Advancing pectus deformity care: evaluation of current treatments, complications and future innovations

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Part IV

Summary and appendices

Chapter 11

Summary and discussion

SUMMARY

Pectus carinatum (PC) and pectus excavatum (PE) are chest wall deformities that can be treated successfully with both conservative and surgical approaches, each yielding good long-term outcomes. **Part I** focused on PC, comparing Dynamic Compression System (DCS) bracing to Ravitch surgery and demonstrating the advantages of DCS-bracing as the preferred first-line treatment. It also explored the positive impact of bracing on quality of life, highlighted the need for objective outcome measures, and evaluated the potential of 3D scanning for diagnosing PC and monitoring treatment progress. **Part II** addressed PE, assessing the effectiveness of vacuum bell (VB) therapy, comparing pain management strategies following the Nuss procedure, and providing practical guidelines for managing postoperative complications such as pleural effusion, postoperative infections, and allergic reactions. **Part III** examined the impact of surgical wait times on treatment withdrawal among pediatric patients, identifying key predictors of withdrawal and underscoring the importance of psychological factors in treatment decision-making.

PART I: PECTUS CARINATUM

In **Chapter 2**, we compared the outcomes of DCS-bracing and Ravitch surgery in 738 patients with pectus carinatum over a 10-year period. The results showed that DCS-bracing should be the preferred first-line treatment due to a combination its non-invasive nature, good success rate, and lower complication risk compared to surgery. For patients with high initial compression pressures and in those with syndromic conditions such as Marfan and Poland syndrome, however, treatment success of DCS-bracing appeared lower compared to surgery, and poor compliance remained a major challenge in achieving optimal outcomes. Surgical correction, particularly Ravitch surgery, thus remains a valuable alternative for patients with poor bracing prognosis.

In addition to evaluating ability of DCS-bracing to correct PC, in **Chapter 3**, we also report a study that examined whether treatment improved quality of life by assessing the impact of DCS-bracing on quality of life in 225 PC patients aged 10–21 years. The results showed significant improvements in physical complaints, pain, psychological health, self-esteem, and overall quality of life across multiple validated questionnaires, particularly within the first 6–12 months of treatment. No improvement was observed in patients with unsuccessful treatment outcomes. Nearly 90% of all patients would choose bracing again if given the choice, and 95% were satisfied with the treatment.

Despite high satisfaction rates, the absence of standardized objective endpoints continues to complicate DCS-brace treatment. This is addressed in **Chapter 4**, which reports assessment of inter- and intraobserver agreement in the visual evaluation of PC using standardized photographs of 201 patients before and after treatment. Both surgeons and peers showed inadequate consistency in rating esthetic outcomes, severity, and symmetry, with only slight to moderate agreement. Ravitch-treated deformities were perceived as more severe but yielded better esthetic results, while peers rated scars more negatively than surgeons. No associations were found between outcomes and age or treatment duration. These findings underscore the limitations of subjective evaluation and advocate the use of objective measurement tools to assess treatment outcomes.

In response to the need for objective assessment tools, we explored the potential of 3D body imaging as a standardized method to support clinical decision-making in **Chapter 5**. In a cross-sectional study, we compared the External Haller Index (EHI) of 43 patients with PC to that of 50 healthy adolescents. While EHI was significantly lower in patients with PC, the considerable overlap between patients with PC and healthy peers limits its use as a strict diagnostic cut-off. The observed correlation between EHI and Body Mass Index (BMI) suggests that unadjusted EHI values alone are insufficient for reliably monitoring deformity severity or treatment progress, highlighting the need for BMI-adjusted reference values and further validation of 3D imaging parameters.

PART II: PECTUS EXCAVATUM

In **Chapter 6**, we investigated the long-term outcomes and factors influencing the success of vacuum bell (VB) therapy in 259 patients (<18 years) with PE. Among those who completed treatment, success rate was 52.1%. A higher success rate was associated with longer total treatment duration, greater daily use, and overnight application. Deeper deformities, flexible chest walls, and symptomatic presentation were associated with lower success rates. Complications were mostly minor, and recurrence was rare. Notably, 26.7% of patients treated while awaiting a Nuss procedure no longer required surgery. Female patients faced specific challenges, with 39.3% discontinuing treatment due to breast development. Early initiation or watchful waiting may be a more appropriate treatment in this group. These findings underline the need for individualized treatment planning based on patient characteristics to improve outcomes with VB therapy.

