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THE IMPACT OF 3D-PRINTING IN SURGICAL TRAINING FOR THE NUSS PROCEDURE

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Abstract

Introduction: The Nuss procedure is a highly technical, minimally invasive alternative to the open corrective surgery of Pectus Excavatum of which perioperative complications depend heavily on the surgeon's experience and caseload. To overcome the learning curve, and allow faster proficiency, simulation-based teaching has been adopted in many teaching hospitals, either virtual, physical, or hybrid. Our study aims to show the impact of a high fidelity physical Nuss simulator on surgeon's skill acquisition. **Material and methods:** We conducted a two-day training workshop using a physical Nuss simulator targeting surgeons and surgical trainees with no prior experience in performing this procedure; using a rating scale from 1 to 5, independent expert surgeons assessed performances by evaluating 15 key steps of the Nuss procedure of two participants groups, one of which (group 1) had two training sessions on the mannequin and the other (group 2) only one. Following the simulation, participants rated their feedback on a 5-point Likert scale. **Results:** Participants who did the simulation twice scored a mean of 68.8 /75 on the second day evaluation; while the participants who only had the second-day simulation, had a mean of 49.6/75 (with a significant p-value < 0.001). Concerning feedback, for the realism of the simulator, the percentages of participants who gave a score of 4/5 or higher (agree or strongly agree) were 100% for sternal elevation, 80% for introducer manipulation during mediastinal dissection and 85% for overall simulation realism. For the pedagogic utility of the simulator, 16 participants (80%) chose a rating of 4/5 or higher (agree or strongly agree), while the remaining 20% chose a score of 3/5 (neutral).
Regarding self confidence in eventually replicating the procedure, participants of the first group had a mean of 4.2/5, The second group a mean score of 2.7/5 with a significant p-value of 0.002. **Conclusion:** Our study suggests that a fully physical, 3D-printed, simulator of the Nuss procedure is a better alternative to traditional surgical teachings of PE's minimally invasive corrective surgery.

Keywords: 3D-Printing, Nuss Procedure, Medical simulation, Pectus, Excavatum, Thoracic Surgery.

Introduction

Simulation-based training has significantly increased in the medical field over the last decade. Surgical simulators whether physical, virtual, or hybrid have been used to teach different skills in a low-risk teaching environment and modify the learning curve allowing healthcare professionals to reach proficiency in a shorter time [1].
Pectus excavatum (PE), or "funnel chest" is a congenital deformity of the anterior chest wall believed to be caused by abnormal growth of the cartilages in the chondrocostal region [2,3].
]Surgical correction of PE can be achieved either by the Ravitch[4] or the minimally invasive Nuss procedure, demonstrated to have a shorter operative time with reduced blood loss [5].
The authors organized a training workshop on the Nuss technique using an all-physical simulator with a 3D-printed mannequin of which the deformity was based on a real PE case. This study highlights the impact of an all-physical, high-fidelity, simulation of the minimally invasive repair of pectus excavatum on surgeons' and trainees' skill acquisition.

Material and methods

Simulation program:

In collaboration with surgeons who frequently perform the procedure, the organizing committee identified the key steps of the Nuss procedure that

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the participants would be evaluated on, in preparation for the workshop.
The training Workshop lasted 2 days.
On the first day, the 20 participants attended an instructional briefing about the simulation with the aid of a video of the real surgery.
Knowledge on the Nuss procedure before and after the briefing was evaluated using a single-answer 10-question quiz.
Participants then attended a live demonstration on the simulator with step-by-step briefing by an expert surgeon.
Participants were randomly divided into 2 equal training groups; the first group had supervised hands-on training on the mannequin with real-time feedback on day one, followed by another simulation on day two; while the second group only had hands-on experience on the second day.

We considered the second-day simulation an evaluation resembling a real-life scenario in adherence to surgical ethical practices, thus providing a safe environment for the participants to assess their performance without jeopardizing patients' safety.
2 independent expert surgeons assessed performances using a rating scale evaluating 15 key steps of the Nuss procedure. Each step was evaluated on a 5-point Likert scale with 15 being the minimum possible overall score and 75 the highest. **(Table 1).**
After completing the simulation, each participant was asked to fill a feedback form evaluating the fidelity and training capacity of the simulator as well as confidence in eventually replicating the procedure.

