



Novel techniques and future developments in minimally invasive pectus repair

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Abstract: After the paradigm shift in the treatment of excavated deformities caused by the introduction of the Nuss technique in 1998, several innovative technical modifications and new treatment modalities have radically changed the surgical approach of pectus excavatum in the last couple of years. These new trends attain different topics. On one hand, the use of three-dimensional (3D) printing and implant customization surge as a possibility for a wider audience as 3D printers become available with lower costs. They provide the surgeon with new elements that enable precise planning, simulation, and customized prostheses amidst a tendency to abandon standardization and incorporate personalized medicine. Another topic comprises mandatory sternal elevation, in the continuous search for safety first always. Complete thoracic remodeling as a goal of repair instead of addressing only focal depressions, leaving the upper chest or focal protrusions unresolved. Finally, although the current surgical approach has evolved significantly, many groups still use lateral stabilizers or direct implant fixation with sutures or wires to the ribs. These systems continue to prove unreliable in preventing implant displacement. Fortunately, the bridge technique, described in this review, has come to address this sometimes fatal issue with encouraging results. We provide an updated overview of the latest developments regarding these concepts, related to the current state-of-the-art of the treatment of pectus excavatum.

Keywords: Funnel chest; three-dimensional printing (3D printing); sternal elevation; total chest wall remodeling; bridges

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Introduction

The minimally invasive repair of pectus excavatum (MIRPE) described by Dr. Donald Nuss more than 20 years ago was a paradigm shift in the treatment of chest wall excavated deformities. Ever since, several modifications have been described in the search for improvement in

technical, procedural, and clinical outcomes. In this article, we provide an in-depth discussion of the most relevant innovative concepts related to the treatment of chest wall malformations; including three-dimensional (3D) printing and implant customization, compulsive sternal elevation, complete thoracic remodeling as a goal of repair, and

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implant fixation with bridges.

3D printing and implant customization

Although the use of 3D technology in medicine is a very current topic, publications on its use for the resolution of pectus excavatum are scarce, limited to scattered reports mainly related to simulation and educational purposes (1,2).

Other authors, such as Lai *et al.* and Lin *et al.* (3,4), have reported the implementation of 3D technology for implant customization. In their study, Lai *et al.* compared the resultant shape of the implant using the traditional method of adding 2.5 cm laterally to the mid-axillary line and a computed tomography (CT) model in 75 patients and found that the CT model was more precise and accurate. Lin *et al.* used 3D-printed templates designed using software on CT reconstruction to model implants in 10 patients. In 2014, Vilaça *et al.* (5) reported one of the first large experiences with automatic pre-bent customized implants for 41 patients showing that automatic-made implants were more precise than manually bent implants when calculating the skin-to-costal margin distance. Using customized implants based on real-size chest wall models of 15 patients, Huang *et al.* reported a propensity score matching using 342 cases undergoing repair with manually bent implants. They found that patients with customized implants had a shorter surgical time, a decreased number of bar placements, and improvement in postoperative Haller indexes measured with X-rays in the postoperative period (6).

In 2020, we reported our experience using 3D technology in several steps of the MIRPE (7). In this report, we used 3D technology for the preoperative planning process, using 3D reconstructions of end-expiration chest CT as an adjunct to determine the number, direction, and position of the implants in each case. Next, the exact shape and size of each implant were designed virtually by a software program (Erkom Pro 3.0, Buenos Aires, Argentina) (Figure 1A) and 3D printed templates created from standard tessellation language (STL) files were measured on the patients' chest wall at a fitting session at an outpatient setting (Figure 1B). If the templates were correct, we subsequently approved the pre-bent customized manufacture of the metallic bars with a proven implant/deformity match over 90% (Figure 1C).

This approach might save time in the operation room, facilitating the process, especially for surgeons performing less than 20 procedures per year, and avoiding the creation of scar-forming scratches and notches on the implants' surface. In 2017, Alvarez-Garcia *et al.* published a survey to

Chest Wall International Group members on bar removal complications (8). Severe bleeding from the bar tunnel due to adhesions was experienced by 26.9% of the respondents. Thus, we might infer that any strategies that decrease the formation of ossification and fibrous adhesions to the bars due to scratches and notches might decrease the possibility of bleeding during bar removal.