The majority of patients with PE are treated with the Nuss procedure. Prior to the introduction of intercostal nerve cryoablation, this minimally invasive surgery was associated with significant postoperative pain, often resulting in extended hospital stays and high opioid consumption. In **Chapter 7** we compared the effectiveness of intercostal nerve cryoablation to continuous epidural analgesia (CEA) in 66 children undergoing the Nuss procedure for PE. The results demonstrated that cryoablation significantly reduced postoperative pain scores, shortened hospital length of stay, and led to markedly lower opioid use both at discharge and one week postoperatively. These findings establish cryoablation as a superior analgesic strategy compared to CEA. Additionally, the data suggest that routine prophylactic use of gabapentin may be unnecessary, given its limited added benefit in patients receiving cryoablation.

Although the Nuss procedure generally yields good results, it is associated with complications, one of which is pleural effusion, a poorly understood and frequently misdiagnosed condition. In **Chapter 8**, we presented three unique, illustrative cases of pleural effusion following the Nuss procedure, showing that in the absence of bar infection or bar displacement, the effusion may represent a reactive inflammatory response that mimics pneumonia, and may respond well to corticosteroid therapy. These cases underscore the importance of thorough diagnostic evaluation and support the use of pleural fluid analysis to guide management. Based on our experience with this complication, we proposed a diagnostic and treatment protocol to help clinicians recognize and manage this complication more effectively.

Another complication of the Nuss procedure is postoperative infection. In **Chapter 9**, we analyzed the incidence, characteristics, and management of Nuss bar infections in 695 patients treated between 1999 and 2024, identifying an overall infection rate of 4.0%. Infections typically presented with erythema, pain, and exudate. Over time, infections shifted from early- to late-onset, with most being deep infections, requiring surgical intervention. Superficial infections were managed with antibiotics, though treatment strategies varied. Bar dislocation and stabilizer plate loosening were significant risk factors for infection. Infections also prolonged bar removal procedures. Based on our findings, we developed a structured diagnostic and treatment protocol, recommending six weeks of oral flucloxacillin and biofilm-active rifampicin for acute infections, and long-term amoxicillin or clindamycin for low-grade cases until bar removal. In patients with persistent erythema but no systemic signs or abnormal imaging, implant allergies should be considered. We also highlighted terra firma-forme dermatosis as a benign postoperative skin condition easily treated with alcohol wipes.

PART III: CROSS-CUTTING PERSPECTIVES

In **Chapter 10**, we investigated the impact of prolonged waiting times, largely due to the COVID-19 pandemic, on patients' decisions to proceed with surgery for pectus deformities. In a cohort of 107 patients, only 40.2% still wished to undergo surgery after an average wait of nearly five years. Withdrawal rates differed by deformity type and were primarily driven by increased body acceptance in patients with PE and by physical development through strength training or weight gain in those with PC or flaring. Patients who withdrew reported greater reductions in both physical and psychosocial symptoms than those who remained on the waitlist. Younger age and absence of physical symptoms at the time of waitlist entry were significant predictors of withdrawal. Conservative treatment was successful in a minority of cases during the waiting period. These findings highlight the importance of early psychological counseling and physical training as part of routine care for young, asymptomatic patients, potentially reducing the need for surgery in selected cases.

DISCUSSION

This thesis explores the current management and future directions in the treatment of patients with pectus deformities. Pectus excavatum (PE) and pectus carinatum (PC) are the most common congenital chest wall deformities and can significantly impact physical function, psychological well-being, and quality of life.[1] Despite advancements in both surgical and conservative treatment modalities, several challenges remain. These include identifying objective criteria for treatment success, managing complications effectively, and improving patient-centered decision-making. This thesis addresses these themes across nine chapters, which can be categorized into three parts. **Part I** evaluates treatment outcomes and quality of life in PC patients, and explores the need and development of 3D body scanning as an objective tool to guide and monitor non-invasive treatment. **Part II** focuses on PE, evaluating (VB) therapy, comparing pain management after the Nuss procedure, and offering practical guidelines for managing complications like pleural effusion, postoperative infections, and allergic reactions. Finally, **Part III** examined the impact of surgical wait times on treatment withdrawal among pediatric patients, identifying key predictors of withdrawal and underscoring the importance of psychological factors in treatment decision-making.

