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Initial experience with 3D printing in the use of customized Nuss bars in pectus excavatum surgery

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ABSTRACT

Introduction. Pectus excavatum (PE) surgical repair according to Nuss procedure is based on the intrathoracic insertion of one (or more) metallic bars for anatomical defect repair. Number of bars, bar length, bar shape, and thoracic insertion site are established during surgery, according to patient morphology, CT-scan, and especially the surgeon's experience.

Objective. To assess the usefulness of the design, simulation, and 3D printing of customized Nuss bars for each patient.

Materials and methods. A prospective descriptive study of all patients undergoing PE surgery under 3D printing from June to December 2019 was carried out. Curvature, bar length, and optimal intercostal space were designed based on diagnostic CT-scan, and they were 3D printed full size. The resulting model was reproduced preoperatively on the usual prosthetic material, sterilized, and kept until surgery.

Results. The study cohort consisted of 6 patients. Median age was 15 years old (interquartile range: 14.25-15.25), median Haller index was 4.05 (interquartile range: 3.5-4.49), and repair index was 36.98% (interquartile range: 33.86-38.48%). A Nuss bar was introduced in all cases, without requiring removal or re-insertion. Median operating time was 79.5 minutes (interquartile range: 72.5-103). No postoperative complications were noted during follow-up (12 months).

Conclusions. The preoperative design of Nuss bars with customized shape and size facilitates surgical planning. It also allows for the most optimal and accurate morphological repair possible, according to patient anatomy, thus reducing the risk of requiring removal and/or re-insertion, and therefore, of surgical complications.

KEY WORDS: Pectus excavatum; 3D printing; Nuss.

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EXPERIENCIA INICIAL EN LA IMPRESIÓN 3D PARA EL USO DE BARRAS DE NUSS PERSONALIZADAS EN LA CIRUGÍA DEL PECTUS EXCAVATUM

RESUMEN

Introducción. La corrección quirúrgica del pectus excavatum (PE) con técnica de Nuss, se basa en la inserción intratorácica de una (o más) barras metálicas para la corrección del defecto anatómico. El número de barras, su longitud, forma y punto de inserción torácico, se deciden durante la cirugía, según la morfología del paciente, el TC y, fundamentalmente, la experiencia del cirujano.

Objetivos. Evaluar la utilidad del diseño, simulación e impresión 3D de barras de Nuss personalizadas para cada paciente.

Material y métodos. Estudio descriptivo prospectivo, incluyendo a todos los pacientes intervenidos de PE bajo impresión 3D entre junio-diciembre 2019. Se diseñó la curvatura, longitud de la barra y espacio intercostal óptimo, en base al TC diagnóstico, y se imprimió en 3D en tamaño real. El modelo resultante se reprodujo prequirúrgicamente sobre material protésico habitual, se esterilizó y se reservó hasta la cirugía.

Resultados. Se recogieron 6 pacientes, mediana de edad 15 años (rango intercuartil 14,25-15,25 años). Mediana del Índice de Haller 4,05 (rango intercuartil 3,5-4,49) e índice de corrección 36,98% (rango intercuartil 33,86-38,48%). Se introdujo una barra de Nuss en todos los casos, sin precisar retirada ni reinserción. Mediana del tiempo quirúrgico 79,5 minutos (rango intercuartil 72,5-103 min). Ninguna complicación postquirúrgica durante el seguimiento (12 meses).

Conclusiones. El diseño prequirúrgico de la barra de Nuss, mediante forma y tamaño personalizados, facilita la planificación del procedimiento. A su vez, permite conseguir la corrección morfológica más óptima y precisa posible, según la anatomía del paciente, disminuyendo el riesgo de precisar retirada y/o reinserción de la barra, y por ende de complicaciones quirúrgicas.

PALABRAS CLAVE: Pectus excavatum; Impresión 3D; Nuss.

INTRODUCTION

Pectus excavatum (PE) is the most frequent congenital chest deformity[1,2]. It is defined as the depression of the anterior chest wall, which gives rise to a "funnel chest." Typically, it involves from the third to the seventh rib or rib cartilages, with xiphoid depression being more severe[3].

PE accounts for 90% of all chest wall deformities, with a prevalence of 1/300-1/1,000 live newborns, and a male/female ratio of 5:1[3].