However, studies with objective, measurable endpoints and larger cohorts are still necessary to ascertain the benefits of the implementation of 3D technology in chest wall malformations.

Sternal elevation

One of the most feared complications of the Nuss procedure is cardiac and pulmonary perforation during "blind" retrosternal tunneling. This was clearly evidenced in a case report by Beati *et al.* (9) about a 13-year-old patient with a deep, asymmetric pectus excavatum undergoing MIRPE without sternal elevation who suffered one lung and two cardiac perforations when the introducer was passed from right to left under thoracoscopic guidance.

Various strategies have been proposed to overcome this potentially ominous complication. In 2001, Miller *et al.* acknowledged this issue for the first time and reported no cardiac injury after implementing blunt retrosternal dissection through a subxiphoid incision (10). In 2005, Schier *et al.* reported the use of a vacuum bell for intraoperative sternal elevation in 14 patients (11). They reported a clear elevation of the sternum confirmed by thoracoscopy in all patients, although it sunk back after a few minutes.

In 2008, Park *et al.* described several modifications to the original Nuss procedure (12), being one of these the successful elevation of the sternum in 122 adults using trans sternal percutaneous wire sutures and a crane ("the crane-technique") before precardiac dissection to decrease intercostal muscle tearing and the force required to rotate the bars.

In the following years, several sternal elevation techniques emerged including the use of wire stitches and a Kent retractor (13), a manual sternum elevator (14), two Langenbeck retractors (15), a Lewin Spinal Perforating Forceps (V Mueller NL6960; CareFusion, Inc., San Diego, CA, USA) and a table-mounted retractor (7,16), a vacuum bell (17), a sternal lift and an anchor through a subxiphoid incision (18), a Wolkman bone hook (19), and a T-fastener suture technique (20). Also, other approaches aimed at

