Age-related change of postoperative pain location after Nuss procedure for pectus excavatum

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Abstract

Objective: The present study aims to evaluate age-related change of postoperative pain after the Nuss procedure by referring to clinical cases, and to elucidate the biomechanical aetiology of the change by using the finite element method.

Methods: Twelve paediatric patients (paediatric group: 9.4 ± 2.3 years old) and 13 adult patients (adult group: 26.3 ± 5.5 years old) who received the Nuss procedure for pectus excavatum were included in the study. On the second postoperative day, the patients were asked to indicate regions on the thorax where they felt the greatest pain. The locations of these regions were compared between the two groups. In addition, stress-distribution patterns were examined using finite element models produced by simulating the thoraces of the patients. The stress-distribution patterns were compared between the two groups.

Results: The patients of the paediatric group and adult group tend to have pain on the anterior and posterior regions of the thorax, respectively. The finite element study revealed that paediatric thoraces and adult thoraces develop intensified stresses in the anterior region and the posterior region, respectively.

Conclusion: Postoperative pain tends to occur in the anterior part of the thorax for paediatric patients and in the posterior part of the thorax for adult patients, reflecting the stress distributions of these two distinct patient populations.

Keywords: Pectus excavatum; Thorax; Pain; Stress; Finite element analysis

1. Introduction

Pectus excavatum is one of the most common congenital deformities of the thorax [1,2]. Deformation of the thorax impairs patients' quality of life [3]. In particular, adolescent patients tend to develop introverted personalities due to the presence of deformity. The Nuss procedure — introduced at the end of the past century — enabled correction of the deformed thoraces with simpler and less invasive manoeuvres than conventional methods [4–6], making the surgical treatment of pectus excavatum easier than before.

Despite these advantages, the Nuss procedure is not free from complications. Since the thoraces are forcibly distorted by the placement of correction bars, patients often develop serious postoperative pain [7,8]. Because of the pain, sputum evacuation is often disturbed, causing pneumonia. When the pain is intolerable for the patient, premature removal of the bars may be required.

Understanding the pattern of postoperative pain occurring on the thoraces after the Nuss procedure would provide useful information in preventing these complications. Although the Nuss procedure was mainly used for paediatric patients immediately after its introduction, the application of this method is expanding to adult patients [9–12]. The present study elucidates age-related change of pain location after the Nuss procedure. In the former part of the study, pectus excavatum patients treated with the Nuss procedure are classified into two age-based groups, and the location of postoperative pain is compared between these two groups. In the latter part of the study, stress-occurrence patterns on the thoraces are compared between the two groups using finite element models. Thereby, the aetiology of the differences in pain-occurrence patterns between the two groups is elucidated from a biomechanical standpoint.
2. Materials and methods

2.1. Study sample

Twenty-five patients, who received the Nuss procedure for pectus excavatum at the authors' institutes between June 2005 and August 2009, were involved in the study. Twelve patients were under 14 years of age; 13 patients were above 18 years of age. These patients were categorised as paediatric group (9.4 ± 2.3 years of age, seven males and three females) and adult group (26.3 ± 5.5 years of age, eight males and five females), respectively. For all 25 patients, the concavity of the thoraces was corrected by placing one bar at the fifth inter-costal space. Haller's index scores showed no statistically significant differences for the two groups (6.0 ± 2.8 for the paediatric group; 5.9 ± 2.6 for the adult group).

2.1.1. Clinical study

On the second postoperative day, regions of the thorax where patients felt pain were identified. To identify the painful locations, the thorax was mapped by dividing it into small regions (Fig. 1, left). On the left and right sides of the thorax, each rib, together with its corresponding inter-costal space, was divided into six regions by equidistant arcs, as shown on the right in Fig. 1. For the arcs, designators ranging from R1 to R6 or L1 to L6 were assigned, depending on distance from the spine. Each region of the thorax was named after the number of the corresponding rib, and the indicator for the appropriate arc. For instance, the three regions that constitute the anterior half of the third rib and inter-costal space on the right side of the thorax are termed III–R6, III–R5 and III–R4 (Fig. 1, left). The number of patients who had pain in each region was tallied for the paediatric and adult groups. Patients typically had pain in three to six regions. Distribution patterns for the paediatric and adult groups were evaluated using bar-graph plots.