PE surgical repair according to Nuss procedure is based on the intrathoracic insertion of a metallic bar (Nuss bar) for anatomical defect repair[4,5]. It is a standardized, well-established, thoracoscopy-guided minimally invasive surgical procedure. However, in the classic procedure, number of bars required, bar length, bar shape, and intrathoracic insertion site are established during surgery itself[4,5].

Traditionally, bar length has been determined by placing a bar-shaped "phantom" above the patient's external contour, while considering it should cover the space between both midaxillary lines[5].

Bar shape is determined based on external chest morphology and thoracic CT-scan[6,7]. This allows the surgeon to predict the number of bars required for an optimal repair, and establishes the most suitable intercostal space(s) for bar insertion, according to the maximum anterior projection points of the chest[4-7].

Once definitive bar configuration has been achieved, the bar is manually molded, while reproducing the intraoperatively designed "phantom" on biocompatible prosthetic material. Therefore, surgery success depends on the surgeon's experience and intraoperative assessment[1,7,8].

In case of insufficient repair or unsatisfactory esthetic results, bar removal, remodeling, and thoracic re-insertion may be required, with the resulting increase in time[8] and potential surgical risks[1,9].

In the last years, the use of tridimensional printing in medicine has soared, allowing a virtually unlimited number of 3D structures to be created with the utmost accuracy according to image quality and the technology chosen[10]. It also provides with a wide array of materials, including metals, plastics, and even live cells[11]. 3D printed anatomical models are useful both for preoperative planning and surgical assistance, and they have become a useful educational tool for patient and medical training[10,11]. However, nowadays, there are still few publications on chest malformation and PE surgery in the literature[1,2,8,9,12-14].

The objective of this study was to assess the usefulness of the design, simulation, and 3D printing of customized Nuss bars for each patient preoperatively.

MATERIALS AND METHODS

A prospective, longitudinal, descriptive study of all PE patients requiring surgery who accepted to participate in the research from June to December 2019 was carried out.

Demographic variables including sex, age, weight, size, and BMI were collected, as well as pathology-related variables: history of PE surgery (No - Yes), Haller index (through preoperative CT-scan), repair index (through preoperative CT-scan), echocardiography (normal-pathological), spirometry (normal-pathological), operating time (minutes), number of bars introduced, number of bars requiring removal and re-introduction, intraoperative complications, and complications during hospital stay.

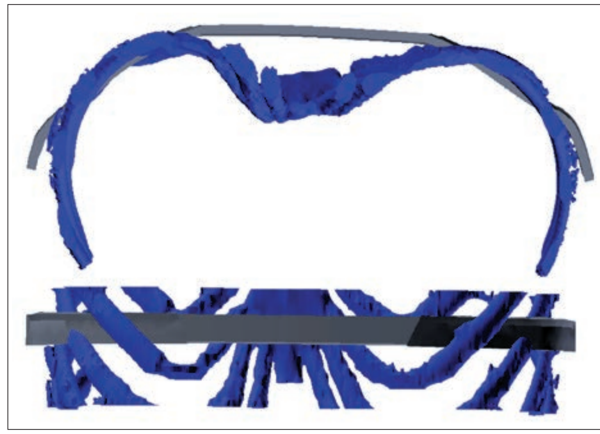

Figure 1. 3D reconstruction of the anterior rib wall visualized at diagnostic CT-scan, and axial (above) and front (below) views of Nuss bar simulation.

Design, simulation, and 3D printing

Diagnostic CT-scan was carried out using the *Somatom Emotion CT-scanner* with the following characteristics – minimum cutting thickness: 0.625 mm (maximum: 1 mm), adjacent or superimposed cuts (no spaces allowed), matrix size: 512 × 512, voxel size: 0.6, default anatomical region nucleus (standard or high resolution): 90-120 kVp.

Based on each patient's physical characteristics and diagnostic CT-scan, the number of Nuss bars required and the intercostal space most suitable for thoracic insertion –the chest site with the greatest anteroposterior depression, except for the xiphoid process– were established preoperatively.

