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IMPROVEMENT OF TREATMENT TACTICS FOR SEVERE DEGREES OF PECTUS EXCAVATUM IN PRESCHOOL-AGED CHILDREN

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Abstract. The pathogenesis of pectus excavatum involves not only osteochondral structures but also the soft tissue components of the anterior chest wall, including the sternodiaphragmatic ligament, which plays an important role. **The aim** of this study was to improve the treatment strategy for severe forms of pectus excavatum (PE) in preschool-aged children. **Clinical material:** the treatment outcomes of 30 children aged 1 to 6 years diagnosed with grade III–IV pectus excavatum were analyzed. **Methods:** the degree of deformity was determined using multislice computed tomography (MSCT). In all patients, the morphological and functional status of the sternodiaphragmatic ligament (SDL) was additionally assessed by ultrasonography (US). Based on these findings, an individualized treatment strategy was selected. In patients with grade III–IV deformities and the presence of contracture and fibrotic changes of the SDL, ligament release was performed followed by correction using the vacuum bell technique. **Results:** In preschool-aged children with severe pectus excavatum, assessment of the sternodiaphragmatic ligament using ultrasonography is of great importance for selecting the appropriate treatment strategy. In patients with a morphologically preserved ligament, vacuum bell therapy was effective, whereas in cases with fibrotic changes and contracture, the use of vacuum bell correction combined with ligament release provided significantly better clinical and anatomical outcomes. Statistical analysis of the obtained results demonstrated a significant association between anterior chest wall deformation and mechanical stresses and the severity of the deformity. According to MSCT and computational biomechanical modeling, both the compression depth and the maximum von Mises stress values increased in a statistically significant manner with increasing deformity severity ($p < 0.01$). Compared with patients with grade II deformity, those with grade III–IV deformities showed significantly higher compression depth values at the central anatomical points (P3–P5) ($p < 0.01$), while the differences at the peripheral points (P1–P2) were less pronounced ($p < 0.05$). This indicates that mechanical loading is predominantly concentrated in the central regions of the anterior chest wall. **Conclusion:** In the treatment of severe pectus excavatum in preschool-aged children, an individualized approach based on ultrasonographic evaluation of the sternodiaphragmatic ligament demonstrates high clinical efficacy, reduces the extent of invasive surgical interventions, and expands the possibilities for early correction.

Key words: pectus excavatum; preschool age; sternodiaphragmatic ligament; ultrasonography; vacuum bell; contracture.

Relevance of the topic: Pectus excavatum is the most common congenital deformity of the anterior chest wall in children and adolescents, accounting for 80-90% of all chest wall deformities [1,3,5]. Epidemiological studies indicate that the incidence of this pathology ranges from 1:300 to 1:1000 live births and is observed 3-4 times more frequently in boys [5,8]. Although in preschool age the deformity is often clinically mild, recent years have shown an increasing detection of severe grade III–IV forms even at an early age [2,10]. This condition is significant not only as a cosmetic defect but also because of the risk of developing functional impairments of the respiratory and cardiovascular systems [4,7].

The pathogenesis of pectus excavatum involves not only osteochondral structures but also the soft tissue components of the anterior chest wall, including the sternodiaphragmatic ligament, which plays an important role [8,9]. Particularly in severe deformities, the development of contracture and fibrotic changes in this ligament serves as an additional mechanical factor contributing to posterior displacement of the sternum [9,10]. In this context, in preschool-aged children with severe forms of the deformity, ultrasonographic assessment of soft tissue structures and the individualization of vacuum bell therapy and minimally invasive correction techniques based on these findings represent one of the current scientific and practical challenges in modern pediatric surgery [2,6,9].

Purpose of study: To determine the clinical effectiveness of an individualized treatment strategy based on ultrasonographic assessment of the sternodiaphragmatic ligament in the management of severe forms of pectus excavatum in preschool-aged children.

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Materials and methods: The study was conducted at the Andijan Regional Children's Multidisciplinary Medical Center. Thirty pediatric patients diagnosed with pectus excavatum were enrolled. The patients' ages ranged from 1 to 6 years, which is considered a relatively optimal age group for conservative treatment using the vacuum bell method. The severity of chest wall deformity was assessed in all patients using multislice computed tomography (MSCT). According to the tomographic findings, 6 patients (20%) had grade II, 15 patients (50%) had grade III, and 9 patients (30%) had grade IV pectus excavatum. In determining the degree of deformity, chest wall geometry, the depth of sternal depression, and the internal thoracic dimensions were taken into account.

