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Mathematical modeling of the chest, its funnel-shaped deformation and thoracoplasty

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The most common method of treating of the congenital funnel-shaped chest is thoracoplasty method by D. Nuss. During this surgery, a significant mechanical effect is created on the ribs, sternum, spinal column, which act instantly and continuously for a long time and create new biomechanical conditions for the «chest – rib – spine» system. Objective. To construct a functional model of the chest with a spinal column, which takes into account the movements in the costal-vertebral joints, it allows modeling the funnel-shaped deformation in conditions close to the reality, its operative correction, predicting the results and choosing the optimal parameters of thoracoplasty. Methods. Normal and funnel-shaped chest models based on the articular connection of the ribs to the spine were created using SolidWorks. The main calculations were made using the ANSYS program. To estimate the stress-strain state (SSS), stresses are selected by Mises. Results. The created dynamic mathematical model of the chest makes it possible to conduct a reliable analysis of the biomechanical interaction of the plate with the chest, to analyze the stress-strain state of the constructed models in the norm, with and without taking into account the movements in the costal-vertebral joints. In addition, it allows to simulate the operation by D. Nuss and to study the biomechanical changes in conditions close to reality, occurring in the «chest – rib – spine» system, to determine the areas of maximum loads and safety boundaries. Conclusions. The reproduction of articular ribs rotation in the dynamic model changes the picture of the SSS distribution. In the case of modeling the correction of funnel-shaped deformation of the chest by the method by D. Nuss, the largest zone of stress concentration was found on the outer posterior surface of the sixth pair of ribs. The most tense vertebrae were Th_V–Th_{VI}, but the maximum values did not exceed the permissible values. In the case of a lower plate conduction, the correction is achieved with better SSS values in the higher elements of the «chest – ribs – spine» system. Key words. Chest, funnel-shaped, thoracoplasty, mathematical modeling.

Найпоширенішим способом лікування вродженої лійкоподібної деформації грудної клітки (ГК) є торакопластика за методикою D. Nuss. Під час цієї операції створюється значний механічний вплив на ребра, грудину та хребтовий стовп, який діє постійно протягом тривалого часу, та виникають нові біомеханічні умови функціонування системи «грудина – ребра – хребет». Мета. Побудувати функціональну модель ГК із хребтовим стовпом, в якій враховані рухи в реброво-хребцевих суглобах, що дозволяє моделювати лійкоподібну деформацію за наближених до реальності умов, її хірургічну корекцію, прогнозувати результати й обирати оптимальні параметри торакопластики. Методи. Моделі ГК у нормі та з лійкоподібною деформацією з урахуванням суглобового з'єднання ребер із хребтовим стовпом створені за допомогою програми SolidWorks. Основні розрахунки зроблені з використанням програми ANSYS. Для оцінювання напружено-деформованого стану (НДС) обрані напруження за Мізесом. Результати. Створена динамічна математична модель дає можливість провести достовірний аналіз біомеханічної взаємодії пластини з ГК, аналізувати НДС побудованих моделей у нормі, з і без урахування рухів у реброво-хребцевих суглобах. Крім того, дає змогу відтворити операцію за D. Nuss і вивчити біомеханічні зміни в системі «грудина – ребра – хребет» за наближених до реальності умов, визначити ділянки максимальних навантажень і меж безпечності. Висновки. Відтворення в динамічній моделі можливості суглобової ротації ребер змінює картину розподілу НДС. У разі моделювання корекції лійкоподібної деформації ГК за методикою D. Nuss найбільшу зону концентрації напружень виявлено на зовнішній задній поверхні шостої пари ребер. Найбільш напруженими були хребці Th_V–Th_{VI}, але максимальні показники не перевищували допустимі значення. У разі більш низького проведення пластини необхідна корекція досягається з кращими показниками НДС у розташованих вище елементах системи «грудина – ребра – хребет».

