Is a Shorter Bar an Effective Solution to Avoid Bar Dislocation in a Nuss Procedure?

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Background. **A variety of expedients to minimize bar dislocation in the Nuss procedure has been reported. The aims of this study were to create a mathematical model to define mechanical stresses acting on bars of different lengths in the Nuss procedure, and to apply this model to clinical scenarios.**

Methods. **Finite element model analyses were used to outline the mechanical stresses and to mathematically define different cases. Data from a group of patients with procedures carried out using standard Nuss criteria (NC group; bars half an inch shorter than the distance between the mid-axillary lines) were compared with data from a second group treated by applying model-based suggestions (MS group; bars approximately 3 inches shorter than the distance between the mid-axillary lines).**

Results. **Mean patient age in the NC group (48 cases) was 16.4 years old (84% males). The mean operating time was 57 minutes, and the mean bar length was 14.19 inches. There were 5 cases (10.4%) of bar dislocation. Mean patient age in the MS group (88 cases) was 16.2 years old (87% males). The mean operating time was 43 minutes and the mean bar length was 11.67 inches. There was only 1 bar dislocation, a reduction from 10.4% (NC) to 1.1% (MS) odds ratio 0.0989 (confidence interval 0.0112 to 0.8727), p = 0.0373.**

Conclusions. **A shorter Nuss bar reduces tension on the sutures applied at bar extremities. This leads to enhanced bar stability and a reduced risk that the bar will flip. The use of a shorter Nuss bar may reduce the incidence of bar dislocation.**

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Pectus excavatum (PE) is the most common anterior chest wall deformity and is associated with cardiorespiratory and cosmetic problems. Until 2 decades ago, the most frequent operation in use for PE correction was the Ravitch procedure. This entailed complete removal of the abnormal cartilages while sparing the perichondrium, followed by sternal elevation and stabilization [1]. In 1998, Nuss and colleagues [2] described a minimally invasive technique for anterior chest wall remodeling, employing a metal bar and avoiding the need for cartilage resection. This approach was designed to enable improved functional and cosmetic outcomes. However, this technique is associated with a high risk of postoperative bar displacement, especially in the early postoperative period [3], due to an imbalance between the high rotational torque and a poor bar stabilization or fixation.

To date, several strategies have been described in order to minimize the risk of bar dislocation. Although a lateral stabilizer is not always necessary for the prevention of bar displacement in younger patients whose ribs and rib cartilage are still soft [4], lateral alloy stabilizers were proved popular [5, 6]. A variety of bar fixation techniques have also been suggested [7–9]. These methods have contributed to a reduction in the incidence of bar displacement. However, there is still a significant risk of complications (hemothorax and pneumothorax) due to the procedure itself. Notwithstanding the accrued experience of the past decade, bar dislodgement still occurs in around 5% of cases [10].

To date, there are no reports on the effects of bar length on the incidence of bar dislocation. We developed a model to improve understanding of the mechanism underlying bar dislocation, considering both forces and torques acting on the bar and the correspondent mechanical constraints, and focusing in particular on bar length. In order to outline the mechanical forces acting on bars of different lengths, we generated a computer-assisted design (CAD) model coupled with a finite element model (FEM)-based mechanical simulation. We then applied the outcomes of the model to a prospective case series and compared the surgical outcome of this new group with our historical surgical series.

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Material and Methods

After Ethical Committee approval, we retrospectively reviewed the records from patients undergoing PE repair by the Nuss procedure between March 2006 and December 2009. All data related to hospital stay, rate of postoperative complications, and follow-up results were reviewed. This group of patients had standard procedures according to the Nuss criteria (NC, as described above).