All patients underwent ultrasonographic examination to assess the condition of the soft tissues of the anterior chest wall, recognizing the morphological and functional status of the sternodiaphragmatic ligament (lig. sternodiaphragmaticum). During ultrasonography, the ligament's length, thickness, echogenicity, and degree of tension at rest and during functional strain were evaluated.

Deformities and stress within the anterior chest wall arise as a result of mechanical forces acting on various anatomical regions of the anterior thoracic wall; therefore, their assessment requires a comprehensive approach. For this purpose, clinical, instrumental, and computational methods were employed.

Results: To assess deformities and internal stresses of the anterior chest wall caused by mechanical forces in pectus excavatum, a comprehensive clinical, instrumental, and computational analysis was performed in 30 patients. The patients were divided into groups II, III, and IV according to the severity of the deformity.

The clinical assessment showed that in patients with grade II deformity, deformational changes of the anterior chest wall in response to mechanical loading were relatively limited, and mobility of the anterior wall during respiration was partially preserved. In patients with grade III and especially grade IV deformities, mobility of the anterior chest wall was markedly reduced, and increased passive resistance to external mechanical forces was observed.

Instrumental analysis using MSCT revealed the depth of deformity in various anatomical regions of the anterior chest wall and the relationships between the sternum and the ribs. The data showed that in patients with grade III–IV deformities, the depth of deformation was greatest in the central regions of the anterior chest wall, whereas relatively fewer changes were observed in the peripheral regions. Ultrasonographic examination in 30 patients made it possible to assess the morphological and functional state of the sternodiaphragmatic ligament (SDL). The results demonstrated that with increasing severity of pectus excavatum, consistent morphofunctional remodeling of the SDL occurs.

In the six patients with grade II deformity, the mean length of the sternodiaphragmatic ligament was 22.1 ± 1.3 mm, and its thickness was 4.1 ± 0.4 mm. The echostructure was predominantly hyperechogenic, and functional tension was of moderate degree. Clinically, this condition corresponded to the subcompensation stage, with partial preservation of the elastic properties of the ligament.

In the 15 patients with grade III deformity, a statistically significant shortening of the sternodiaphragmatic ligament (18.5 ± 1.5 mm) and an increase in its thickness (4.9 ± 0.5 mm) were observed ($p < 0.01$). Echogenicity became heterogeneous, and functional tension was markedly expressed. These findings indicated the development of a contracture process within the ligament.

In the nine patients with grade IV deformity, the most severe morphological changes of the sternodiaphragmatic ligament were observed. The ligament length was reduced to 15.9 ± 1.7 mm, while its thickness increased to 5.7 ± 0.6 mm. The echostructure exhibited a fibrotic pattern, and functional tension was strongly expressed. Clinically, this condition corresponded to the stage of decompensation.

Table-1. Ultrasonographic parameters of the sternodiaphragmatic ligament according to the severity of pectus excavatum (n = 30).

Degree of deformation	n	SDL length (mm)	SDL thickness (mm)	Echogenicity	Functional tension	Clinical assessment
Grade-II	6	22,1 ± 1,3	4,1 ± 0,4	Hyperechogenic	Moderate	Subcompensation
Grade-III	15	18,5 ± 1,5	4,9 ± 0,5	Heterogeneous	Marked	Contracture
Grade-IV	9	15,9 ± 1,7	5,7 ± 0,6	Fibrotic	Severe	Decompensation

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Statistical analysis of the data in Table 1 revealed a strong inverse correlation between sternodiaphragmatic ligament length and the severity of the deformity ($r = -0.71$; $p < 0.01$), as well as a direct correlation between ligament thickness and deformity severity ($r = +0.68$; $p < 0.01$).

Computational biomechanical analysis using the finite element method was performed on individualized three-dimensional models generated from MSCT data of 30 patients. External mechanical loading was simulated at five standard anatomical points (P1–P5) of the anterior chest wall, and the depth of compression and internal mechanical stresses were calculated for each point.