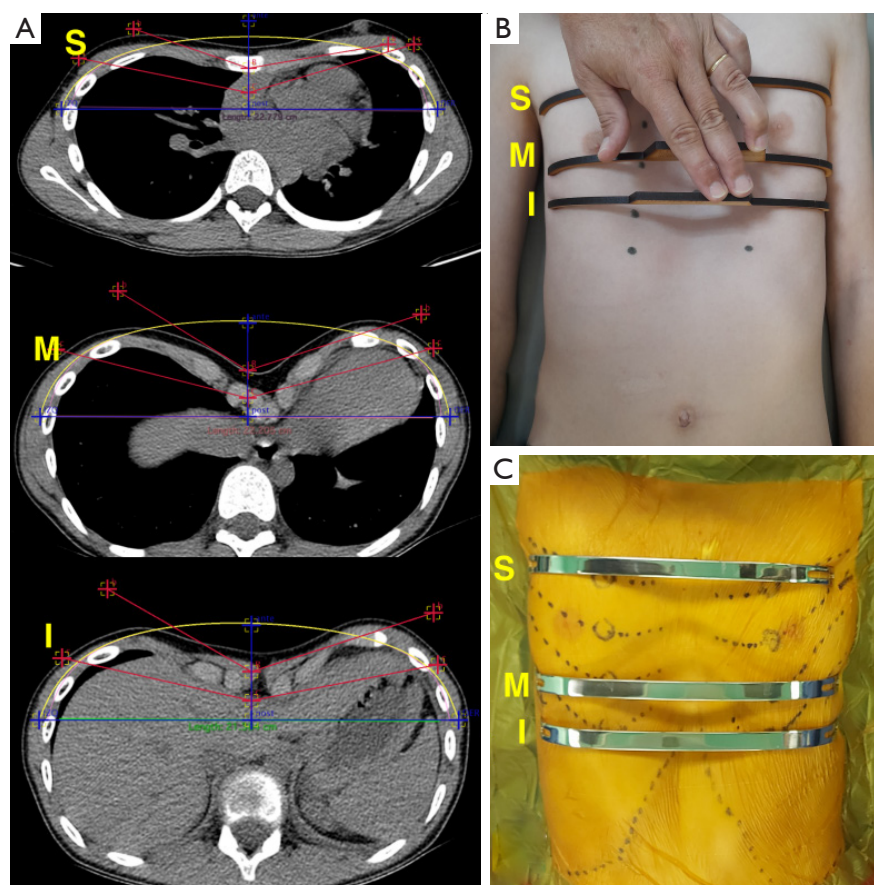


Figure 1 The preoperative process for the manufacture of customized, transthoracic implants of a patient with pectus excavatum is shown. The three implants are marked throughout the three panels with letters (S for superior, M for middle, and I for inferior). (A) Length and shape of the three implants are designed using a semi-automatic software (Erkom Pro 3.0, Buenos Aires, Argentina). (B) Customized 3D printed templates are checked on the patient at a fitting session at the outpatient clinic. (C) Intraoperative final check of the metallic implants on the patient's chest. 3D, three-dimensional.

avoiding injury to the mediastinum include dissection of the retrosternal tunnel from the left to the right side to avoid the use of the thoracic introducer (21), among others. Since cardiac perforation is infrequent, the comparison between these techniques is limited to the size and number of additional incisions and sternal retraction stability.

Nowadays, the two most widely used strategies for sternal elevation are the intraoperative use of a vacuum bell, later popularized by Haecker and Sesia (17,22,23), and the application of a crane or retractor. Adult chest wall surgeons such as Jaroszewski *et al.* who described the use of a Rultract Retractor (Rultract Inc., Cleveland, OH, USA) for forced sternal elevation in 63 patients between 2010 and 2013 (24), recommended the use of a retractor in all cases with rigid chest walls (*Figure 2*). In 2021, de Loos *et al.*

reported a quantitative analysis of the degree of superficial correction achieved with a crane attached to the sternum by a wire suture in 30 patients undergoing MIRPE (25). They used an optical scanner to compare external pectus depth before and after sternal lifting and found that it decreased by 78% [interquartile range (IQR), 63%, 100%]. Although they concluded that the technique might be effective in providing a safer retrosternal passage, they found less degree of correction in more severe cases. Further studies are warranted to determine whether a different attachment element such as the Lewin clamp or the new Screw developed by Dr. Park or the duplication of the attachment elements are effective in improving these findings.

In our own practice, the crane is applied in all procedures regardless of the patient's rigidity or age, as we reported



Figure 2 Sternal elevation is a key element in reducing the risk of pericardial and pulmonary lacerations, as well as useful to reduce intercostal muscle stripping when passing the first introducer in rigid chest walls. One of the sternal devices used to elevate the sternum is the Lewin clamp, which can be located in a transverse or longitudinal position at the caudal end of the sternal body.

in 2020 in 130 patients (7). Alternatively, we believe that the vacuum bell might only be used as a second-best complementary choice since, in our experience, it can provoke subcutaneous emphysema and petechiae, and retraction lasts for a few minutes before it is necessary to apply suction again.

According to a recent review by Notrica, “*This modification [sternal elevation with a crane] has been the single most important, breakthrough modification in improving the safety of the technique.*” (26).

Complete chest wall remodeling

Total chest wall remodeling is a novel concept amongst the pectus surgeon community. It refers to a new goal when repairing chest wall deformities that originated in recognizing that this ailment is diverse and that a single technique cannot possibly resolve all the phenotypic variations. In pectus excavatum, it consists of remodeling not only the deepest point of the excavation but the whole anterior chest wall, including the upper chest, asymmetries, and deformed rib-flares.

One of the pioneers of this concept is Dr. Park who, in 2010, introduced the multiple target approach, the terrain contour matching, and the multiple momentum theory (27). In keeping with this, in 2016, Park *et al.* reported the sandwich technique, consisting of the utilization of intra and extrathoracic implants to press-mold asymmetries and complex excavatum-carinatum cases (28).

In parallel, more adult patients visited the chest wall surgeon clinics requesting a MIRPE. However, adult chest wall is more rigid than that of teenagers requiring more implants to achieve appropriate remodeling as stated by Jaroszewski *et al.* in 2016 (29) in a retrospective report including 207 patients older than 30 years.

However, this concept’s implementation requires an extensive review of the usual practice and the disposition for change. In our experience, after understanding this postulation, we were able to recognize that patients from our previous cohorts were under-corrected (Figure 3).