Table 1: Evaluation Criteria and scoring system for both simulation days

Nuss procedure steps	Excellent (5)	Satisfactory (4)	Could be improved (3)	Unsatisfactory (2)	Poor (1)
Placement of skin incisions					
Choice of Bar length					
Quality of bar modelling to fit the deformity					
Sub-cutaneous tunnelling					
Thoracoscope insertion and orientation					
Sternal elevation					
CO insufflation					
Dissection using the bar introducer under thoracoscopic guidance					
Mediastinal dissection					
Passage of the sterile tap followed by the bar.					
Synchronized flipping of the bar					
Bar stabilizer insertion					
Coherence of the procedure steps					
Pleural exsufflation					
Stress degree					

Training thorax:

Based on a real case; after obtaining patient’s consent, chest CT Figures were used to make a 3D reconstruction of PE chest wall.

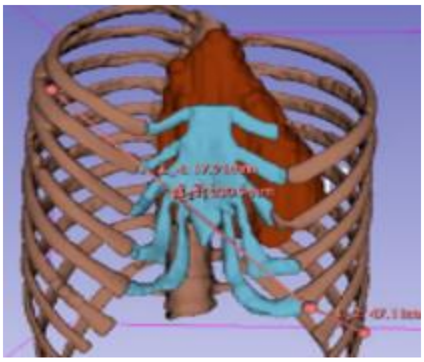

Figure 1: 3D reconstruction of the chest wall following segmentation of previously obtained CT Figures.

The model of the chest wall was then printed using thermoplastic polyurethane (TPU), a highly resistant and elastic elastomer often used in fused filament deposition in 3D printing (Figure 2).

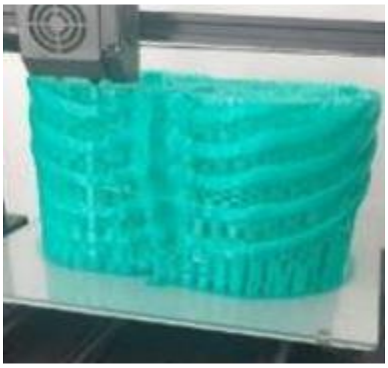

Figure 2: The 3D printed model of the chest wall using TPU in the fused filament fabrication process.

Since the simulator is fully physical, the majority of the chest wall, as well as the pericardium were 3D-printed. The resulted print was then filed down and polished to shape the training thorax (Figure 3).

Figure 3: Filed down and polished thorax model.

Foam silicone and smooth-on synthetic material were used to shape multiple layers for the external intercostal muscle and subcutaneous tissue (Figure 4,5).

Figure 4: Painted silicone placement secured to the chest wall simulating the intercostal space.

(It should be noted that only the intercostal spaces that would be exposed during the simulation on the right side were covered by the muscle-like material).

Figure 5: Foam material simulating the subcutaneous tissue.

Then a strong yet elastic tissue was placed on top of the foam layer and the ribcage allowing for a more realistic dissecting simulating the skin. The synthetic material for skin and subcutaneous tissue is reusable and replaceable. A bolted hook was then finally added to the sternum at the deepest point of the excavation to allow proper sternal elevation (**Figure 6**).

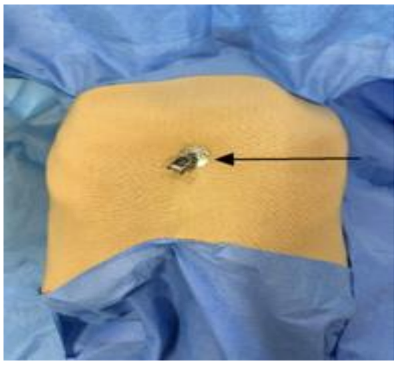

Figure 6: draped surgical model with a hook bolted at the deepest point of the sternal excavation (arrow).