Surgical Management

At our Pediatric Surgery Department the standard procedure is as follows: (1) when the patient is positioned at the operating table, the most depressed area of the sternal plate and determined points on both sides of the chest ridge of the patient are identified; (2) a 5-mm thoracoscope is inserted 2 intercostal spaces above the right incision site to verify the deepest point of sternal depression and to monitor the procedure; (3) 2 curved skin incisions of 3 to 4 cm in length are made at the mid-axillary lines on both sides, and a subcutaneous tunnel is created up to the determined points on the chest ridge; (4) a metal introducer is inserted into the thorax at the determined point of the right chest ridge to dissect the plane separating the sternum from the pericardium; the introducer is exteriorized on the left side and pushed through the skin incision. A tie is tightly attached to both the introducer tip and the bar and the introducer is pulled backward, allowing the passage of the bar through the dissected plane. The bar is inserted with the concave side anterior; (5) the bar is rotated 180 degrees around its axis, thus pushing up the sternum. Stainless-steel stabilizers are routinely inserted on both sides of the bar, as close as possible to the bar end. These are secured with pins and are eventually fixed to intercostal muscles by interrupted polyglactin sutures. An additional bar is introduced if the cosmetic result is unacceptable with a single Nuss bar, and a single stabilizer per bar is placed on opposite sides. If pectus excavatum is asymmetrical, the bar is curved asymmetrically according to a previously described method [9]. All procedure-specific instruments are supplied by Medexpert, Eschbach, GmbH, Germany.

Postoperative pain is managed with epidural analgesia and nonsteroidal antiinflammatory drugs. The follow-up protocol included outpatient visits at 1 month and 6 months, and then annually for 3 years. Light physical activity was reintroduced a month after surgery, and more rigorous sports (except contact sports) were allowed after 6 months. The bar was removed after the 3-year follow-up period.

Chest x-rays were taken postoperatively in all patients to document the result of the procedure and to allow assessment of the position of the bar during the follow-up period. We classified "bar dislocation" as an altered, "flipped" position apparent on a lateral chest x-ray film. Bar dislocations were classified as mild (15 to 30 degree angle formed between the bar and the horizontal plane), moderate (angle between 30 and 60 degrees), or severe (beyond 60 degrees) (Fig 1).

Mechanical Model

We investigated the underlying mechanisms of "bar dislocation," generating a mechanical model that took into account both the forces and torques acting on the bar-stabilizer complex, and the correspondent mechanical constraints. In order to develop a model that included all the different cases we encountered in the clinical setting, we outlined 7 chest size configurations with increasing thoracic girth (A to G), to which corresponded 7 short and 7 long Nuss bar types (Appendix Fig 1). The CAD representations of these bars were developed. The FEM-based simulations were then performed to estimate the distribution of the physical stresses acting on the system. For CAD representations, engineering design-dedicated three-dimensional software was used (Pro/Engineer, or ProE, version no. 5.0; Parametric Technology Corporation, Needham, MA). For FEM analyses, a finite