This new conception led us to the introduction of multiple implants as reported in 2020 (7) (2.6 ± 0.5 implants per patient *vs.* 1.7 ± 0.6 in a previous cohort) (Figure 4). We recently reported the use of a CT index, the Titanic Index, to determine the number of implants necessary to achieve complete thoracic remodeling (30). This index measures the cephalocaudal extent of sternal sinking behind the anterior costal line and the cut point between two and three bars was 66.5%, or in other words, two-thirds of the sternum.

Aspects to be considered for complete chest wall remodeling include:

- (I) Sternal depression: the degree of depression of the sternum has been categorized using classifications such as the one described by Lawson *et al.* in 2006 (31), the “titanic index” by Bellía-Munzón *et al.* (30), or the “vertebral-level-specific-pectus indices” by Moon *et al.* (32). These classifications aim to provide a practical tool to determine the number of bars required.
- (II) Symmetry: the asymmetric pectus excavatum deformities are difficult to repair, and the implants need to be shaped accordingly to reduce the possibility of over or under-correction (31,33).
- (III) Sternal rotation: commonly detected in asymmetrical deformities. In significantly rotated sternums, it might be necessary to consider osteotomies.
- (IV) Mixed deformities: includes excavated/carinated deformities that may require strategies such as “the sandwich technique” (28).
- (V) Banana-like sternum (7): which may be approached