Simulation steps:

Preprocedural planning:

The chest is marked in the deepest portion of the pectus, on the pectus ridge on both sides of the deepest excavation point which will be the bar's endothoracic entry and exit points, and on the right and left sides following the midaxillary line, horizontal to the ridge markings corresponding to the skin incisions **(Figure 7).**

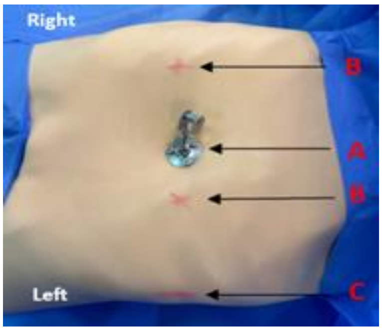

Figure 7: A: Deepest point of the excavation, **B**: Left and right pectus ridges, **C:** Left skin incision site on the midaxillary line.

The length of the pectus bar is determined by measuring the distance from the anterior axillary line on the right side to the opposite posterior axillary line **(Figure 8).**

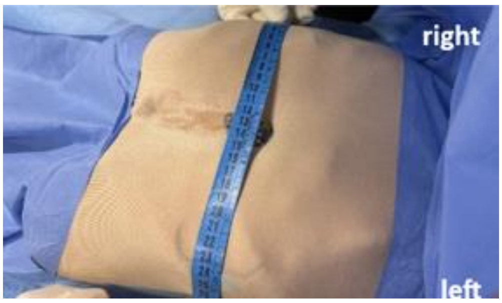

Figure 8: Measuring the bar length.

The participant uses a bar template to choose the correct bar length and shape as well as the stabilizer's insertion sites. Using a bender, the bar is bent from the center out to either end, with small gradual bends to fit the chest deformity. The surgeon then slightly exaggerates the curvature at the level of the deepest point of the excavation and near the stabilizer's insertion sites allowing respectively, an optimal correction of the deformity and a secure fit of the stabilizer (Figure 9).

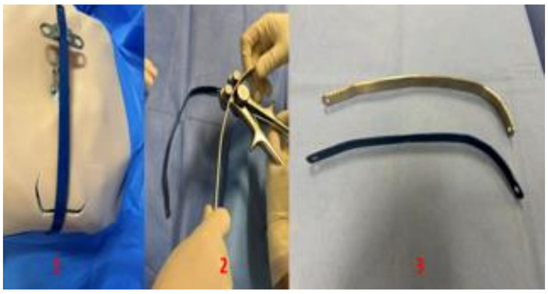

Figure 9:1: the bar template bent to fit the chest deformity
2: The correct size bar is chosen, then bent using a bar bender
3: Side-by-side comparison of the bar and template

It should be noted that the bars used in the simulation are made of stainless steel as it is softer and bends easily compared to titanium, and therefore is more beginner-friendly. One the trainee has acquired sufficient knowledge of the procedure; titanium coated bars will be added during simulations in preparation for real cases.

Procedure steps:

Placement of incisions and creation of the skin tunnels:

Bilateral skin incisions are made on the midaxillary lines on each side of the chest, at the level of the deepest part of the defect[3].
Dissectors allows the formation of two sub-cutaneo-muscular tunnels from both incision sites (Figure 10) to the pectus ridges.

Figure 10: Using dissectors on both sides, the surgeon and aid create the sub cunateo-muscular tunnels

Insertion of thoracoscope:

A thoracoscope is inserted into the right pleural cavity on the anterior axillary line (Figure 11). The trocar is placed 2 to 3 intercostal spaces below the level where the bar will be inserted. CO insufflation can help enhance thoracoscopic visibility.
Once placed, the trocar should mandatorily be oriented upwards to avoid any diaphragmatic lesion.

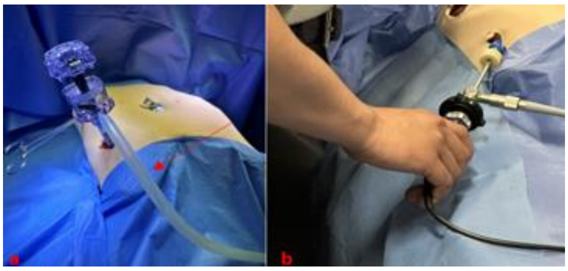

Figure 11: a: Insertion of the trocar and CO insufflation. The arrow points to the CO insufflator.**b:** The correct orientation of the thoracoscope to avoid diaphragmatic lesions.