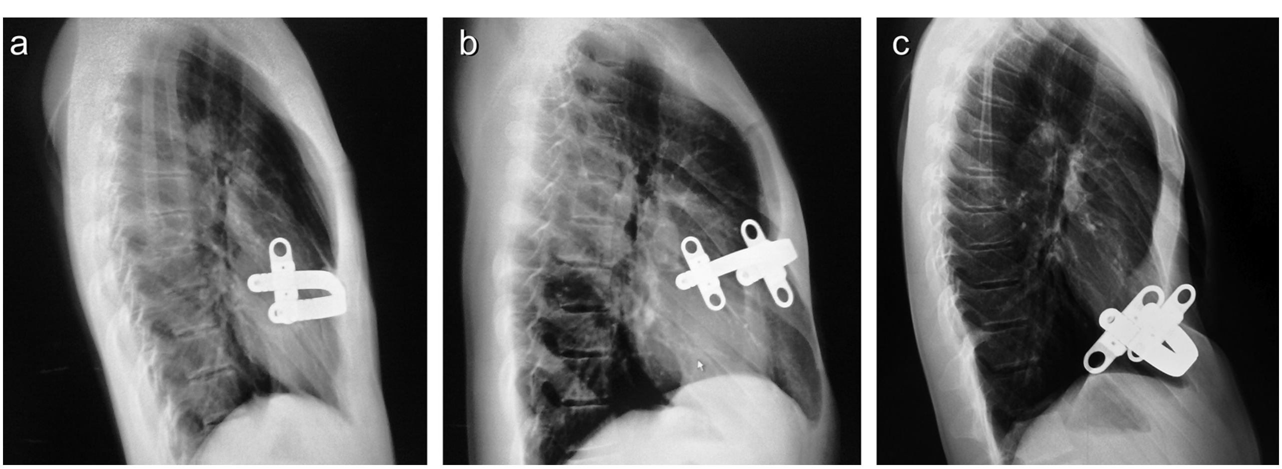

Fig 1. Postoperative lateral chest roentgenograms in 3 different patients: (a) patient with a Nuss bar in place: the angle formed by the bar with horizontal line is less than 15 degrees. (b) Patient with a Nuss bar mildly dislocated (angle between 15 and 30 degrees). (c) Patient with a Nuss bar moderately dislocated (angle between 30 and 60 degrees) which required an early bar removal.

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element-based software was employed (ANSYS; Ansys Ltd, Pittsburgh, PA).

The model was based on the following 3 main assumptions: (1) a shorter Nuss bar is less curved in comparison with a longer one (a longer bar actually has to adapt to the chest curvature) and the stabilizers will be located anteriorly in the chest; (2) all the bars, regardless of length and curvature, have the same "exit point" from the internal chest cavity; (3) bars have a central region which is parallel to the costal plane (the lengths are also the same for every chest size configuration), and 2 extremities that form a certain angle with the central region (and thus with the costal plane). A longer bar will thus have longer extremities and will form a smaller angle with the central region, (in accordance with assumption (1); in these cases the stabilizers are secured more laterally on the chest).

The CAD representations were developed on the basis of archival axial CT scan images from a series of 120 patients; mean values for the length of the central bar region and the curvature angles of the extremities were extracted and normalized to generate the CAD designs of the different bar types. The FEM simulations were performed by applying fixed constraints at the 2 bar extremities (representing the reaction forces due to the fixed stabilizers) and a vertical force to the upper bar surface, slightly dislocated with respect to the longer bar axis (Fig 2). This allowed the simulation environment to recreate conditions that are associated with bar flipping; for example, incorrect placement of the bar or those cases where the asymmetric morphology of the patient's sternum, which has too spiky and sharp undersurface, induces the bar to rotate around its longer axis. We set the force modulus at 250 N Newtons, a value reported in the literature as the maximum force exerted on the implanted bar by the sternum [11] and verified the intensity of the mechanical forces that the bar-stabilizers complex were subjected to.

The outcome measured in each simulation was the maximum von Mises stress at the bar ends (concurring with the 2 fixed constraints, represented by the stabilizers). von Mises stress is a parameter which is often used in continuum mechanics to determine if an isotropic and ductile metal will yield when subjected to a complex loading condition [12]. In our case, these complex loading conditions allowed us to verify if the secured stabilizers were subjected to higher or lower forces, which are associated with an increased or reduced risk of postoperative bar displacement, respectively.

In order to assess the clinical relevance of the insights derived from the mathematical model and software simulations, between January 2010 and June 2012 we prospectively followed up a second group of patients affected by severe PE who underwent surgery (MS group). In this group of patients we placed a metal bar about 3 inches shorter than the distance between the mid-axillary lines, as suggested by our model. The procedure was otherwise as described above.

