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Study of the distribution of stresses in the elements of the sterno-costal complex and metal plates in the case of minimally invasive correction of the funnel-shaped deformation of the chest according to Nuss

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In severe forms, funnel-shaped chest deformity (FSCD) requires surgical correction. The method of choice is the Nuss operation and its modifications. Objective. To study the changes that occur in the stressed-deformed state of the chest model and the fixator under different methods of its implementation during the minimally invasive correction of FSCD according to Nuss. Material and methods. 4 schemes of FSCD correction were modeled: 1 — alignment with one retrosternal plate with transverse stabilizers, the point of entry and exit of the fixator is located parasternal at the level of the bone-cartilage transition, the fixator on the sides of the chest ends at the level of the front axillary line; 2 — sternal plate with transverse stabilizers, the point of entry and exit is located at the level of the front armpit line, the fixator ends at the level of the middle armpit line; 3 — the use of a double plate with transverse bars that connect the plates with the help of screws with medial conduction; 4 — a double plate with transverse slats, which connect the plates with the help of screws with lateral guidance. The models were loaded with a distributed force of 100 N applied to the sternum. The results. When using FSCD correction schemes, the maximum level of stress occurs in the metal plates, because they bear the main loads from the sternum, which tries to return to its original position after correction. The same reason causes the highest level of stress among the elements of the skeleton in the sternum. Conclusions. Under the conditions of using any FSCD correction scheme, the maximum stress level occurs in the metal plates, sternum, fifth and sixth ribs, which are in direct contact with the plates. The use of long plates with lateral points leads to a slight decrease in stress values in all elements of the model. The «Bridge» fastener allows you to significantly reduce the level of stress, both in the plates themselves and in the elements of the skeleton due to an increase in their contact area.

Лійкоподібна деформація грудної клітки (ЛДГК) за виражених форм потребує хірургічної корекції. Методом вибору є операція за Nuss та її модифікації. Мета. Вивчити зміни, які відбуваються в напружено-деформованому стані моделі грудної клітки та фіксатора за різних методик його проведення під час малоінвазивної корекції ЛДГК за Nuss. Матеріал і методи. Моделювали 4 схеми корекції ЛДГК: 1 — вирівнювання однією загрудинною пластиною з поперечними стабілізаторами, точка входу та виходу фіксатора розташована парастернально на рівні кістково-хрящового переходу, фіксатор по бокам грудної клітки закінчується на рівні передньої пахвової лінії; 2 — загрудинна пластина з поперечними стабілізаторами, точка входу та виходу розташована на рівні передньої пахвової лінії, фіксатор закінчується на рівні середньої пахвової лінії; 3 — використання подвійної пластини з поперечними планками, які з'єднують пластини за допомогою гвинтів із медіальним проведенням; 4 — подвійна пластина з поперечними планками, які з'єднують пластини за допомогою гвинтів із латеральним проведенням. Моделі навантажували розподіленою силою 100 Н, прикладеною до грудини. Результати. Під час використання схем корекції ЛДГК максимальний рівень напружень виникає в металевих пластинах, бо саме вони тримають на собі основні навантаження від грудини, яка намагається повернутись у початкове положення після корекції. Та ж сама причина викликає найвищий рівень напружень серед елементів скелета саме в грудині. Висновки. За умов використання будь-якої схеми корекції ЛДГК максимальний рівень напружень виникає в металевих пластинах, грудині, п'ятих і шостих ребрах, які безпосередньо контактують із пластинами. Застосування довгих пластин із латеральними точками проведення веде до невеликого зниження величин напружень у всіх елементах моделі. Фіксатор за зразком «Міст» дозволяє значно знизити рівень напружень, як у самих пластинах, так і в елементах скелета за рахунок збільшення площі їхнього контакту. Ключові слова. Грудина, деформація, корекція, моделювання.