Insertion of pectus introducer

Using a hook bolted to the sternum mimicking the crane technique (Figure 12), the sternum is elevated until maximum correction of the chest wall deformity is achieved and the thoracoscopic view improved (Figure 13).

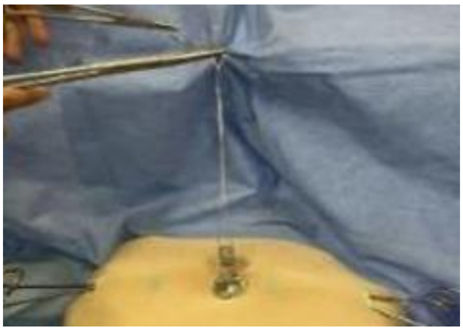

Figure 12: sternal elevation using metal wires secured to a metal ring similar to the crane technique.

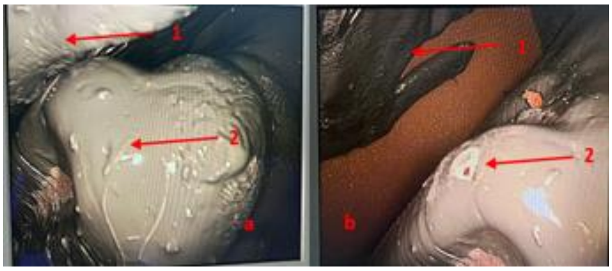

Figure 13: thoracoscopic visualization before (a) and after (b) sternal elevation. Note the space between the sternum (1) and the pericardium (2) following the sternal elevation.

The bar introducer is inserted into the thorax through the right sub-cutaneous-muscular tunnel and slowly advanced across the anterior mediastinal space immediately under the sternum using lateral movements with the tip facing forward. Continuous thoracoscopic visualization and monitoring of the dissector's tip help the surgeon ensure that the instrument is not near the heart or pericardial sac (Figure 14).

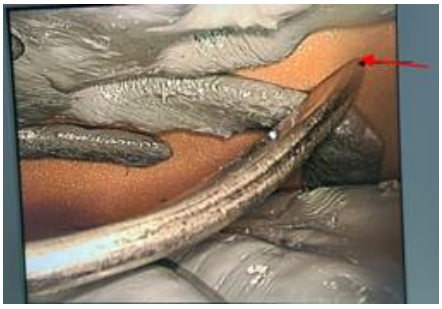

Figure 14: endoscopic view of the introducer. The arrow points at the tip of the introducer pointing forward at the level of left intercostal space near the left ridge of the excavation.

The introducer must pierce only the left intercostal space near the left ridge of the excavation. The participant must then manually lift the left subcutaneous tunnel allowing the surgical aid to push out the introducer through the left cutaneous incision (Figure 15). This creates the mediastinal tunnel where the metal bar will be placed.

Figure 15: a: the surgeon lifting the left subcutaneous tunnel. **b:** Using a metal hook, the surgical aid pushes the introducer through the left cutaneous incision (arrow).

Placement of pectus bar:

A strand of sterile tape is fixed at the tip of the introducer and pulled through the tunnel; (**Figure 16**).

Figure 16: The tape is fixed to the tip of the introducer then pulled through the mediastinal space (endoscopic view).

The curved pectus bar is attached to the tape and then pulled under thoracoscopic guidance by using traction on the tape (Figure 17).

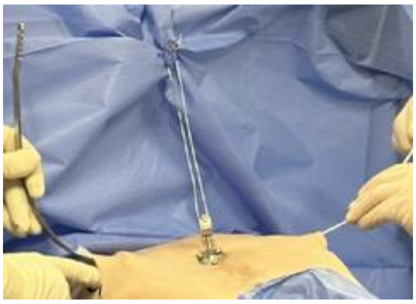

Figure 17: The bar is pulled through the dissected mediastinal space guided by the sterile tape.

Once the bar is inserted, the metal wire elevating the sternum is removed, the participant and the surgical aid must rotate the bar using two flippers for a synchronized 180 ° rotation of the bar until it assumes the optimal convex position to correct the sternal excavation (Figure 18).

