, the load of 10 kg represents a cough equivalent to 120 mmHg intrathoracic pressure, assuming that six wires are used for the closure.

The displacement at maximum and minimum loads was measured during each cycle. The results were obtained in the form of displacement curves. Cutting through bone, was measured as the displacement at the maximum load between the 1st and 150th cycles.

2.1. Statistical analysis

Each type of closure was compared with standard steel wire closure as a control. The values are expressed as means \( \pm \) SD in Table 1. Statistics were carried out using the paired \( t \)-test to compare wire cutting through bone in the four paired sets. The Bonferroni method was used to adjust the \( P \) values from the paired \( t \)-test for multiple comparisons. Analysis of variance (ANOVA) was used to assess differences between the different closure types. Due to the skewed distribution of the data, logarithmic transformation of the raw data was performed for the paired \( t \)-test and ANOVA test. A \( P \) value of less than 0.05 was considered significant.

3. Results

There was no statistical difference in the characteristics of the paired bone samples with regard to bone thickness and cortex/medulla ratios. The results for the wire cutting through bone parameters are presented together with 95% confidence intervals (CI) in Fig. 1a–d. Cutting through bone with polyester, figure-of-eight, peristernal and sternal band groups were significantly different than with standard stainless steel wire closure. The results for the paired \( t \)-test (Bonferroni correction) for the eight pairs of experiments showed significance and are shown in Table 1. There were statistically significant differences in the percentage cut-through between the different closure types at the 150th cycle (ANOVA, \( P < 0.001 \)), shown in Fig. 2 and Table 2.

4. Comment

No median sternotomy closure technique is entirely free of the risk of sternotomy dehiscence. The purpose of this study was to assess the fatigue properties of various median sternotomy closure techniques using a biological bone model. Due to the high degree of inter-specimen variability [12], adjacent bone samples were tested with standard sternum closure against a test method (polyester, figure-of-eight, peristernal or sternal bands). Therefore, each bone sample had a standard wire control. The variability in bone quality is shown by the different values for standard steel wire closure. A standard method of fatigue testing was used [2,13].

The curve for the stainless steel wire in Fig. 1 is very flat, as the rate of cutting through bone diminishes progressively with repeated load cycles. This may be due to bone compaction occurring under the ‘footprint’ of the wire reducing further cutting through. The shape of the stress strain curve for femoral trabecular bone is similar to our results, as opposed to the shape of the stress strain curve for femoral cortical bone [14], indicating similar biomechanical characteristics between femoral trabecular bone and sternum bone.

Polyester has been utilized as the method of closure of choice in osteoporotic sternums in our institutions, especially in the case of elderly females. Our results show that polyester cuts through bone significantly faster than standard steel wire closure, at over four times the rate. The curve for polyester in Fig. 1a shows a continuing and constant rate of cutting through bone. The rate of cutting through by polyester (1.01 mm) is almost half that (2.0 mm) considered as sternotomy failure [13], after only 150 cycles.

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### Table 1

<table>
<thead>
<tr>
<th>Closure type</th>
<th>Displacement (mm)</th>
<th>Student’s ( t )-test (Bonferroni corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester</td>
<td>1.01 ± 0.17</td>
<td>0.001</td>
</tr>
<tr>
<td>Figure-of-eight</td>
<td>0.52 ± 0.36</td>
<td>0.001</td>
</tr>
<tr>
<td>Peristernal</td>
<td>0.72 ± 0.51</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Sternal band</td>
<td>0.66 ± 0.26</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

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^ Values are expressed as means \( \pm \) SD.

^ The Bonferroni adjusted results of Student’s \( t \)-test for each closure method versus standard steel closure are shown.
Based on the formula, $T = r l P$ [9,11], chest wall tension is likely to be smaller in elderly females as they have a smaller chest size compared with young males and are less likely to be able to generate high intrathoracic pressures on coughing. The formula predicts that chest wall tension is related to the square of the chest size. Therefore, a population of elderly females, at high risk of osteoporosis, will develop low chest wall tension on coughing, which lessens the chance of sternotomy dehiscence.

Another factor that may diminish the risk of cutting through bone in polyester closures is the tendency to use more polyester sutures (8–10) for each median sternotomy closure, compared with stainless steel wire sutures (6–8).

Although the nominal gauge of the stainless steel wire and polyester is identical (no. 5), under load, polyester stretches significantly more than stainless steel wire, thus decreasing the actual diameter of the suture. We believe that it is this high elasticity of polyester compared with wire [9], that makes polyester cut through bone significantly more than stainless steel wire.