Key words. Chest, funnel-shaped, thoracoplasty, mathematical modeling

Introduction

The most common method of treatment of congenital funnel-shaped deformity of the chest (CFDC) is surgery by the method of D. Nuss, which is considered a minimally invasive technology [1, 2]. During the operation, the funnel-shaped deformation is eliminated by installing a plate behind the sternum, which is fixed to the ribs in the desired position. The advantages of surgery include minimal injury and maximum cosmetic effect.

But it is known that simultaneous surgical correction of CFDC by the method of D. Nuss creates a significant mechanical effect on the ribs, sternum, spine, which acts constantly for a long time, developing new biomechanical operating conditions for the «sternum – ribs – spine» system [3].

The postoperative stress-strain state (SSS) of the chest and plate components is insufficiently covered in the literature, which would allow predicting the results of future surgery [4]. In addition, the interaction of the ribs with the vertebrae was not taken into account during the SSS study on the chest models.

Therefore, it is important to elaborate and create a dynamic functional model of the thorax with the spine, the closest to reality, which takes into account the possibilities of movable connection in the anterior part between the sternum and ribs and in the posterior support complex between the joint masses of the ribs and spine. This will make it possible to study the abnormal conditions occurring in funnel-shaped deformity of the chest, to study the SSS of the «sternum – ribs – spine» system during surgical correction in thoracoplasty modeling by D. Nuss.

The aim of the study: to elaborate a functional model of the chest with the spine, taking into account possibility of articular connection between the ribs and spine, allowing to model funnel-shaped deformity in near-reality conditions, its surgical correction, predict results and choose optimal parameters for future thoracoplasty.

Material and methods

The study aimed at elaboration of a calculation model was based on a model of the spine, developed in the laboratory of biomechanics Sytenko Institute of Spine and Joint Pathology National Academy of Medical Sciences of Ukraine. Based on the data on the properties of ribs given in the works of R. Schwend, Z. Li [5, 6], and the anatomical features of their functional motion [7, 8], a calculated geometric model in the norm (Fig. 1, a–d) and with funnel-shaped deformation was created (Fig. 1, e–i).

The material was considered homogeneous and isotropic. The properties of the materials are selected from the literature [9–12], the characteristics used (E — Young's modulus of elasticity, ν — Poisson's ratio) are given in the table.

To assess the impact of the possibility of a movable connection of the created model in the norm for the load, the action of a force of 40 N in the sagittal plane applied to the sternum handle (Fig. 2, a, b) was chosen.

In reproduction of the operation by D. Nuss, the action of forces is applied according to the scheme proposed by T. Nagasao et al. [13], i. e. a load of 160 N is applied to the sternum in the sagittal plane, and in the places of plate attachment to the costal pair R6 reference reactions of 80 N (Fig. 2, c, d). Such loading is associated with an alignment of the simulated defect of 5 cm.

For the normal model, the procedure was performed by fixing the lower body of the L_V vertebra and its joint masses, and for the model with deformation the lower body of the L_V vertebra and its joint masses and additionally the upper body of ThI vertebra. Muscle strength was not taken into account.

The model was built in SolidWorks software [14]. The main calculations were made using the ANSYS software. To assess the stress state, the stresses according to Mises [15] were chosen as the most informative.

Results and their discussion

To compare and evaluate the impact on SSS of movement in the articular surfaces of the junction of the ribs with the vertebrae, calculations were performed on two variants of the normal chest model: in the first model mobility is allowed in the articular junctions of the ribs with the vertebrae («No Separation» modification of contact) and in the second one it was not allowed («Bonded»).

The assessment of the results for the first variant of the calculation showed (Fig. 3, a–c) that the tensest areas were the outer, lateral surfaces of the ribs I–V, as well as the posterior part of the lumbar spine L_I–L_V.