Figure 18: a: two flippers (arrows) used to rotate the bar. b: endoscopic view after flipping the bar with correction of the sternal deformity after the sternal elevation is removed.

Stabilization and securing of pectus bar

Next, the bar is fixed using a right unilateral stabilizer. While the aid secures the bar using a hook, the participant pushes the stabilizer near the curvature using two hooks; allowing a secure placement with no additional screws (Figure 19).

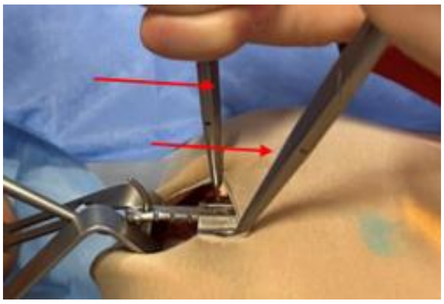

Figure 19: While the aid keeps the bar in place, the surgeon pushes the stabilizer using two hooks (arrows) to secure it against the bar curvature.

The correct position of the bar is evaluated visually through the correction of the thoracic defect, as well as thoracoscopically by re-examining the retrosternal space, the sternum, the pericardium, the lung, and the diaphragm to exclude any injuries.

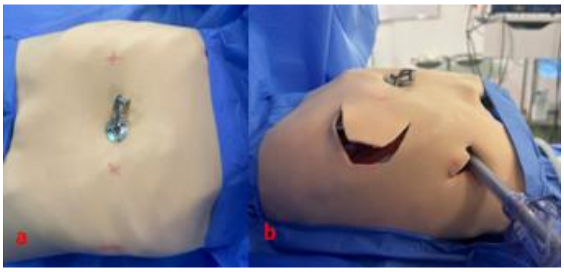

Figure 20: a: initial chest deformity **b:** Correction of the pectus excavatum after bar insertion.

Finally, a chest tube is temporarily placed through the trocar site under a water seal to evacuate any residual intrapleural air. (Figure 22).

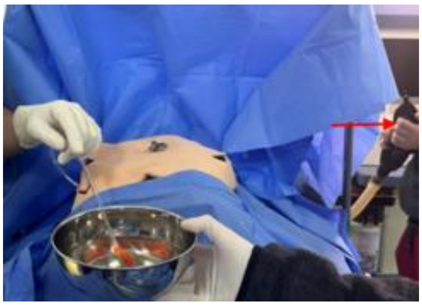

Figure 22: Exsufflation to evacuate residual pneumothorax with an aid simulating the air leaving the pleural space using a manual pump (arrow).

End of the procedure:

Using an in-situ bender, the right and left extremities of the metal bar are tightly inserted in the subcutaneous space.

Figure 21: in situ bender used to further secure the bar in the subcutaneous space (a) and the final result with the bar deep in the right subcutaneous space (b)

The simulation ends once the pneumothorax is evacuated i.e. after the bubbling stops.

Results

20 surgeons and surgical trainees attended the Nuss simulator Workshop; all of whom had no prior experience with the procedure.
Of the 20 participants, as highlighted in **figure 1**:

- 3 were cardiovascular surgery residents
- 3 general surgery residents
- 3 paediatric surgery residents
- 7 thoracic surgery residents and 4 thoracic surgeons

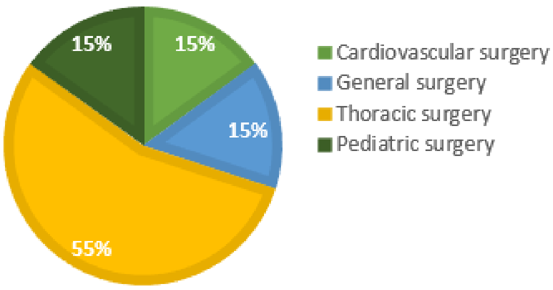

Figure 1: participants in the Nuss training workshop by specialty.