In this chapter we discuss the main findings of our thesis and outline directions for future research.

PECTUS CARINATUM

In **Part I** of this thesis, we compared the outcomes of Ravitch surgery and Dynamic Compression System (DCS) bracing in patients with PC, assessed the impact of DCS-bracing on quality of life, and explored the need for objective treatment endpoints, highlighting the potential of 3D scanning as a tool to facilitate standardized, non-invasive assessment and treatment monitoring.

Before the introduction of the DCS-brace, Ravitch surgery was considered the standard of care for patients with PC. Although DCS-bracing gradually became the preferred first-line treatment due to its non-invasive nature, comparative data on its effectiveness versus surgical correction to date remained limited. In **Chapter 2**, we addressed this gap by directly comparing DCS-bracing to Ravitch surgery in a large cohort. The results showed that while surgery offered slightly better outcomes (92.4% versus 73.8% of patients treated successfully), DCS-bracing should be treatment of first choice because of its non-invasiveness, very few complications and high patient satisfaction. However, there are some exceptions. Bracing should not be initiated before the pubertal growth spurt, as the risk of relapse is higher and long-term retainer use is required, demanding

sustained motivation. Similarly, in patients with a high Pressure of Initial Correction (PIC) (>8.5 PSI), treatment success depends heavily on compliance; if motivation is lacking, outcomes are likely to be poor.[2] Finally, in patients with syndromes such as Marfan or Poland syndrome, or in cases of anatomically complex deformities, Ravitch surgery may be more appropriate than bracing.

Given that treatment outcomes are closely tied to consistency of use, the success rate of DCS-bracing might increase even further if patient compliance could be further improved through more structured and standardized follow-up using, for example, 3D body imaging and digital adherence tracking. Future research should therefore explore interventions aimed at improving compliance, especially in adolescents, who may struggle with long-term treatment commitment.

We do not recommend the Abramson procedure[3] for pediatric PC patients unless specifically requested, as most eligible candidates can also be managed non-operatively with DCS-bracing, thereby avoiding the risks associated with two surgical interventions.

Beyond correction of the physical deformity, we aimed to determine whether treatment with DCS-bracing also resulted in improvements in quality of life for patients with PC, an aspect of pectus deformity care that had not been investigated prior to our study. Therefore, in **Chapter 3** we aimed to investigate the impact of DCS-bracing on quality of life in patients with PC. The results of this study show significant improvements in physical complaints, pain, psychological well-being, self-esteem, and overall quality of life, particularly within the first 6–12 months of treatment.

The results of this study show that patients with PC do profit from DCS-bracing. However, our study had a follow-up of only 24 months. In light of the findings in Chapter 10, it would be valuable to examine whether the distinction between successfully and unsuccessfully treated patients remains relevant in the long term. As some individuals may no longer perceive a need for treatment in adulthood, due to increased body acceptance or physical development, the gap in quality of life between both groups may diminish or even disappear altogether.

Despite the good results of DCS-bracing, determining when treatment can be considered successful remains a challenge. As discussed in **Chapter 4**, current evaluation methods, based on subjective visual assessment, are inconsistent and show poor inter- and intraobserver agreement among both surgeons and peers. To address this, **Chapter 5** explored the potential of 3D body imaging as an radiation free, objective tool to support treatment monitoring and establishing objective outcomes measures. We compared

the External Haller Index (EHI) between PC patients and healthy adolescents. The results show a significant difference in EHI between healthy adolescents and peers, but there was substantial overlap in EHI between the two groups and both cohorts were rather small. While 3D body imaging appears to be a promising non-invasive method for treatment monitoring,[4-7] further research is essential to fully establish its clinical utility. First, a larger cohort of healthy controls is needed to create robust, age- and sex-specific reference values. In addition, development of a BMI-adjusted External Haller Index (similar to existing adjustments in PE care[8]) is critical, as our results demonstrate that BMI significantly influences EHI values. Furthermore, longitudinal studies should assess whether EHI can reliably track deformity progression and treatment response over time. In the future, these measurements could even be integrated into predictive models for treatment planning, optimizing the duration and intensity of bracing therapy. Finally, although EHI represents a useful parameter, it need not be the only or optimal option; alternative indices could be developed that more accurately characterize the deformity and its clinical implications.