Table

Mechanical characteristics of materials used for modeling

Material	Young's modulus (E), MPa	Poisson's ratio (ν)
Cortical bone	18 350.0	0.30
Spongy bone	330.0	0.30
Sternum	1500.0	0.30
Cartilage	24.5	0.40
Intervertebral disc	4.2	0.45

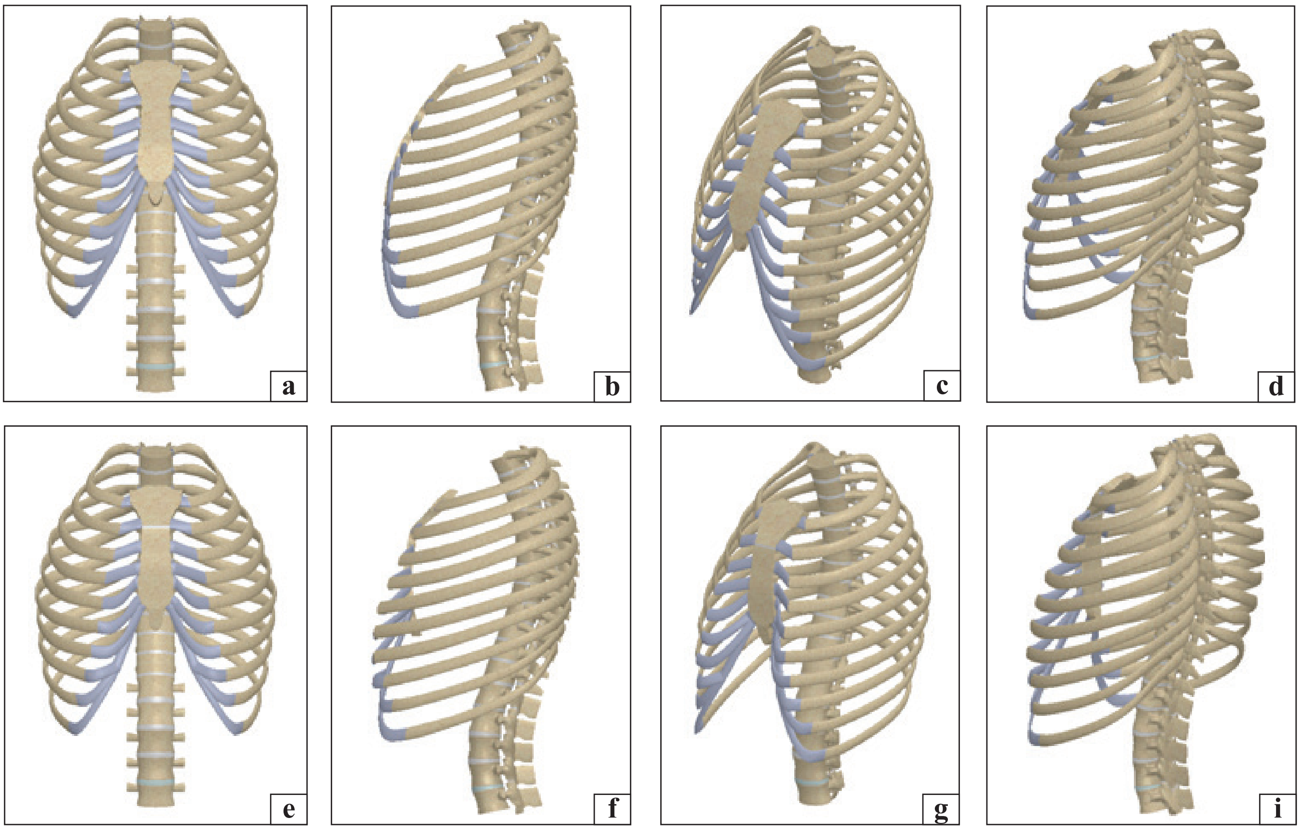

Fig. 1. Geometric model of the thorax in norm (a–d) and in funnel-shaped deformation (e – i)