The participants' overall performance and feedback was analysed using IBM SPSS Statistics Software (Version 29), and the p-value determined using Mann-Whitney U test.
It was noted that at the pre-lecture quiz, only 8 (40%) participants could score above 7/10. In contrast, at the end of the lecture, all participants could score above 7/10. Additionally, significant differences in the scores obtained on the evaluation form were observed for all the participants with a mean score of 7.90 before and 9.50 after the lecture ($p<0.001$).
On the second-day evaluation, participants who did the simulation twice (group 1) scored a minimum of 60/75 and a maximum of 74/75 with a mean of 68.7/75; while the participants who only had the second-day simulation (group 2), had a minimum score of 36/75, a maximum of 56/75 and a mean on 49.8/75 (with a significant P value<0.001).
After using the simulator, participants were asked to fill a feedback form to evaluate the pedagogic utility of the simulator compared to classical teaching methods (I.e the lecture); the realism of the simulator; and the participants self-confidence in performing the procedure on a real-life patient.
A 1–5 Likert scale was employed for this form, with 1 being *strongly disagree* and 5 being *Strongly*

agree.

Self-confidence

Of the first group, 80% of participants gave a score of 4/5 or higher (agree and *strongly agree*) and 20% a score of 3/5 with a mean of 4.2/5; compared to the second group of whom 80% gave a score of 2/5 or lower (disagree and strongly disagree) with a mean of 2.7/5 and significant p-value of 0.002 (figure 2).

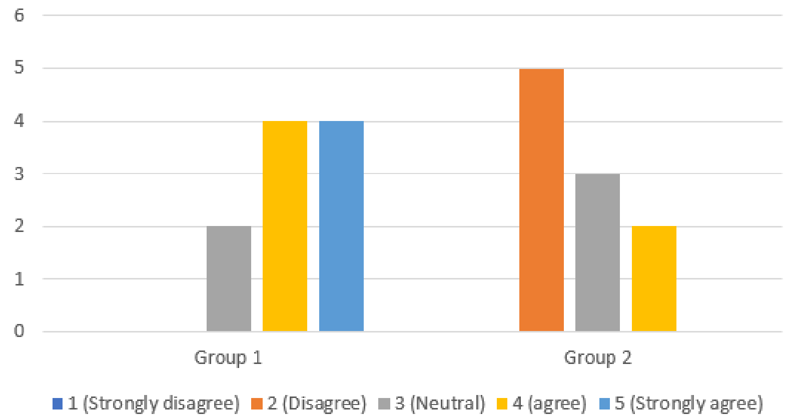

Figure 2: Participants rating their self confidence in replicating the procedure on a real patient.

Pedagogic utility

Overall, for the pedagogic utility of the simulator, 16 participants (80%) chose a rating of 4/5 or higher (agree or strongly agree), while the remaining 20% chose a score of 3/5 (neutral) (figure 3).

Figure 3: Participants evaluation of the simulators pedagogic utility compared to traditional teaching methods.

Simulator fidelity:

Participants were asked to evaluate the simulator's realism, and experience manipulating the various surgical instruments with focus on three aspects: realism of the sternal elevation, realism of the mediastinal dissection process, and overall realism of the simulator.

For the two groups combined, Results show that the percentages of participants who gave a score of 4 or higher (agree or strongly agree) were: 100% for sternal elevation, 80% for introducer manipulation during mediastinal dissection and 85% for overall simulation realism (fig 4).

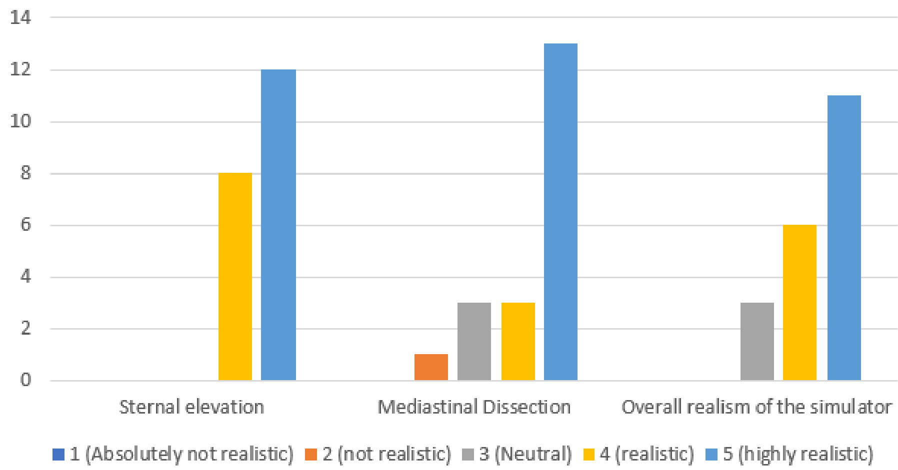

Figure 4: Participants evaluation of different realism parameters of the simulation.