Keywords. Breast, deformation, correction, modeling

Introduction

Funnel-shaped chest deformity (FSCD) requires surgical correction in severe forms [1]. The method of choice is the Nuss operation and its modifications. It requires installation of retrosternal plates that align the deformed sunken part of the chest [2]. This technique is the opposite of resection methods proposed by Ravich in 1949, widely used until the 2000-s. After Donald Nuss published in 1998 the results of 10-year treatment of patients with FSCD using non-resection modeling of the anterior chest wall [3], this method quickly gained popularity due to better cosmetic results. However, it remains unclear what stresses occur in the sternocostal complex during minimally invasive correction, as well as whether the choice of fixator length, plate tunneling point, and number of fixators affects the change in the stress-strain state of the thorax and fixator, as well as the effect of using more fasteners [4].

Purpose: to study the changes occurring in the stressed-deformed state of the chest model and the fixator under different methods of its implementation during the minimally invasive correction of funnel-shaped chest deformity according to Nuss.

Material and methods

The model of the spine, developed in the laboratory of biomechanics of the State Institution Professor M. I. Sytenko Institute of Spine and Joint Pathology of the National Academy of Sciences of Ukraine, was taken as the basis for the construction of the calculation model [5–7]. On the basis of information about the properties of the ribs provided by R. Schwend, Z. Li [8, 9], and the anatomical features of their functional movement [10, 11], a calculated finite element model was created in the norm (Fig. 1) and with funnel-shaped deformity (Fig. 2). Calculations were performed using the finite element method.

We modeled 4 schemes for the correction of the funnel-shaped deformity of the chest:

1. Straightening with the help of one retrosternal plate with transverse stabilizers, the point of entry and exit of the fixator from the retrosternal space is located parasternally at the level of the bone-cartilage transition (hereinafter referred to as the medial delivery point), fixator on the sides of the chest ends at the level of the front axillary line (hereinafter referred to as the short plate), shown in Fig. 3.

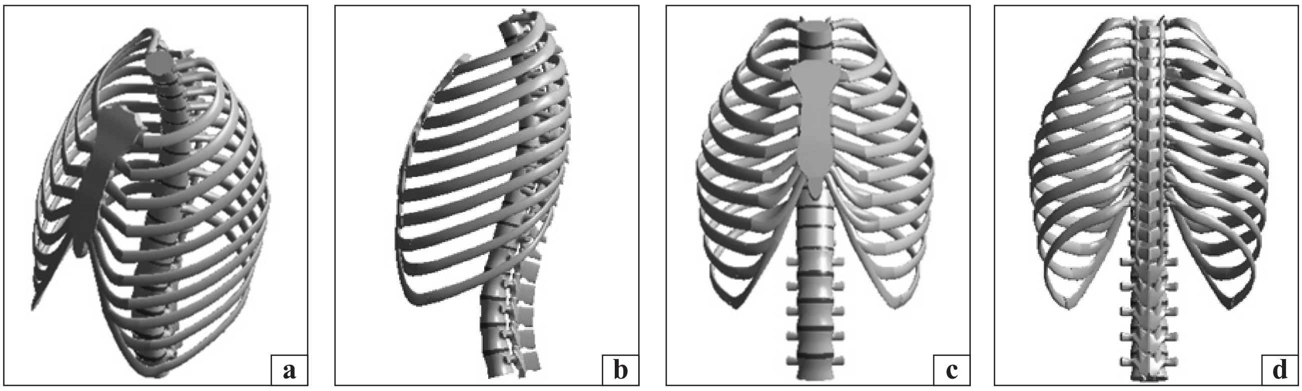

Fig. 1. Basic geometric model of the spine with a normal chest, view: a — general; b — in sagittal plane; c — in front; d — behind