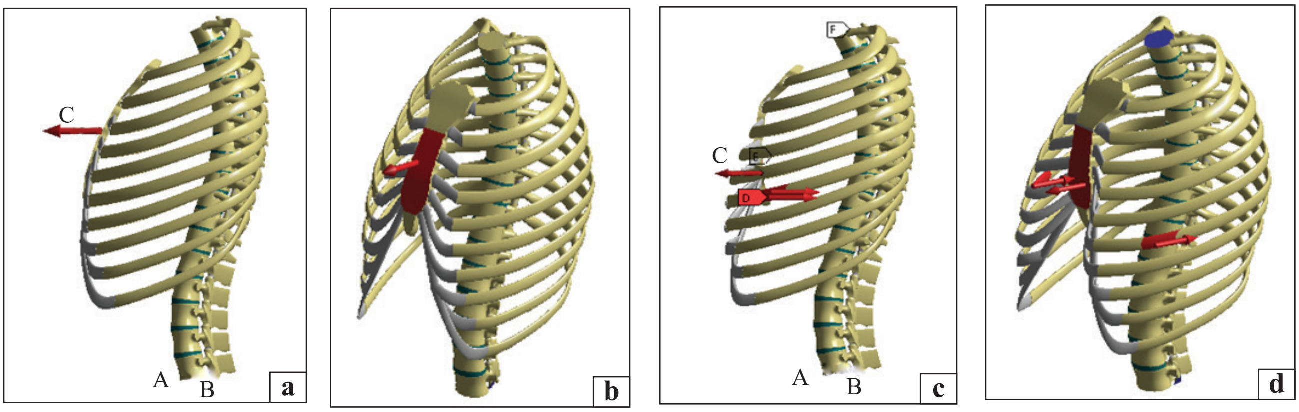

Fig.2. Loading and fixing of the model in norm (a, b) and in funnel-shaped deformation of the thorax (c, d). A, B — fixation, C — force

Fig. 3, b also shows a non-deformed model, which clearly demonstrates that the deformation occurs due to the rotation of the ribs in the joints and the displacement of the sternum in the forward and upward direction. The displacement of the spine was insignificant.

In the second variant of the calculation (Fig. 3, d–e) the ribs IV–VII and the posterior part of the lumbar spine L_I–L_V were tenser. Fig. 3, d, as for the first calculation option, shows the non-deformed model. The nature of the deformation was found to be changed: it was formed due to the displacement of the sternum forward. The downward shift occurred due to greater inclination of the spine. That is, in the presence of movements in the joints, the deformation is due to the displacement of the ribs, and in the absence of movement in the joints, the curvature is largely due to the inclination of the spine.

The calculation of the SSS of the chest of the model with a funnel-shaped deformation showed that the correction by D. Nuss provides complete elimination of the deformation. The maximum displacement of the edge of the sternum and the xiphoid process was 5.3 cm. The main displacement occurred due to the ribs lying above the plate support (Fig. 4).