Discussion:

Of chest wall deformities, pectus excavatum (PE) is the most frequent [6]. Although its pathophysiology remains unclear, this deformity primarily causes concavity of the inferior one-third to one-half of the sternum, which is the target for repair7. Correction techniques for pectus range from non-invasive, external vacuum devices to minimally invasive (Nuss procedures) and open surgical repair4 (Ravitch procedure), all of which aim to correct the anatomic deformity [5,8,9].

Due to its minimally invasive nature, its short operative time and the few complication associated, the Nuss technique remains actually the most favoured technique by surgeons and patients alike [5,9].

However, in minimally invasive surgeries, patient outcome is heavily dependent on the surgeon's caseload and experience [10] .

For inexperienced surgeons, the Nuss procedure has been noted to last longer compared to open operative times, and the probability of intraoperative complications during training could be higher too11 especially with a typical learning curve of performing at least 1 surgery every 35 days [10].

It should be noted that traditional apprenticeships following the Halsted approach12 by which once a skill has been observed, the surgeon is expected to perform it, can compromise the safety of patients and hinder the trainee's learning progress [13,14].

This shift in the healthcare paradigm of patient well-being has pushed training hospitals to embrace simulation tools as the keystone of surgical training15; as was the case for the Nuss procedure as highlighted in several studies [16,17].

In our experience, even though all participants had high scores on the knowledge evaluation following the lecture, only surgeons who practiced twice on the training model had a significantly better score during the simulation evaluation and reported higher confidence in replicating the procedure on a real case.

The participants also greatly appreciated the realism of the simulator and its pedagogic utility in the surgical teaching of the Nuss procedure compared to traditional teaching methods.

This further supports studies that showed the benefits of simulation-based training in the safe and fast acquisition of surgical skills as well as handling real cases especially when clinical exposure is limited 18,19.

To our knowledge, our study is the second to use a Simulator for the teaching of the Nuss corrective surgery and the first to implement a fully physical Nuss simulator.

Compared to the Nuss hybrid training model described by Obeid et al [20], we believe a high-fidelity physical model for the teaching of the Nuss procedure to be more efficient as Virtual or hybrid teaching methods can lack haptic feedback and realistic tissue handling, and often, don't allow full technical proficiency due to the highly specialized instruments used this procedure [21].

In comparison, fully physical simulation training specific to the procedure can allow surgeons to overcome the traditional learning curve compared to both conventional and virtual/hybrid surgical teaching, as it involves the use of different instruments, ergonomics, spatial awareness all while being easier to access [21,22]. This applies to the Nuss procedure due to its highly technical nature as we believe its key steps namely: the proper identification of the incision sites, choice of bar length and adequate shaping, sternal elevation, mediastinal dissection; and finally, the correct placement of the stabilizer, require not only good instrument manipulation but most importantly, communication and coordination between the surgeon and aid which cannot be taught without a fully physical simulator.

Conclusion

The Nuss procedure is a revolutionary surgical alternative in the minimally invasive management of pectus excavatum. However, it is highly technical with considerable perioperative risks and a challenging learning curve[10].

Therefore, we believe that the Nuss procedure requires rigorous training and adequate preparation; with skill evaluation criteria as precise as those implemented in the aviation teaching process. On one hand, theoretical or virtual teaching approach can be lacking/insufficient to reach proper surgical proficiency, and the traditional "learning on the job" approach has been a source of ethical conflict due to the risks it poses to patient safety[23]. On the other hand, fully physical training models can improve surgical skills in a secure and risk-free environment. With the increasing availability of 3D printers in teaching university hospitals, PE cases should be simulated via mannequin as often as possible before the intervention to allow adequate surgical planning and rehearsal, therefore reducing potential perioperative complications all while providing teaching opportunities and patient education material.

Conflict of Interest: The authors report no conflict of Interest.

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