Following CT-scan, bone tissue segmentation was initiated in order to generate full size rib cage and sternum components, apt for design. Specific segmentation of the relevant areas was performed using the *Mimics 21.0* software (Mimics Innovation Suite, Materialise MV, Belgium), with three options: 1) thresholding (> 226 UH), 2) region growing algorithm, and 3) manual repairs. Mesh volume files were transferred to the *3-matic 13.0* design software (Mimics Innovation Suite, Materialise MV, Belgium) to establish Nuss bar size and design with the most optimal morphological repair possible – theoretically speaking – (Fig. 1).

The resulting simulated bar model was printed full size, on PLA (polylactic acid), using the *Ultimaker S5* 3D printer (Ultimaker B.V., Utrecht, the Netherlands) (Fig. 2).

Figure 2. Full size 3D printing of the anterior rib wall and the simulated Nuss bar. Axial view.

Figure 3. Titanium Nuss bar reproducing the exact shape of the 3D simulated and printed bar. Axial view.

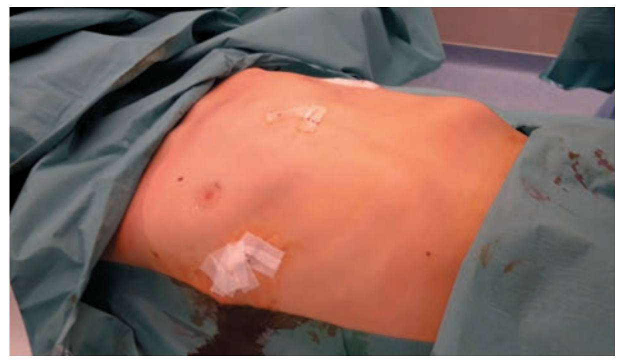

Figure 4. Final surgical result following 3D assisted PE repair.

Subsequently, the 3D simulated bar model was reproduced on the titanium Nuss bar (Fig. 3). And finally, the customized Nuss bar was autoclave-sterilized (Matachana) at 134º C and kept until surgery.

The price of the image segmentation and treatment required for the creation of the chest anatomical model, along with the 3D design of Nuss bar, was 300 €/unit. The price of printing the resulting model on PLA was 100 €/unit.

Surgical procedure

Surgery was carried out according to Nuss procedure, with some small changes with respect to the standard technique – such as preoperative sternal elevation – which are usually applied at our institution. At the level of the most depressed site of the sternum, a metallic suture stitch with Bryant's traction was placed in order to extend the substernal space during mediastinal dissection.

Under general anesthesia, a 2 cm bilateral skin incision was performed at the confluence of the pectoral border and the midaxillary line. The subcutaneous plane –with creation of a "subcutaneous pouch"– and the muscular plane were dissected, while identifying the intercostal space most suitable for Nuss bar placement according to 3D planning design.

A 5 mm port was introduced via the right skin incision, through the intercostal space immediately inferior to the one selected for the bar, and the thoracoscope was passed through the latter. Under videothoracoscopic control, mediastinal dissection was carried out using the sword-dissector until reaching the incision of the contralateral hemithorax. Once substernal dissection had been performed, a ribbon was knotted to the distal end of the sword-dissector, which was removed, leaving the ribbon in place as a guide.

The Nuss bar, which had been previously molded and sterilized –customized for the patient–, was knotted to the end of the guiding ribbon, and traction was exerted on the latter in the opposite direction, until the proximal side of the Nuss bar was visualized through the substernal passage. Once the bar had been introduced, it was rotated 180º, which allowed for an immediate morphological repair of PE.

Subsequently, a stabilizer was introduced in each "subcutaneous pouch" and sutured with 2-0 absorbable stitches. At our healthcare facility, two stabilizers are used in all cases.

In case further Nuss bars are required, the procedure is to be repeated.

Finally, the sternal stitch and the port were removed, a water-seal thoracic drainage tube was placed to evacuate the pneumothorax, and a layered suture was performed (Fig. 4).

RESULTS

The study consisted of 6 patients –100% of the patients undergoing surgery during the inclusion procedure. Demographic data and other pathology-related variables are featured in table I.

Median age was 15 years (interquartile range: 14.25-15.25), median Haller index was 4.05 (interquartile range: 3.5-4.49), and repair index was 35.9% (interquartile range: 33.86-38.48%).