Results

Nuss Criteria Group Results

Between March 2006 and December 2009, 48 patients affected by severe PE (84%, n = 40, were male) underwent a Nuss procedure at the Surgical Unit of Meyer Children's Hospital. The mean age at time of surgery was 16.4 years (range 12 to 26) and the mean Haller Index was 5.18 (range 2.60 to 10.24). Mean bar length was 14.33 inches (range 11 to 17), and mean operating time was 57 minutes (40 to 115). There were 5 cases of bar dislocation (10.4%), which varied in severity; in 2 cases, a mild displacement occurred, in 1 the rotation angle was moderate, and in the other 2 the bar was severely displaced. Both these patients required an early bar removal. Other relevant data regarding demographics and complications are reported in Table 1.

CAD Representations and FEM Simulations

Figure 3 shows a CAD representation of a Nuss bar and the forces and torques acting on it (when in situ). If the sternum exerts an asymmetrical pressure on the upper part of the bar, a net resulting force F may generate a torque τ, thus inducing bar rotation around its axis. Bar dislodgment, in general, is prevented by both the contact between the bar and the costal plane, and the sutures that

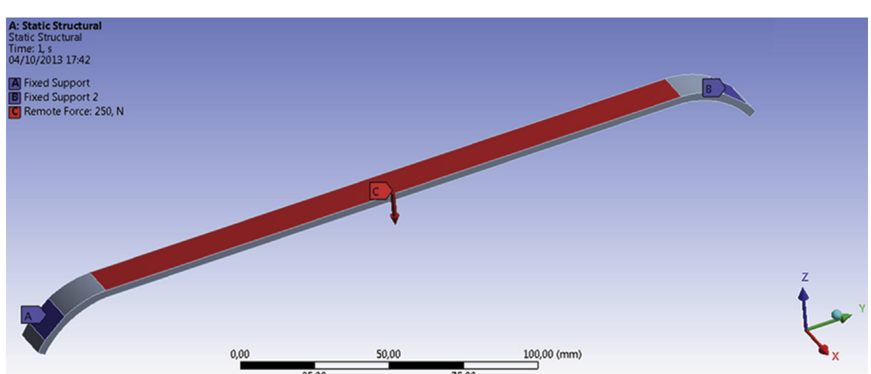

Fig 2. Fixed constraints (A) and (B) and force applied (C) on a computer-assisted design model of the bar, imported in the finite element model simulation environment.

Table 1. Demographics and Complications

Variable	NC Group (48)	MS Group (88)
Mean age, years (range)	16.4 (12–26)	16.2 (12–25)
Male to female ratio	40:8	76:12
Mean Haller CT index (range)	5.18 (2.6–10.24)	5.23 (3.6–9.2)
Mitral valve prolapse	12 (25%)	20 (22.7%)
Pulmonary function test		
Mild restrictive disease	23 (47.9%)	34 (38.6%)
Moderate restrictive	5 (10.4%)	13 (14.7%)
Severe restrictive	1 (2.0%)	3 (3.4%)
Single Nuss bar	44 (91.6%)	76 (86.3%)
Double Nuss bar	4 (8.4%)	12 (13.7%)
Mean bar length (range)	14.33 (11-17)	11.15 (9-15)
Operative time, minutes (range)	57 (40–115)	43 (30–75)
Mean length of stay, days (range)	7.9 (6–25)	7.3 (6–20)
Deaths	0	0
Cardiac perforation	0	1
Pneumothorax spontaneous resolution	34 (70.8%)	65 (73.8%)
Requiring chest tube	5 (10.4%)	8 (9.0%)
Pericarditis	1	2
Wound infection	2	3
Bar dislocation	5 (10.4%)	1 (1.1%)
Requiring repositioning	2	1

CT = computed tomography; MS = model-based suggestions; NC = Nuss criteria.