2.1.2. Biomechanical study

Prior to operation, computed tomography scanning is performed for all patients, for the planning of the operation. For each of the twenty-five patients, a simulation model is produced using the CT data in the following way. First, the part representing the thorax is extracted from the CT data using graphic software (Rhinoceros 4.0, Applicraft Co., Tokyo, Japan). Then, the data are further edited using structural analysis software (ANSYS10.0, ANSYS Co., Chicago, IL, USA) to produce a finite element analysis model. In the models, each rib, the sternum, and the 12 vertebrae are simulated using 6-, 18- and 36-beam elements, respectively. The costal cartilages are simulated using different numbers of beam elements, according to morphological complexity. The 1st to 5th costal cartilages, 6th to 10th costal cartilages and 11th to 12th costal cartilages are modelled with 5-, 5- to 10- and 3-beam elements, respectively. Kopperdahl provides a formula by which Young's moduli can be obtained based on the CT density of bone. This formula is $E = 34.7 + 3230QCT$, where $E$ and $QCT$ refer to Young's modulus (in megapascals) and CT density (in grams per millilitre), respectively.[13]. Using this formula, Young's moduli are calculated and allotted to each component of the thorax. Thus-obtained Young's moduli are 1580—1920 kg mm$^{-2}$ for cortical bone; 160—200 kg mm$^{-2}$ for cancellous bone; 60—108 kg mm$^{-2}$ for costal cartilage.

Using the finite element method, the Nuss procedure is simulated in the following manner (Fig. 2). First, three points are marked at the fifth inter-costal space. These three marking points are, P — the rib—cartilage junction on the right side; Q — the inferior aspect of the sternum; and R — the rib—cartilage junction on the left side. By elevating Q until it reaches the line connecting P and R, the application of a correction bar is simulated. Under these dynamic conditions, stresses on the thoraces are calculated using the finite element method. For each model, the point at which the greatest stress occurs is marked.

2.1.3. Statistical evaluation

For the purpose of comparing pain distribution patterns of the paediatric and adult groups, statistical evaluation is performed. According to the designators defined later, regions of the thorax are categorised into two parts. Regions with designators R4—R6 or L4—L6 are defined as 'anterior'; regions with designators R1—R3 or L1—L3 are...
defined as 'posterior'. Referring to this partition, the results of the clinical and biomechanical studies are evaluated by comparing these two groups. For statistical calculation, SPSS version 10 for Windows (SPSS Inc., Chicago, IL, USA) is used. $P$-values < 0.05 are considered to be statistically significant.

2.1.3.1. Statistical evaluation of clinical study. The location of the patients’ pain is evaluated by summing up the numbers of painful regions within the anterior and posterior classifications. These scores are defined as pain frequency scores. Suppose a group consists of two patients. When one patient has pain in IV—R1 and IV—R4, and the other has pain in III—R1, III—R2 and IV—R5, the posterior pain frequency score for this group is 3, since one region (IV—R1) in the first patient and two regions (III—R1 and III—R2) in the second patient belong to the posterior classification.

In this way, anterior and posterior pain frequency scores are calculated for the paediatric and adult groups. Based on the calculated data, the hypothesis 'the anterior and posterior pain frequency scores present equal proportion between the paediatric and adult groups' is statistically evaluated using Pearson’s chi-square test.

2.1.3.2. Statistical evaluation of biomechanical study. The location of the greatest stresses on the thorax (anterior or posterior) was examined for each patient. Based on this result, the hypothesis 'the point at which the greatest stress occurs is equally distributed to the anterior and posterior areas in the paediatric and adult groups' was statistically evaluated using Pearson’s chi-square test.

Furthermore, a quantitative comparison of the maximum stresses was conducted between the paediatric and adult groups. Since the maximum stresses presented a skewed distribution, the Mann–Whitney test was used for the comparison.

3. Results

3.1. Clinical study

Frequency of pain for the thoracic regions is demonstrated in Fig. 3. The patients of the paediatric group and adult group tend to have pain on the anterior and posterior regions of the thorax, respectively.

3.2. Biomechanical study

Representative stress-distribution patterns for the paediatric group and adult group are demonstrated in Figs. 4 and 5, respectively. The distribution of the points of greatest stress on the thoraces is demonstrated in Fig. 6. Intensified stresses develop on the anterior part of the thoraces for the paediatric group and on the posterior part of the thoraces for the adult group.
3.3. Statistical evaluation

3.3.1. Clinical study

With the paediatric group, the anterior and posterior pain frequency scores were 44 and 2, respectively; with the adult group, the anterior and posterior pain frequency scores were 14 and 76, respectively. Pearson’s chi-square test on these data denies the validity of the hypothesis ‘the anterior and posterior pain frequency scores present equal proportion between the paediatric and adult groups’, with a \( P \)-value < 0.0001. Thus, different distribution patterns for paediatric and adult patients — paediatric patients tend to have pain on the anterior side of the thorax, and adult patients tend to have pain on the posterior side of the thorax — are proven.