Another factor against the use of polyester is that, mechanically, polyester closure is less rigid, by a factor of more than ten times, than a standard steel wire closure [9]. Fixation techniques which ensure a secure, rigid fixation of the sternum result in earlier union with primary osseous healing (osteosynthesis) [15].

Sternal instability, wound infection, osteomyelitis and dehiscence are related [16]. Theoretically, there is a higher risk of infection with Ethibond inherent in its nature as a

<p>| Table 2: Percentage cut-through of different sternotomy closures versus standard closure |
|-------------------------------------------------|---------------|-------------|-------------|</p>
<table>
<thead>
<tr>
<th>Closure type</th>
<th>Number of cycles</th>
<th>25</th>
<th>75</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester</td>
<td></td>
<td>427 ± 157</td>
<td>454 ± 109</td>
<td>453 ± 137</td>
</tr>
<tr>
<td>Figure-of-eight</td>
<td></td>
<td>234 ± 72</td>
<td>196 ± 37</td>
<td>232 ± 35</td>
</tr>
<tr>
<td>Steel wire</td>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Peristernal</td>
<td></td>
<td>43 ± 22</td>
<td>40 ± 14</td>
<td>34 ± 7</td>
</tr>
<tr>
<td>Sternal bands</td>
<td></td>
<td>51 ± 29</td>
<td>34 ± 14</td>
<td>23 ± 8</td>
</tr>
</tbody>
</table>

*a Values are expressed as mean ± SD.
braid suture, compared with steel wire as a non-braid suture. Also, the coating on Ethibond (braided polyester coated with polybutylate) increases the adherence of bacteria to the suture material. In an in-vitro study [17], the adherence of staphylococci to Ethibond was three times higher than Mersilene (braided polyester). In one study using polyester closure, Ethibond was used in 2437 patients, with a sternal revision rate of 1.8%, painful stitch granuloma of 0.7% and sternotomy dehiscence of 0.9% [18].

The trans-sternal figure-of-eight closure cuts through bone at over twice the rate of standard sternal wire closure. The figure-of-eight closure has only 65% of the rigidity of standard wire closure [9]. The peristernal interlocking figure-of-eight wire closure [6,19] was not tested, but would be expected to cut through bone significantly less than standard trans-sternal figure-of-eight wires [20]. The standard trans-sternal figure-of-eight closure would be useful across a fracture in the sternum where its configuration acts to compress the sternal fragments together. However, in a routine closure, it is inferior to a standard closure in terms of rigidity or fatigue resistance, and therefore, standard or peristernal closures would be preferable.

Peristernal closure cuts through bone at approximately just over a third the rate of standard sternal wire closure. The resistance of peristernal closure to cutting through bone is due to lateral reinforcement through inclusion of the lateral cortex of the sternum. For example, for a sternum that is 11 mm thick with cortices 2 mm thick, a wire placed peristernally is in contact laterally where the cortices merge with 11 mm of cortical bone. A wire placed through the sternum is in contact with the anterior and posterior cortices, and therefore, with 4 mm of cortical bone. Peristernal closure is also more rigid than polyester or figure-of-eights closure [9]. The wire placed through the sternum has an area of contact that is 36% that of the wire placed peristernally. Peristernal closure is very simple technically, and multiple wires can be inserted up to a wire for every 10 kg body weight [21] if required.

Sternal band closure cuts through bone the least quickly, at approximately a quarter the rate of standard sternal wire closure. However, in this comparison, we have compared one Sterna-band versus one wire. In practice, more wires are usually used in a closure (6–8) than Sterna-bands (four). Therefore, some of the biomechanical advantage would be lost. Sterna-band closure is also, however, twice as rigid as sternal wire closure [9]. The resistance of Sterna-band to cutting through bone is due to its width and area of contact. For a wire of 0.787 mm diameter (no. 5), the area of contact is 1.24 mm/unit length. For the Sterna-band, the area of contact is approximately 3.64 mm/unit length. The ratio of the areas of contact is 34%, predicting the differential rate of cutting through bone. Sterna-band closure also results in a reduction in both postoperative pain and postoperative hospital stay [22].

In conclusion, we have shown, in an ex-vivo biological model using paired adjacent sternal bone samples, the differing rate of cutting through bone of five types of median sternotomy closure techniques. We have controlled for bone variables by testing each closure versus standard closure using adjacent bone samples. Peristernal and sternal band closure techniques are significantly superior on fatigue testing to standard closure. The use of polyester and figure-of-eights requires caution as they cut through bone significantly faster than the standard wire closure. Since polyester also produces a significantly less rigid closure mechanically than stainless steel, we question its use in median sternotomy closures.

References