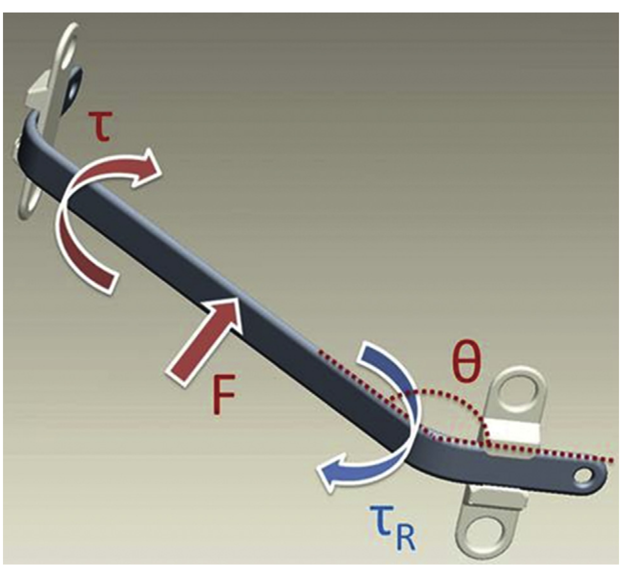

Fig 3. Computer-assisted design representation of a Nuss bar (with stabilizers). Bar curvature is represented by the angle θ that bar extremities (or stabilizers) form with the central (flat) part of the bar. In the representation, F represents the force exerted by the sternum on the bar, which is placed non-symmetrically with respect to the bar center, thus generating a torque τ. Such torque induces bar rotation, which is normally prevented by sutures able to generate a reaction torque τ_R.

Table 2. Results Obtained for the Different Chest Size Configurations

Chest Size	Anterior Chest Length (Inches)[a]	Stresses at the Stabilizer Area: Short Bar (N)	Stresses at the Stabilizer Area: Long Bar (N)
A	11.5	27.2	189.7
B	12.5	37.8	191.8
C	13.5	52.2	211.5
D	14.5	74.0	233.9
E	15.5	85.3	240.8
F	16.5	96.3	262.3
G	17.5	108.1	284.0

[a] Distance measured between the mid-axillary lines. N = Newton.

are directly (or indirectly, by means of stabilizers) applied to the bar. The contact with the ribs mainly prevents bar movements in the sagittal plane, while sutures do not generally permit the bar to rotate on its axis, generating a proper reaction torque (τ_R) that balances τ. When τ is greater than the structural limit of the sutures they break down, thus causing bar rotation. This is the most frequent cause of bar dislodgment. Our aim was to demonstrate by means of FEM simulations that longer bars, which necessarily have a smaller θ, and whose stabilizers are placed in a more lateral position, show a higher risk of dislodgement due to a higher torque acting on their sutures, which in turn generates a higher stress. We analyzed 7 increasing chest size configurations (A to G), including relatively short and long bar types, by applying the same constraints and the same force and by evaluating the stress generated on the stabilizer area (Appendix Figs 1, 2). Table 2 shows the results obtained for the different chest size configurations (A to G). It is evident that shorter Nuss bars (characterized by larger θ values) were subjected to lower stresses in comparison with longer bars (characterized by smaller θ values). Figure 4 shows a magnified graphical representation of the stresses exerted on a short bar (A) and a long bar (B), respectively.

High stress peaks were found around the stabilizer areas in the long bar, while much lower values were found on the same region in the short bar. Figure 5 shows the maximum stress at the bar end as a function of bar length in an average size chest configuration (D). A linear increase in stress with increasing bar length is clearly visible, providing further evidence that shorter Nuss bars minimize the stress in corresponding stabilizer areas.