3.3.2. Biomechanical study

In all 12 thorax models for the paediatric group, anterior points were identified for the greatest stress; in all 13 thorax models for the adult group, posterior points were identified for the greatest stress. Pearson’s chi-square test on these data denies the validity of the hypothesis ‘the point at which the greatest stress occurs is equally distributed to the anterior and posterior areas in the paediatric and adult groups’, with a \( P \)-value < 0.0001. Thus, it is biomechanically proven that the location of the maximum stresses takes different patterns between paediatric and adult patients, demonstrating that ‘the maximum stresses tend to develop on the anterior side of the thorax in paediatric patients, and on the posterior side of the thorax in adult patients’.

The averages and ranges of the maximum stresses for the paediatric and adult groups are shown in Table 1. The maximum stresses are significantly greater (\( P < 0.001 \)) for the adult group than for the paediatric group.

4. Discussion

In the Nuss procedure, thoraces with pectus excavatum are forcibly corrected by reconfiguring the deformed ribs and cartilages using correction bars [14]. Because of this forcible correction, some patients develop serious pain postoperatively.

The present study consists of two parts — pain evaluation in clinical cases and theoretical reasoning using a biomechanical technique. The former part reveals differences in pain-occurrence patterns between paediatric and adult patients, demonstrating that paediatric patients tend to have pain on the anterior side of the thorax, and adult patients tend to have pain on the posterior side of the thorax.

Seeking reasons for these differences and assuming that pain occurring on the thoraces correlates with the intensity of local stresses, the authors examined stress-occurrence patterns on the thoraces, and found that the maximum stresses tend to develop on the anterior side of the thorax in paediatric patients, and on the posterior side of the thorax in adult patients.

To evaluate the stresses occurring on the thoraces, the authors used the finite element method, an established research technique used for biomechanical analyses of various organs, including the bones [15,16], skin [17], cardiac valves [18] and vessels [19]. The results reveal that the maximum stress occurs in the anterior region of the thorax for paediatric patients and in the posterior region for adult patients, supporting the findings of the clinical study.

Why do the stresses present different occurrence patterns between adult and paediatric patients? The difference can be explained by referring to the differences in flexibility of the thoraces of paediatric and adult patients (Fig. 7). The material properties of the costal cartilage present differences according to patients’ ages. The costal cartilage of paediatric patients is flexible, with little ossification. Therefore, a child’s sternum can be elevated easily. Since the posterior part of the thorax — mainly consisting of bone — is much harder than the anterior part, the transformation of the anterior part exerts little stress on the posterior part. On the other hand, due to ossification, the costal cartilages of adult thoraces are much harder than those of paediatric patients. Because of this hardness, the correction bar needs to exert a considerable upward force to elevate the sternum.

Table 1

<table>
<thead>
<tr>
<th>Child group</th>
<th>Adult group</th>
<th>Statistical significance</th>
</tr>
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<tbody>
<tr>
<td>0.64 (0.34–0.96)</td>
<td>2.10 (1.42–2.90)</td>
<td>( P &lt; 0.001 )</td>
</tr>
</tbody>
</table>

The figures outside the parentheses are the average values for the two groups; the figures inside the parentheses indicate the range of the data for each group.
Accordingly, strong counteracting forces work on the correction bar, pushing it in the posterior direction (red arrows in Fig. 7). This force is transmitted to the posterior part of the thorax, causing intensified stresses there. As demonstrated in Table 1, significantly greater stresses develop on the thorax for adult patients than for paediatric patients, signifying that the correction of the deformed thoraces by means of the Nuss procedure is biomechanically more difficult for adult patients than for paediatric patients. This finding is compatible with other reports referring to higher rates of complication for adult patients than for paediatric patients [9, 20].