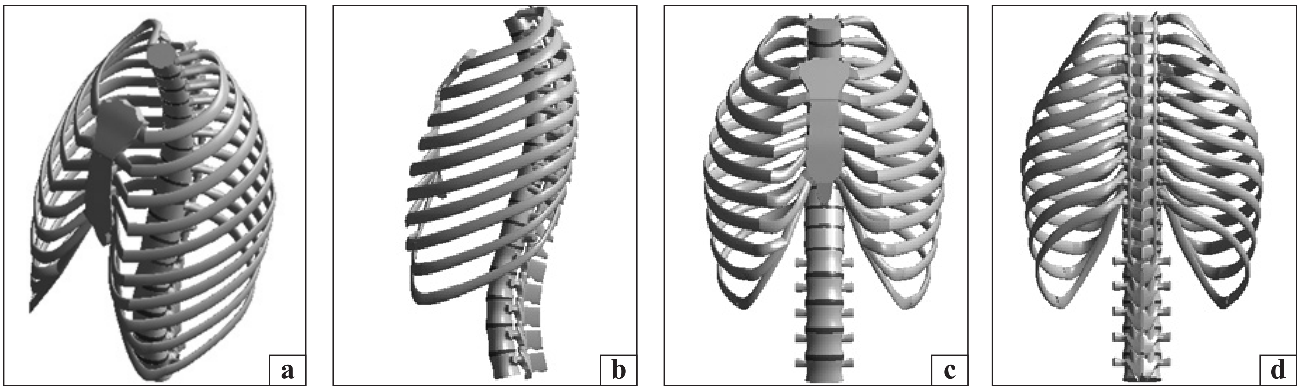

Fig. 2. Geometric model of the spine and chest with a funnel-shaped deformity, view: a — general; b — in sagittal plane; c — in front; d — behind

2. Correction using one sternal plate with transverse stabilizers, the point of entry and exit from the sternal space is located at the level of the front axillary line (hereinafter referred to as the lateral delivery point), fixator on the sides of the chest ends at the level of the middle axillary line (hereinafter referred to as the long plate) , fixator installation scheme is shown in Fig. 4.

3. A double plate with transverse slats is used, the plates are connected with the help of screws (a bridge-type fixator) with a medial delivery (hereinafter referred to as the short bridge-type fixator), plate installation schemes are shown in Fig. 5.

4. A double plate with transverse slats, the plates are connected with the help of screws (a bridge-type fixator) with a lateral delivery (hereinafter referred

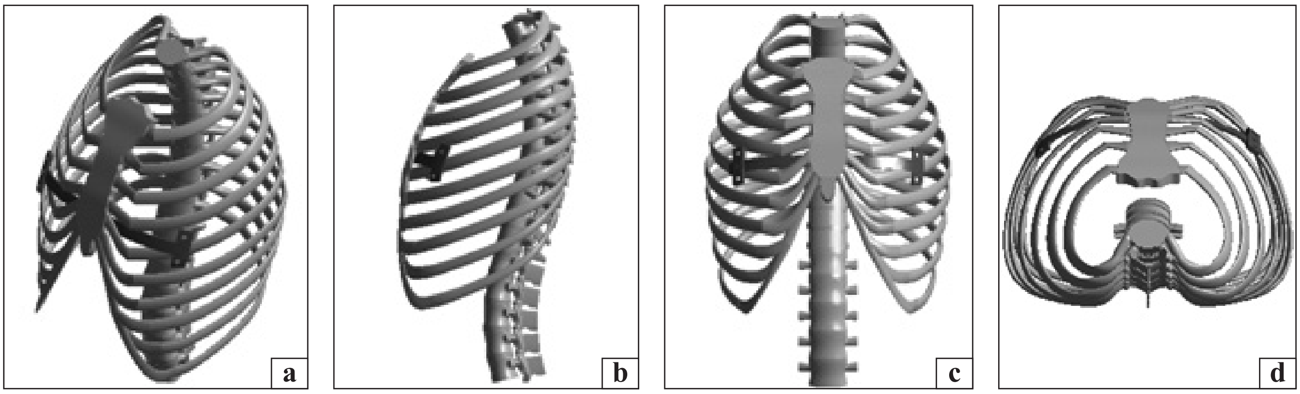

Fig. 3. Scheme of correction of the funnel-shaped chest using one short plate with transverse stabilizers and medial transfer points, view: a — general; b — in sagittal plane; c — in front; d — from above