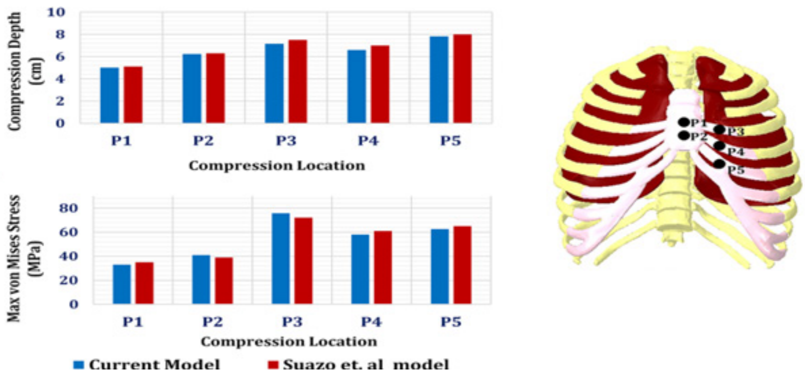
Statistical analysis of the obtained results demonstrated a significant association between anterior chest wall deformation and mechanical stresses and the severity of the deformity. According to MSCT and computational biomechanical modeling, both the compression depth and the maximum von Mises stress values increased in a statistically significant manner with increasing deformity severity ($p < 0.01$).

Compared with patients with grade II deformity, those with grade III–IV deformities showed significantly higher compression depth values at the central anatomical points (P3–P5) ($p < 0.01$), while the differences at the peripheral points (P1–P2) were less pronounced ($p < 0.05$). This indicates that mechanical loading is predominantly concentrated in the central regions of the anterior chest wall.

A moderate to strong positive correlation was identified between maximum von Mises stress values and the clinical severity of the deformity ($r = 0.62–0.74$; $p < 0.01$). In addition, a significant positive correlation was found between compression depth and von Mises stress ($r = 0.66$; $p < 0.01$), confirming that morphological deformation and internal mechanical stresses of the anterior chest wall are interrelated processes.

Analysis of variance (ANOVA) revealed statistically significant differences in mechanical parameters among the deformity severity groups ($F > F\_critical$; $p < 0.01$), confirming the sensitivity and representativeness of the applied assessment methods.

Figure 1. Comparative analysis of compression depth (cm) and maximum von Mises stress (MPa) at different chest wall compression points (P1–P5) based on the present model and the model proposed by Suazo et al. The diagram reflects deformities and stresses generated by mechanical loading in various anatomical regions of the anterior chest wall.



In 24 patients with grade III–IV pectus excavatum, signs of contracture and fibrosis of the sternodiaphragmatic ligament were identified, and these morphofunctional changes were found to limit the effectiveness of vacuum bell therapy when used alone. Therefore, in these patients, sternodiaphragmatic ligament release followed by stepwise correction using the vacuum bell was applied. After treatment, a significant reduction in chest wall depression and a reliable increase in anterior chest wall mobility were observed.

The sternodiaphragmatic ligament release was performed under general anesthesia with the patient in the supine position. After standard antiseptic preparation of the anterior chest wall, a 2–3 cm transverse incision was made at the projection of the tip of the xiphoid process. Through the incision, the skin, subcutaneous tissue, and fascial layers were dissected layer by layer. In the region of the xiphoid process, the sternodiaphragmatic ligament was carefully separated from the surrounding soft tissues and completely transected. After achieving hemostasis, the wound was closed in layers.

After surgical intervention, vacuum bell correction procedures were initiated once the early postoperative rehabilitation period had ended, primary wound healing had occurred, and all signs of inflammation had completely resolved. The optimal time to begin

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treatment was considered to be an average of 20–25 days after surgery. This interval was determined based on a comprehensive clinical assessment, including visual evaluation of the wound, absence of local inflammatory signs, and the patient's overall somatic stability. Vacuum bell therapy was applied according to current international clinical guidelines using an individually selected regimen (Figure 3) [2,6,9]. In this study, the Vacuum Bell® device (Eckart Klobe GmbH, Germany) was used for correction of pectus excavatum.

Figure 2. Schematic illustration and intraoperative view of sternodiaphragmatic ligament release.

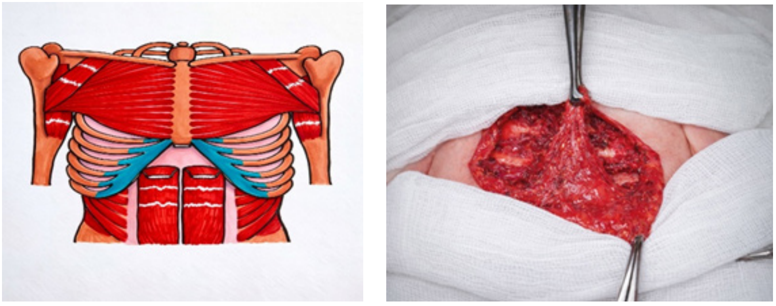

Figure 3. Preoperative, postoperative, and vacuum bell–applied views of an 18-month-old patient with grade III pectus excavatum.