PECTUS EXCAVATUM

In **Part II** of this thesis we focused on PE, assessing the effectiveness of VB therapy, comparing intercostal nerve cryoablation to epidural analgesia for postoperative pain management following the Nuss procedure, and providing guidance for the diagnosis and treatment of complications such as pleural effusion, postoperative Nuss bar infections, and allergies.

In **Chapter 6**, we evaluated the long-term outcomes of vacuum bell (VB) therapy as a non-invasive alternative to surgical correction in patients with PE. Among patients who completed treatment, the success rate was 52.1%, which is consistent with outcomes reported in the available literature.[9] Importantly, complications were rare and mostly minor, and recurrence occurred in only 2.3% of patients during long-term follow-up. These findings support VB therapy as a viable treatment option in several patient groups.

First, patients awaiting surgery. In our cohort, 26.7% of patients who initially chose VB therapy while waiting for a Nuss procedure ultimately avoided surgery altogether. Although the numbers are small, this suggests that VB therapy can be a useful interim or even definitive treatment. The second group that might profit from VB therapy are younger patients not yet eligible for surgery. VB therapy may serve as a temporizing measure to preserve thoracic flexibility and prevent progression of the deformity in patients who are too young for surgical correction. However, this requires careful monitoring. The third group that might profit from VB therapy are highly motivated

individuals not willing to undergo surgery. As with DCS-bracing, motivation and compliance are essential. In our study, patients who adhered to longer treatment durations and overnight use had significantly better outcomes. If a patient is highly motivated, a stiff chest wall, contrary to what is generally reported in the literature,[10, 11] should not be considered a contraindication for VB therapy. Notably, female sex should indeed be considered a relative contraindication for VB therapy.

The primary limitation of VB therapy, comparable to DCS-bracing, is patient compliance. In our study, 17.6% of patients were lost to follow-up, and it is likely that treatment adherence was suboptimal in many others. This underscores once again the need of developing improved strategies to support adherence in the conservative management of pectus deformities. As mentioned before, 3D body imaging could play a significant role in this regard, by offering objective and visual feedback on treatment progress, which may help to maintain patient motivation and improve compliance.

In **Chapter 7** we evaluated the effectiveness of intercostal nerve cryoablation compared to epidural analgesia as postoperative pain management strategies following the Nuss procedure. Prior to the introduction of intercostal nerve cryoablation, this minimally invasive surgery was associated with significant postoperative pain, often resulting in extended hospital stays and high opioid consumption. Our results show that intercostal nerve cryoablation significantly reduced postoperative pain scores, shortened hospital length of stay, and led to markedly lower opioid use both at discharge and one week postoperatively. These findings establish intercostal nerve cryoablation as a superior analgesic strategy compared to epidural analgesia. As a result, it has now been adopted as the standard method of analgesia for the Nuss procedure in our center, with epidural analgesia reserved only for selected cases where cryoablation is not feasible (e.g., when single-lung ventilation cannot be achieved).

Yet, the technique continues to evolve. While cryoablation was applied for two minutes per intercostal nerve in this study, newer protocols using a one-minute application are currently being explored.[12, 13] In addition, percutaneous cryoablation, which is already used but not yet widely implemented in clinical practice,[14-16] can potentially further reduce hospital stay and broaden the applicability of the technique, for instance in the treatment of rib fractures or in patients not eligible for thoracoscopic access.

While the Nuss procedure generally yields favorable outcomes and the technique continues to evolve, complications remain an important concern. In **Chapter 8**, we described a case series of patients who developed pleural effusion following the procedure, an underrecognized and frequently misdiagnosed complication that remains

poorly understood. This condition is often mistaken for pneumonia due to overlapping symptoms such as fever, chest pain, dyspnea, and elevated inflammatory markers.

However, in many cases, these effusions are not infectious but rather represent a reactive inflammatory response, potentially triggered by manipulation of the parietal pleura or irritation caused by the Nuss bar. Imaging alone often fails to differentiate between sterile and infectious effusions, making pleural fluid aspiration and culture the diagnostic gold standard. In patients unresponsive to antibiotics and with negative cultures, corticosteroid therapy proved to be effective, supporting a non-infectious, inflammatory etiology in select cases.[17, 18]

Based on these findings, we developed and implemented a structured diagnostic and treatment protocol, including routine postoperative chest X-rays at three weeks and early consideration of corticosteroids in culture-negative, non-resolving effusions. Future research should aim to better understand the role of tissue manipulation, particularly from cryoanalgesia and sternal elevation, in the development of inflammatory complications such as pleural effusion, and to validate our management strategy in larger prospective cohorts.