The present study reveals that paediatric and adult patients tend to develop pain in different locations of the thorax. The present study further provides a biomechanical explanation for the findings. The knowledge obtained by the present study can be useful in the management of postoperative pain after the Nuss procedure. Since pain tends to locate in anterior regions for paediatric patients and in posterior regions for adult patients, effectiveness of pain control can be improved by selectively anaesthetising the corresponding regions. For pain control after the Nuss procedure, injection of local anaesthetics is often conducted through an epidural catheter [21]. Although an epidural injection is an effective pain-control method, it does not have such selectiveness, equally desensitising anterior and posterior regions of dermatomes. However, the continuous administration of local anaesthetics through subcutaneous infusion systems [22] and cooling enables region-selective pain control. By applying these methods in addition to continuous epidural injection, postoperative pain can be effectively controlled.

Apart from pain control, perception of the age-related pain patterns is also useful in the detection of possible complications. For instance, it is natural that an adult patient has pain on his/her back after the operation, since great stresses tend to develop there. However, if an adult patient has strong pain in the anterior region of the thorax, screening of possible complications is advised. Such complications as cardiac tamponade or haematoma due to injury of the internal mammary vessels can be causative factors of the pain. Thus, recognition of typical pain-occurrence patterns can contribute to early detection of complications.

5. Conclusions

The present study elucidates age-related change of pain locations after the Nuss procedure for pectus excavatum. Clinical evaluation demonstrates that pain tends to develop in the anterior regions of the thoraces for paediatric patients and in the posterior regions for adult patients. These findings are compatible with the findings of biomechanical study of finite element models demonstrating that stresses concentrate on the anterior part of the thoraces in children and on the posterior part in adults. The knowledge that painful regions present different locations between paediatric and adult patients is potentially useful for controlling postoperative pain and in detection of complications.
Pain is one of the most important issues in postoperative management of patients undergoing surgical correction of pectus excavatum. In order to optimise the recovery process and reduce morbidity, effective analgesia is mandatory. The acute pain that accompanies the Nuss procedure is primarily caused by the dislocation of costovertebral joints following the forceful repositioning of the sternum. Common in thoracic surgical procedures, noxious stimuli are due to stretching of the surgical area during mobilisation, breathing and coughing [1]. Inadequately treated pain in patients undergoing the Nuss procedure inhibits the patient’s ability to breathe deeply and cough forcefully. This could result in accumulation of secretions, atelectasis, and, eventually, pneumonia. Moreover, persistent, intolerable pain may lead to early bar removal. An improved understanding of the procedure-specific postoperative pain pattern and its consequences is therefore important as reported by Nagasao et al. published in this issue of the journal [2].

A preoperative chest CT simulation model was constituted of 25 patients. Using the finite element method, the Nuss procedure was simulated and the point at which the greatest stress occurred was marked. The greatest stress developed on the anterior side of the thorax in children and on the posterior side in adults. The location of the greatest stress in the simulation model corresponded to the location identified on the second postoperative day by patients undergoing the Nuss procedure. The children tended to report pain located on the anterior side of the thorax, whereas adults tended to report pain on the posterior side of the thorax.

Neither the postoperative analgesic regimen nor the amount of analgesics used was known to the reader. If the assessment of pain location were performed during epidural analgesia, the findings could be confounded by technical problems with the generation of an epidural block because of the presence of unilateral blockade and/or lack of segmental coverage. Patients were asked to indicate the location of pain on their chest, but pain location was, unfortunately, unaccompanied by reporting and description of pain intensity. Pectus severity as measured by symmetry/asymmetry was not assessed. Thus, whether the simulated model corresponded to the actual postoperative shape of the thorax remains uncertain. Despite these methodological uncertainties, the study has important clinical implications. First of all, the authors assessed the location of postoperative pain following the Nuss procedure in detail and, secondly, the authors provided a biomechanical explanation to their findings.

Their findings seem biologically plausible and are consistent with their previous findings [3] and they corroborate the findings of others [4—6]. Hence, there is now growing evidence that the stress created by the repositioning of the sternum is primarily concentrated around the main growth zones in the chondrocostal junctions and in the connection between the ribs and the vertebra [3,7]. Considering the forces involved in the repositioning of the sternum, Fonkalsrud and Reemtsen [4] showed that elevation of the sternum in patients with pectus excavatum in three different age groups (<11 years, 12—18 years and >18 years) required a traction equivalent to 6.8 kg, 14.5 kg and 18.5 kg, respectively. The required traction for elevation of the sternum appeared to be similar for patients with Haller indices <5 (12.9 kg), but it was demonstrated to be significantly increased in patients with Haller Indices >5 (18.6 kg). Weber et al. [5] also found that the traction required for elevation of the sternum depended on patient age, and that it may reach 250 N. Finally, Boia et al. [6] found...