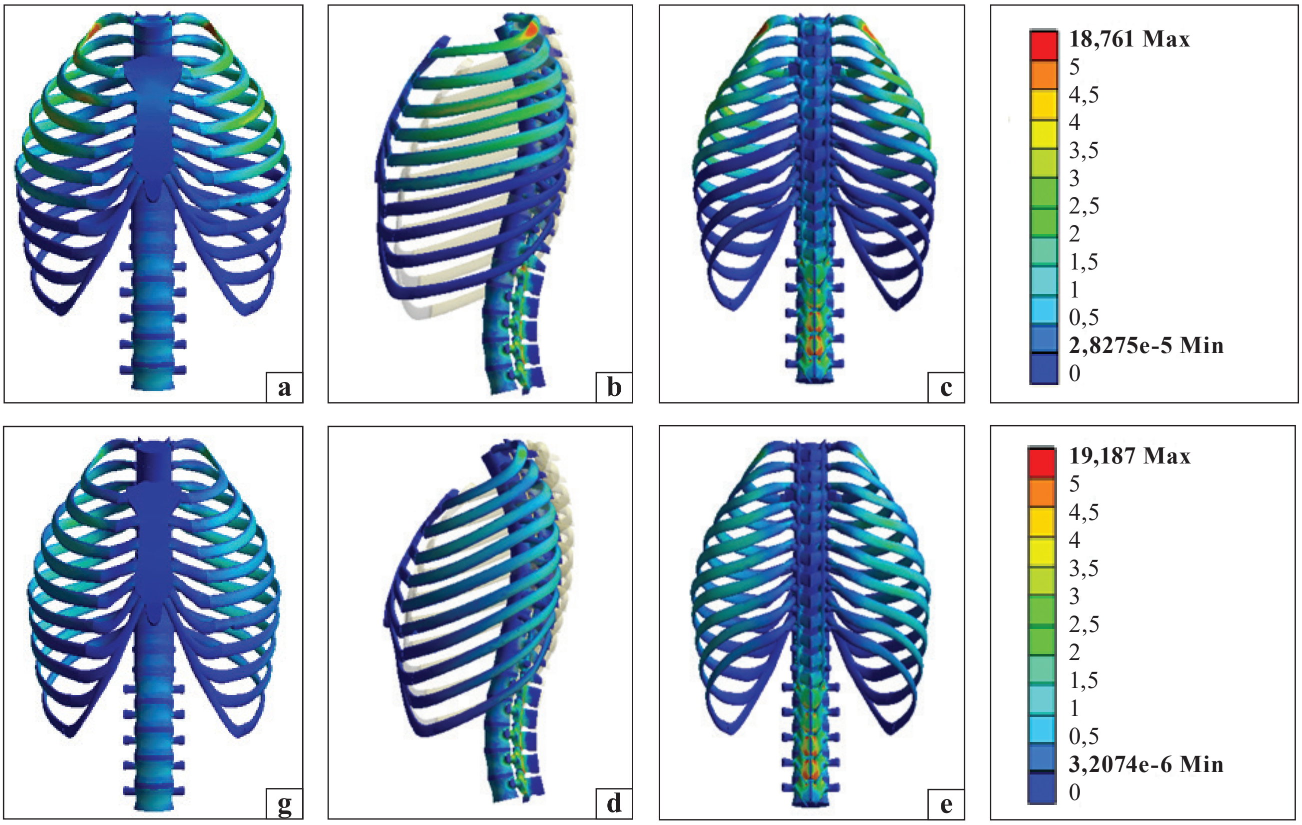

Fig. 3. Mises stress distribution in the calculation model: «No Separation» (a–c) and «Bonded» (g–e) contact variants

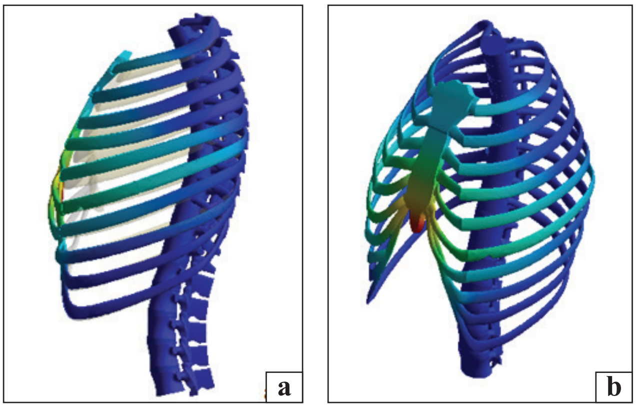

Fig. 4. Displacement of ribs and xiphoid process in the calculation model in funnel-shaped deformation correction according to D. Nuss: lateral (a) and anterior views (b)

The SSS assessment of this model showed (Fig. 5) that the greatest stresses were felt by pairs of ribs V–VII. The maximum value of the Mises stress of 25 MPa was found on the posterior outer surface of the pair of ribs VI (Fig. 5, c). In the spinal column, an increased stress state was recorded in the Th_V–Th_{VI} vertebrae. The stress concentration zone with a maximum value of 9.6 MPa is located at the roots of the Th_{VI} vertebral arches.