Model-Based Suggestions Group Results

Between January 2010 and June 2012 we performed Nuss procedures on 88 patients with PE. This group had a mean age of 16.2 years (range 12 to 25), with a female to male ratio of 1 to 7 (12 females [13%], and 76 males [87%]). The mean Haller Index was 5.23 (range 3.60 to 9.20). The mean bar length in this series was 11.15 inches (range 9 to

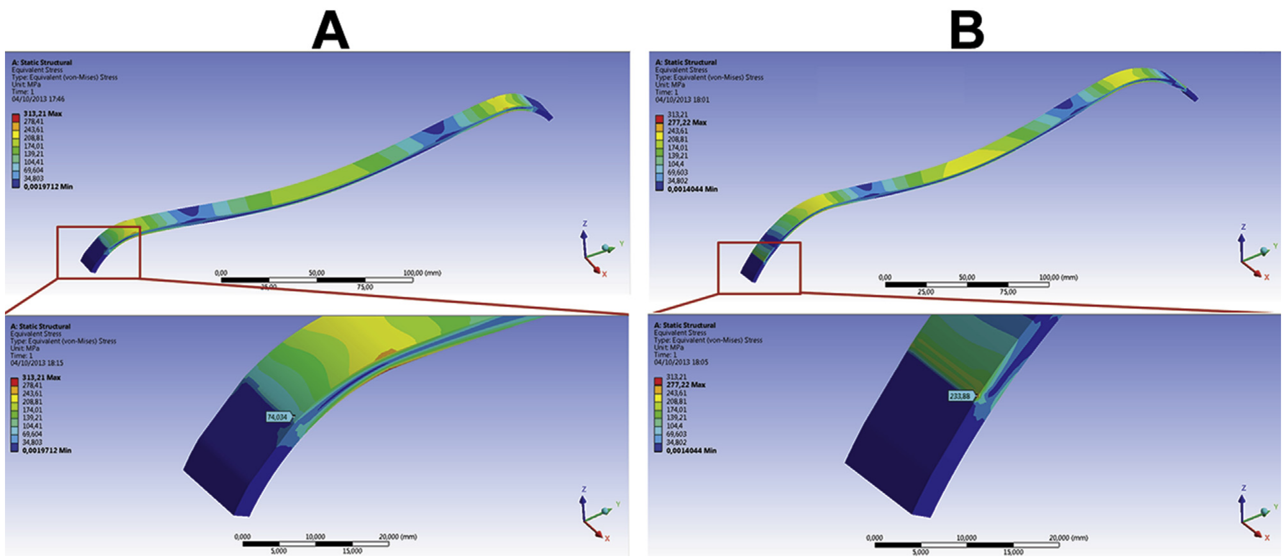

Fig 4. Results of the finite element model simulations performed on a (A) short bar and on a (B) long bar; stress values are graphically shown as a color map. A specific stress value corresponding to the stabilizer regions is evident in the high-magnification images for both bar types.

15), and the mean operating time was 43 minutes (30 to 75). There was only 1 case of bar dislocation, (moderate, requiring early bar removal), thus reducing the incidence of this event from 10.4% to 1.1%; odds ratio 0.0989 (95% confidence interval 0.0112 to 0.8727, $p = 0.0373$). Further data regarding demographics and outcome are reported in Table 1.

Comment

It has been estimated that an average force on the sternum of about 175 N is required to overcome the inward forces generated by the chest in order to correct PE in adolescents by the Nuss procedure; this results in an abrupt elevation of the sternal plate without any cartilage removal. In adults the required force may initially be even higher than 200 N, although the required force progressively decreases over time due to the histologic remodeling of the extracellular matrix in rib cartilage [13, 14]. This pressure is likely to be one of the main reasons for bar dislocation, a common early postoperative complication of the Nuss procedure, reported at a rate of 15% without the use of stabilizers or 6% with stabilizers. The rate of bar dislocation is lower, 5%, when wired stabilizers are used [15–17].