A single Nuss bar was introduced in all cases, without the need for removal or re-placement. Median operating time was 82 minutes (interquartile range: 72.5-103).

Intraoperative complications included a 4 mm distal transfixation perforation in patient number 3. Perforation

Table I. Demographic and pathology-related variables.

Patient	*Age*	*Sex*	*Weight (kg)*	*Size (cm)*	*BMI*	*HI*	*RI*	*Op. time (min)*	*Echocardiography*	*Spirometry*	*Number of bars*	*Previous surgery*	*Intraop. comp.*	*Hospital stay comp.*
P1	13	Male	43	163	16.18	4.55	47.10%	72	Normal	Normal	1	Yes[1]	No	No
P2	15	Male	70	175	22.86	3.4	36.12%	103	Normal	Normal	1	No	No	No
P3	14	Male	44	165	16.16	3.02	22.58%	85	Normal	Normal	1	No	Yes[2]	No
P4	19	Male	40	168	14.13	5.2	37.84%	68	Pathological[3]	Normal	1	No	No	No
P5	16	Male	54	169	18.91	3.8	33.11%	74	Normal	Normal	1	No	No	No
P6	15	Male	51	165	18.73	4.3	38.69%	90	Normal	Normal	1	No	No	No

[1]*Taulinoplasty*[(15)]*.*
[2]*4 mm transfixation perforation at the LLL with self-limited bleeding not requiring additional treatment.*
[3]*Functionally bicuspid tricuspid aortic valve.*
BMI = body mass index; HI = Haller index; RI = repair index, Op. time = operating time; Intraop. comp. = intraoperative complications; Hospital stay comp. = complications during hospital stay.

occurred at the level of the left lung lingula, with self-limited bleeding. Since there was no air leak, no additional treatment was required. No postoperative complications were noted during follow-up (12 months post-surgery).

Morphological repair was subjectively assessed by the surgical team, patients themselves, and their parents. It was defined as “highly satisfactory” in all cases.

DISCUSSION

The angular shape of the 3D simulated bars is remarkable, since they are usually molded with much less marked angles. This can be explained by the specific design on the rib cage as a result of its chest entry and exit sites. However, following insertion and rotation, a sensation of greater adjustment within the rib cage and an optimal repair of the esthetic defect are perceived.

3D simulation does not alter or change the standard surgical procedure, which means it does not represent an extra surgical challenge. It provides the surgeon with safety, so it proves highly useful in less experienced surgeons. This is especially important considering that, with the usual technique, surgical success greatly depends on the experience and art of molding the bar by the surgeon themselves.

On the other hand, the process of bar simulation, printing, and molding does not involve an increase in healthcare burden, since it does not require complementary visits or tests. In addition, the printing material is inexpensive, which means it does not represent an increase in cost. However, it does reduce operating times, since it avoids the intraoperative bar molding process, and it reduces the risk of requiring bar removal and re-insertion or re-placement. This is an important advantage in terms of patient safety as it reduces anesthetic times and potential intraoperative complications associated with the need for bar removal and re-insertion as a result of suboptimal repair.

Even though most of our PE patients are male with a low BMI, 3D simulation designs the shape of the bar directly on the rib cage, omitting the muscular and subcutaneous tissue. Therefore, we believe it can represent a great advantage in girls with mammary gland development and in patients with greater subcutaneous adipose tissue – the latter being less frequent.

In conclusion, preoperative design of the Nuss bar, while customizing shape and size to each patient, facilitates surgical planning. It also allows for the most optimal and accurate morphological repair possible, according to patient anatomy (through CT-scan or MRI), thus reducing the risk of requiring bar re-placement (as a result of suboptimal repair), and consequently, of surgical complications.

Finally, this study has some limitations, the main one being it is an initial experience, with a low number of patients recruited (n = 6). In addition, the objective is to reduce the extension of thoracic diagnostic CT-scan (and thus irradiation) as much as possible, which means there are few anatomical references available allowing the exact position of the simulated Nuss bar to be accurately correlated with the final real position. Last, total operating times may vary according to other factors not related to the surgical technique, such as those associated with the anesthetic procedure, patient preparation, etc., which may have an impact on time analysis.

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