Assessment of the calculation revealed that the correction of the funnel-shaped deformation of the thorax

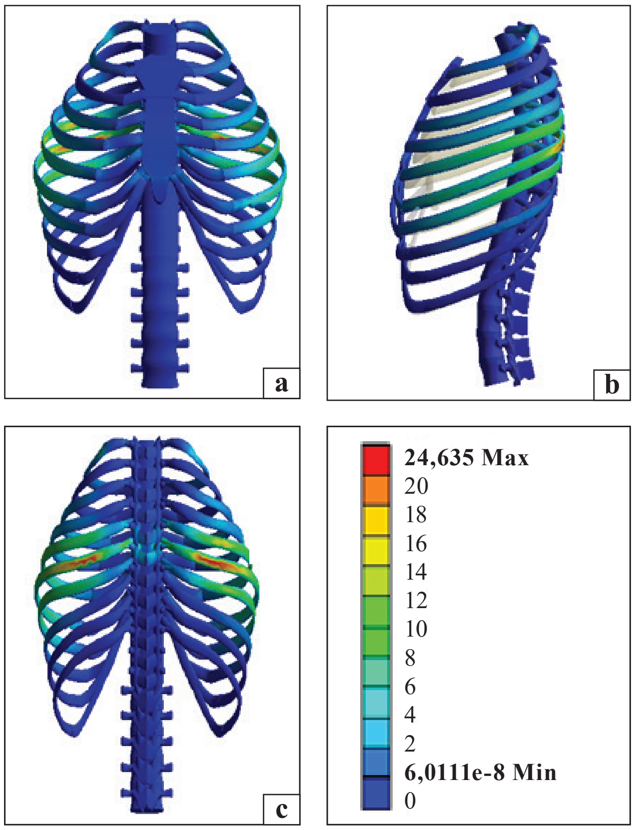

Fig.5. Distribution of stresses according to Mises in the calculation model in correction of funnel-shaped deformation according to D. Nuss: anterior (a), laateraal (b), posterior (c) views

by D. Nuss resulted in an uneven distribution of SSS in the thorax and spine. The largest displacements are observed for pairs of ribs I–V, but the stress state in pairs of ribs I–IV is insignificant, and their displacement occurs due to the possibility of rotation in the costo-vertebral joints. The most tense were the pairs of ribs V–VII with the largest zone of stress concentration on the outer posterior surface of the pair of ribs VI. Among the ribs V–VII, the seventh pair is the least tense.

Th_V–Th_{VI} vertebrae with the largest zone of stress concentration in the roots of Th_{VI} vertebral arches were the most tense in the spinal column.

Thus, the created dynamic mathematical model of the chest makes it possible to conduct a reliable assessment of the biomechanical interaction of the plate with the chest, to analyze the SSS of the built models in the norm, with and without taking into account the articular connections between ribs and vertebrae. In addition, it allows to simulate the operation by D. Nuss and to study the biomechanical changes that occur in the «sternum – ribs – spine» system, to determine the areas of maximum loads and safety margins.

Conclusions

In the process of mathematical modeling of CFDC and its simultaneous correction, it is important to take into account the possibility of mobility in the costo-vertebral joints. The lack of mobility makes the model stiffer and does not provide for a significant change in the volume of the chest, which is observed in reality.

In the case of modeling the correction of funnel-shaped deformation of the chest by D. Nuss, the largest zone of stress concentration was found on the outer posterior surface of the sixth pair of ribs. Th_V–Th_{VI} vertebrae were the most tense in the spinal column, but the maximum stresses did not exceed the permissible values, which are destructive for biological tissues. Under the conditions of the lower conduction of the plate, the necessary correction is achieved with mostly better SSS rates in the higher elements of the «sternum – ribs – spine» system.

Results: the conducted studies provide for the elaboration of rational modifications of CFDC thoracoplasty by D. Nuss, under the conditions of simultaneous complete stable correction and minimal biomechanical loads in the «sternum – ribs – spine» system.

Conflict of interest. The authors declare no conflict of interest.

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