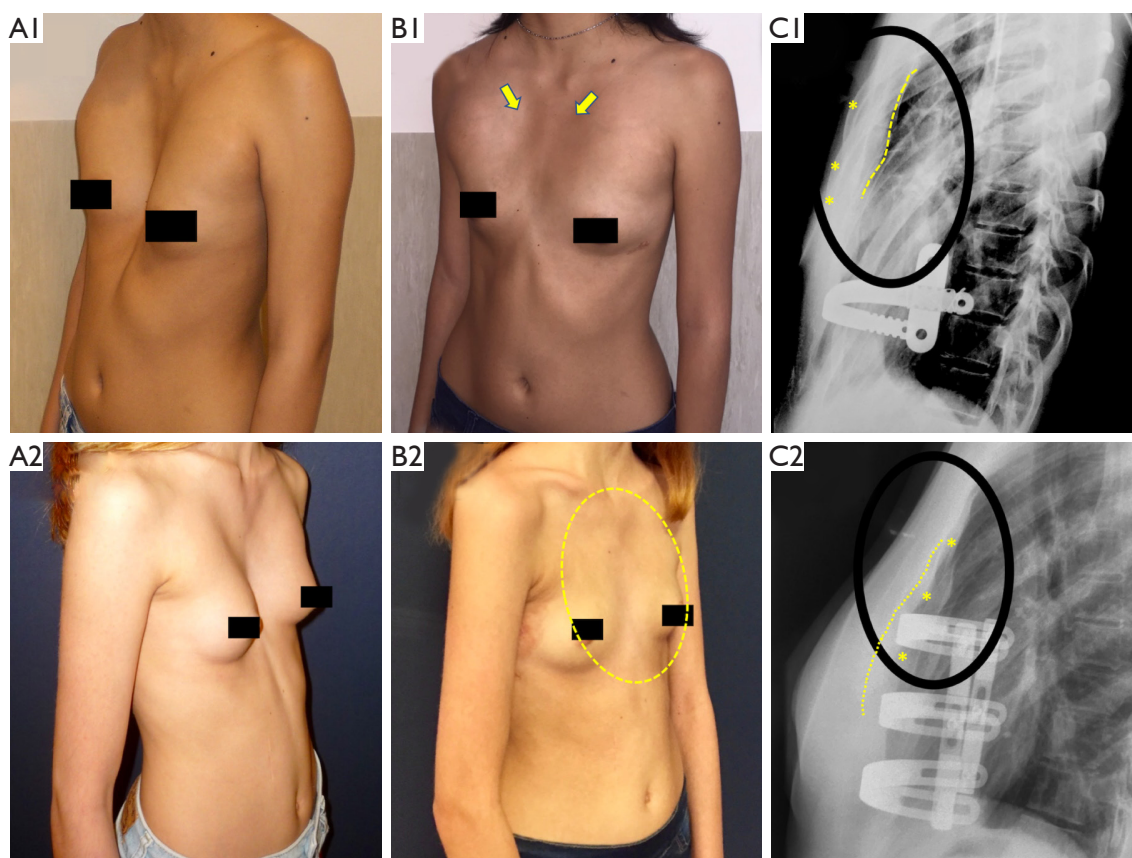


Figure 3 The pre and postoperative appearance of the chest wall of two female patients undergoing MIRPE before and after the concept of complete thoracic remodeling became a therapeutic goal. (A1-C1) A patient with pectus excavatum who underwent repair by our team a decade ago. (A2-C2) A patient with pectus excavatum with a similar deformity as we repair it today. (A1) Preoperative appearance of a female patient with a severe, grand-canyon type of chest wall deformity. (B1) Postoperative appearance of the same patient after MIRPE. Note the yellow arrows marking the still uncorrected upper third of the sternum. (C1) This lateral chest X-ray reveals the posterior aspect of the sternum (dotted line) behind the anterior costal line (asterisks). (A2) Preoperative appearance of a female with a similar deformity as presented before. (B2) Postoperative appearance after MIRPE as performed today. Note the dotted circle marking the upper area of the chest wall after applying the concept of complete chest wall remodeling. (C2) Lateral chest X-ray of this patient. This case required three implants stabilized by lateral bridges (note the smooth edges of the implants). Here, the posterior aspect of the sternum lies at the same level of the anterior costal line (asterisks). MIRPE, minimally invasive repair of pectus excavatum.

with the crossed bar technique using two implants to avoid rotation. If the upper sternum also needs correction, the “XI” technique may be employed.

- (VI) Spine deformities: although the exact interaction between chest wall and spine deformities still needs to be elucidated (34), there seems to be a relationship between them as postural changes become evident after chest wall repair with correction of shoulder and head ante pulsion, and thoracic kyphosis.

All this being said, there is still debate in the community

of chest wall specialists. As Dr. Nuss himself commented in a letter to the editor recently, further studies showing the benefits and safety of the use of multiple bars are warranted for this concept to gain wider popularity (25).

Implant fixation with bridges

As a natural consequence of using multiple implants, the stabilization system had to be reappraised, given that lateral stabilizers were big and bulky when fixating more than one implant on each side. This situation concurred with