In 24 patients with grade III–IV deformities who underwent sternodiaphragmatic ligament release followed by vacuum bell therapy, treatment efficacy was dynamically assessed. The evaluation criteria included chest wall depression depth, anterior chest wall mobility, and the clinical compensation status. Assessments were performed preoperatively, in the early postoperative period (3 months), and at 9 months of follow-up.

Table 2. Dynamics of chest wall parameters after sternodiaphragmatic ligament release (n = 24).

Parameter	Preoperative	After 3 months	After 9 months	p
Chest depression depth (mm)	32,4 ± 3,1	26,8 ± 2,9	21,6 ± 2,7	<0,01
Anterior chest wall mobility	Low	Moderate	Good	<0,01
Clinical status	Decompensation	subcompensation	compensation	<0,01

Statistical analysis showed that after sternodiaphragmatic ligament release, chest wall depression depth decreased significantly at all follow-up stages ($p < 0.01$). At the same time, a consistent increase in anterior chest wall mobility and a transition of the clinical condition from decompensation to compensation were observed.

The obtained results indicate that in preschool-aged children with severe pectus excavatum, the sternodiaphragmatic ligament plays an active mechanical role in the pathogenesis of the deformity. Its shortening, thickening, and fibrosis lead to posterior–inferior displacement of the sternum, thereby limiting the effectiveness of vacuum bell therapy when used alone.

Discussion. The results of this study demonstrate that mechanical factors, particularly the morphofunctional state of the sternodiaphragmatic ligament, play a decisive role in the pathogenesis of pectus excavatum. The clinical, instrumental, and biomechanical data complement each other, showing that as the deformity progresses, internal mechanical

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stresses and passive traction forces within the anterior chest wall increase progressively [1–3].

According to the clinical assessment, in grade II deformity the mobility of the anterior chest wall is relatively preserved, indicating the presence of adaptive responses to external mechanical forces. This reflects favorable anatomical and functional conditions for the effectiveness of conservative methods, including vacuum bell therapy [4,5]. In contrast, in grade III and IV deformities, anterior chest wall mobility was markedly reduced, and passive resistance to external mechanical forces was increased.

MSCT data confirmed that the depth of deformity is mainly concentrated in the central regions of the anterior chest wall. These findings are fully consistent with the biomechanical analysis based on the finite element method, which demonstrated that compression depth and von Mises stress reached their highest values at the central points (P3–P5). According to biomechanical studies by Nuss, Kelly, and their colleagues, as well as by Suazo et al., the high mechanical loads occurring in the central regions of the anterior chest wall play a leading pathogenetic role in the progression of pectus excavatum.

Ultrasonographic findings clearly demonstrated the development of morphological remodeling of the sternodiaphragmatic ligament proportional to the severity of the deformity. While in grade II deformity the elastic properties of the ligament were partially preserved, in grade III–IV deformities its shortening, thickening, and fibrosis were observed [9,10]. These changes identified in the study were regarded as a constant pathological mechanical factor that pulls the sternum posteriorly and inferiorly. The strong inverse and direct correlations identified ($r = -0.71$ and $r = +0.68$) confirm a close relationship between the condition of the sternodiaphragmatic ligament and deformity severity.

The identification of a moderate to strong correlation between maximum von Mises stresses and the clinical severity of the deformity in the biomechanical analysis confirms the important role of internal mechanical stresses in the pathogenesis of the deformity. These internal stresses specifically lead to the breakdown of compensatory mechanisms in the anterior chest wall and to stabilization of the deformity.

The positive dynamics achieved in patients with grade III–IV deformities through sternodiaphragmatic ligament release followed by vacuum bell therapy indicate that this approach is pathogenetically well justified. The significant reduction in chest wall depression, the increase in anterior chest wall mobility, and the transition of the clinical condition to the compensation stage confirm the crucial role of ligament release in eliminating the pathological traction acting on the sternum.

Conclusion: In the treatment of pectus excavatum, an individualized approach based not only on the depth of the deformity but also on the morphofunctional state of the sternodiaphragmatic ligament is required. In preschool-aged children with grade III–IV pectus excavatum, contracture and fibrotic changes of the sternodiaphragmatic ligament predominate. The combined use of ultrasonography, MSCT, and biomechanical analysis enables a rational combination of surgical and conservative methods in severe deformities and significantly improves treatment effectiveness.

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