In **Chapter 9**, we investigated postoperative infections following the Nuss procedure, identifying an overall infection rate of 4.0%. These infections showed a temporal shift from early- to late-onset over time, with Cutibacterium acnes (CA), a low-virulence skin bacterium, becoming increasingly prevalent.

The exact cause of the rising incidence of CA in late-onset Nuss bar infections remains uncertain. This trend may reflect a true increase in CA-related infections, a relative decline in other pathogens, or improved detection methods resulting from more frequent and targeted culturing. Further investigation is warranted, particularly through microbiological analysis of explanted bars, to determine whether CA acts as a true pathogen in these cases or merely represents a contaminant. The increased recognition of CA also highlights the importance of improved fixation techniques and optimal stabilizer placement to minimize mechanical instability. Bar dislocation and stabilizer loosening alter the local tissue environment through micromotion, which may facilitate colonization by low-virulence organisms such as CA.

Over the past 25 years, a wide variety of antibiotic regimens have been employed in managing Nuss bar infections, often based on individual surgeon preference.[19, 20] Based on our findings, we propose a structured, multidisciplinary approach to the diagnosis and treatment of these infections. It is equally important to remain vigilant

for non-infectious causes of postoperative erythema, such as metal hypersensitivity and terra firma-forme dermatosis.[21] The latter, though benign and easily treated with alcohol wipes, may be misinterpreted as infection or allergy, leading to unnecessary interventions.

Looking ahead, further efforts should be directed toward validating our proposed diagnostic and therapeutic protocol in larger prospective cohorts. Simultaneously, optimizing bar fixation techniques will be critical in reducing infection rates and improving long-term outcomes.

Beyond the complications mentioned in **Chapter 8 and 9**, our clinical experience has revealed a number of unusual postoperative skin changes with unclear etiology. We hypothesize that these may be related to the introduction of cryoanalgesia, specifically the effects of temporary intercostal nerve blockade on local skin physiology, leading to atypical appearances. Since these phenomena remain poorly understood at present, they underscore the need for systematic observation and documentation. Future studies should aim to elucidate their underlying mechanisms and clinical significance.

CROSS-CUTTING PERSPECTIVES

In **Part III**, we reported an evaluation of the impact of surgical wait times on treatment withdrawal among pediatric patients, identifying key predictors of withdrawal and underscoring the importance of a patient-centered approach in treatment decision-making.

In **Chapter 10**, we investigated the impact of prolonged waiting times on patients listed for pectus surgery. After an average delay of nearly five years, only 40.2% of patients still wished to undergo surgery. Withdrawal was most common in younger, asymptomatic patients and was associated with psychosocial improvement, body acceptance, and strength training or weight gain.

Interestingly, withdrawal often reflected personal growth rather than dissatisfaction with care. Many patients initially sought treatment for cosmetic or emotional reasons but later reconsidered surgery as their self-image improved. This trend suggests that psychological support and time for natural development can reduce the perceived need for surgery, especially in patients with PC. Structured strength training may help PC patients, especially those who are lean or in early adolescence.[22,23] Given that 70% of patients listed for Ravitch surgery eventually withdrew, surgical indications for PC should be reassessed, favoring non-invasive strategies when appropriate.

For patients with PE, caution is advised regarding reassessing indications for surgery. Although asymptomatic, many patients exhibit subclinical cardiopulmonary impairment that only becomes evident through improvement following surgical correction.[24] This group of patients, although asymptomatic does benefit from surgery.

Additionally, practical barriers also emerged as a reason for withdrawal, such as changes in life circumstances making surgery less feasible. Delays in surgery may result in missed opportunities or increased technical difficulty due to chest wall rigidity with age.[25] Thus, timing remains crucial, and early support, both physical and psychological, should be part of the treatment pathway.

Future efforts should include developing tools to help predict who will benefit most from surgery, integrating psychological counseling early in care, and promoting non-invasive therapies. A nuanced, individualized approach to timing and type of intervention will likely improve long-term outcomes and patient satisfaction.

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