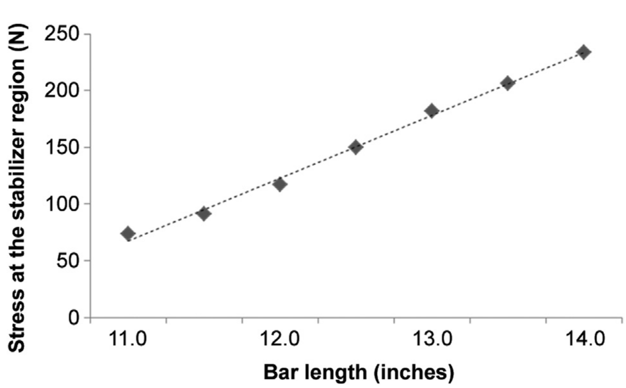

Fig 5. In this graph, stress values at the stabilizer area versus bar length are reported. This simulation was conducted on an average chest size configuration (D); 7 different bar lengths (◆) have been tested. Dashed line represents data trend.

Although stabilizers reduce the rate of bar displacement, this complication remains a significant problem in the context of the Nuss procedure [4], and several other techniques have been proposed in order to try and reduce the risk of bar dislodgement. For example, Hebra and colleagues [7] describe “third point of fixation” in which, under thoracoscopic visualization, a nonabsorbable suture is passed around the bar and around 1 rib in the anterior chest, to the right of the sternum. Schaarschmidt and colleagues [8] reported the “submuscular bar, multiple pericostal bar fixation, bilateral thoracoscopy” technique, which involves positioning the bar in a submuscular pocket directly on the chest wall. Park and colleagues suggest both the “five-point fixation” and the “crane” techniques [9, 18, 19]. In the first technique, steel wires enclose both the rib above and the rib below at each bar extremity. Each wire passes through the end-hole of the bar, and a fifth wire is added on the right side at the hinge point, which encircles both the bar and 1 rib. These multiple point pericostal bar fixation techniques are expected to prevent the bar from migrating in either a superior or inferior direction. The crane technique may be especially useful in adults with an asymmetrical pectus; a percutaneous wire suture is passed through the bony tissue at the xiphoid area, and the wire is connected to a table-mounted crane system. Sternal elevation is achieved before the rotation of the bar, thus alleviating pressure on the hinge points and preventing the tearing of intercostal muscles.

Difficulties with securing bars or stabilizers to the chest wall muscles have been reported [8], in particular with the lateral stabilizers. According to Watanabe and colleagues [4], the use of a stabilizer in a lateral position may increase the rate of wound complications, such as seroma and dermatitis, due to pressure-mediated injury related to the bulkiness of the stabilizer. It is clear that stabilizers, when secured to a shorter Nuss bar, will acquire a more anterior position that will be closer to the hinge point represented by the intercostal passage of the bar.

Other authors reporting reduced incidences of dislodgement with shorter bar lengths have already suggested a reduction in bar length empirically, although no mathematical evidence has previously been presented support these findings [5, 20, 21]. A shorter Nuss bar implies that a larger angle is formed between the stabilizer and the costal plane. With respect to the insertion point between the ribs, therefore, the implanted bar is characterized by less curved and shorter extremities.

Torque is the vectorial product between a force and its arm.

$$\vec{\tau} = \vec{F} \times \vec{r}.$$

A shorter Nuss bar is thus characterized by a shorter arm and therefore smaller torque acting on its sutures, leading to increased bar stability. The FEM analyses carried out in this study confirm these hypotheses, showing higher stress values acting on the sutures of longer bars.

The smaller torque effect of shorter bars, which reduces the risk of the bar “flipping” in the early postoperative period, could also be enhanced by other factors not considered in this model, such as lower overall contact area (associated with a lower risk of being affected by lateral forces that may cause instability). In both the surgical procedures, in the model and simulations we applied a standard position for the stabilizers, which were placed as close as possible to the bar end; anterior in shorter bars and more posterior in longer ones. Further simulations are required to determine the relevance of the stabilizer position in the Nuss technique, regardless of the length of the bar.

Although patient grouping was not randomized but followed sequential operating experience, our clinical data suggest that the use of a shorter Nuss bar may significantly reduce the incidence of bar dislocation. A larger study with a longer follow-up study is necessary to further explore the benefits of using shorter bars as part of the Nuss procedure.

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