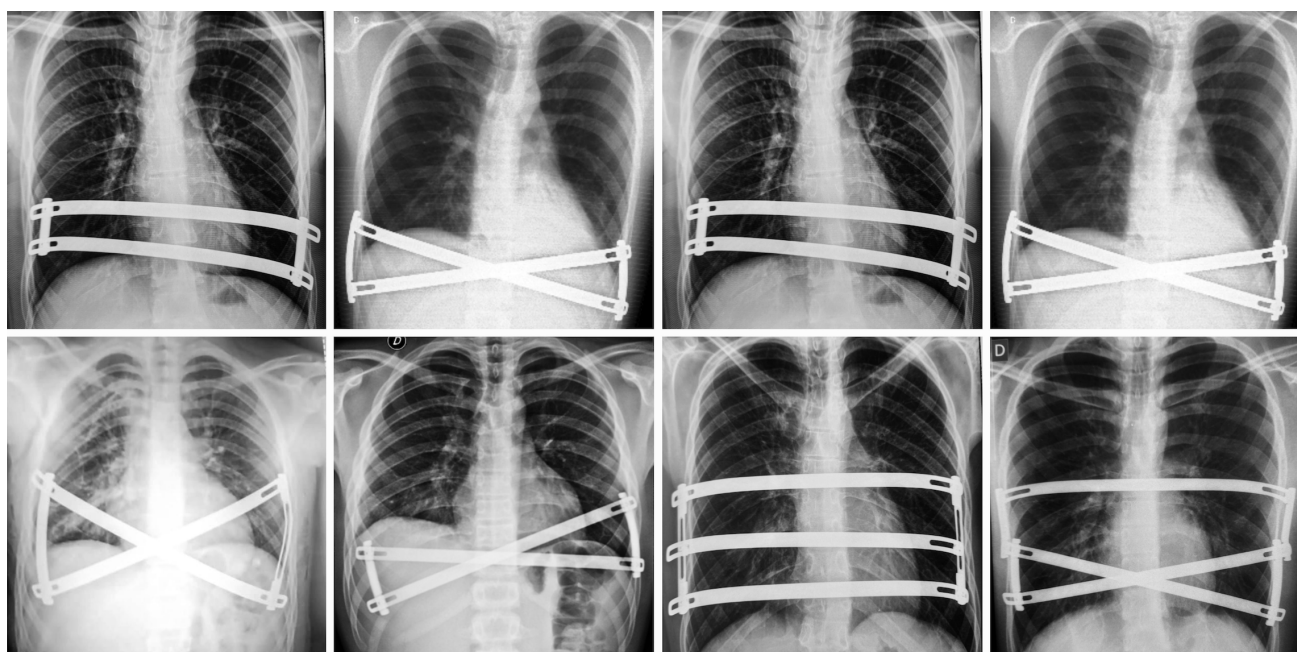


Figure 4 The acknowledgment of the existence of a wide range of chest wall morphologies has driven our group to customize retrosternal implant shape, location, and direction leading to several surgical approaches for the resolution of pectus excavatum.

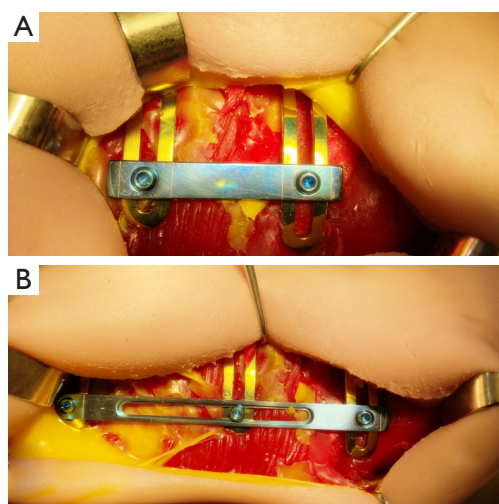


Figure 5 Lateral bridges block two or more implants between themselves. Bridges may be used to block two (A), three (B), or four parallel or crossed implants, they can be combined, and they may be manufactured in steel or titanium. As shown in this figure, bridges don't require fixation to the underlying ribs. Some types have ridges that prevent implant rotation.

the need to reduce the rates of rotation and dislocation of the implants, frequently observed in cases of banana sternum and heavy, rigid chest walls. This aspect was approached by medial fixation including medially placed stabilizers (35), sternal wire interspace reinforcement (the hammock technique) (13,29,36), a hinge reinforcement plate (37), and sternal fixation (38).

In 2015, Park *et al.* (39) reported “the bridge technique”, the implementation of a new device to fixate implants between them and with no need to fixate to the chest wall itself. He reported its use in 80 cases with parallel bars during 1 year with no evidence of implant dislocation or reoperations in any case. In 2020, we also reported the use of implants with self-blocking lateral bridges, and our experience was similar with a zero rate of implant rotation in that series (*Figure 5*). In 2019, a large study by Vinh *et al.* (40) compared 560 cases undergoing bridge stabilization to 1,200 patients with other stabilization techniques, being bilateral stabilization the best approach in terms of bar dislocations.

In 2023, Dr. Kim *et al.* reported another large cohort of cases with pectus excavatum and carinatum focusing on their stabilization system (41). They included 497 cases with the bridge technique, having adopted this approach over the hinge plate technique in all patients since 2022 in search of complete chest wall remodeling with zero rate of bar displacement.

These last three experiences might support the introduction of an implant as high as the second intercostal space without fear of bar rotation and compression of the great vessels or the airway in that area, improving the extent of remodeling in a cephalocaudal direction. However, further studies are warranted showing evidence that this technical aspect is safe and useful.

Conclusions

Twenty-five years after the original description of MIRPE, many modifications and ideas have been proposed and tested in the search for excellence. Conceptual and technical innovations include the use of sternal elevation, complete thoracic remodeling as a therapeutic goal, lateral bridge fixation, and the use of 3D technology for preoperative planning and implant customization amongst other uses. All these strategies and concepts allow the chest wall surgeon to improve efficacy and safety in a procedure meant to improve quality of life and their pursuit and widespread application will likely mark the future of pectus excavatum surgery.

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