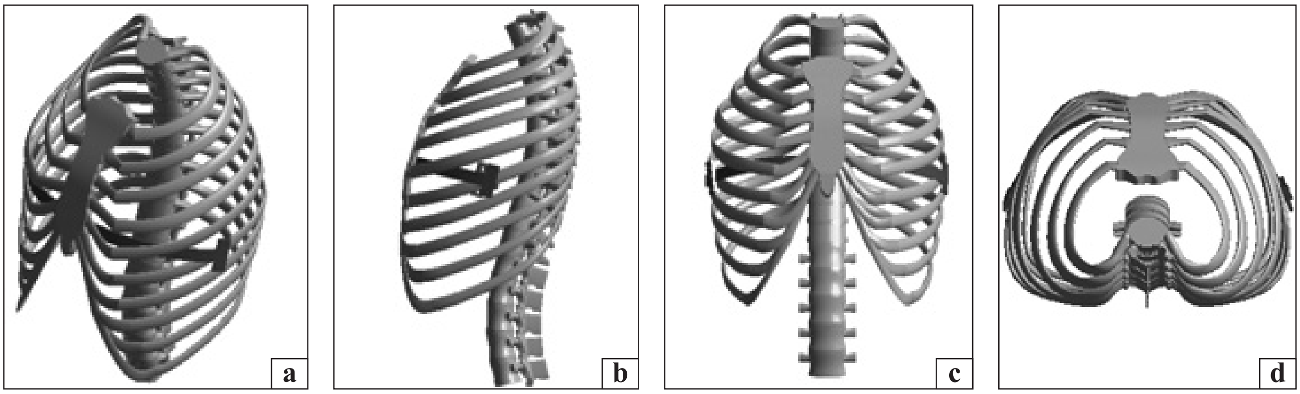

Fig. 4. Scheme of correction of the funnel-shaped deformity of the sternum with the application of one long plate with transverse stabilizers, view: a — general; b — in sagittal plane; c — in front; d — from above

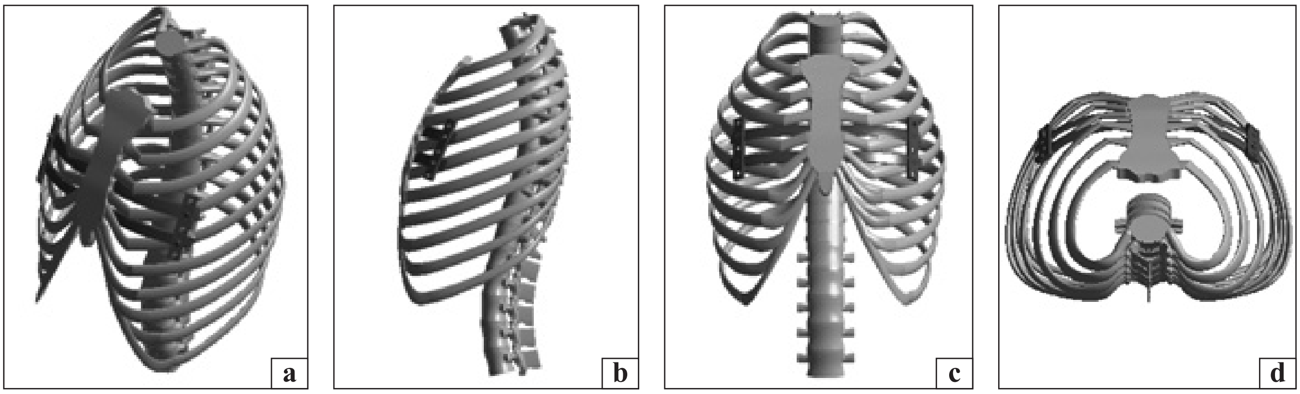

Fig. 5. Scheme of correction of the funnel-shaped deformation of the chest using a short bridge-type fixator, view: a — general; b — in sagittal plane; c — in front; d — from above

to as the long bridge-type fixator), plate installation schemes are shown in Fig. 6.

During modeling, the material was assumed to be homogeneous and isotropic. A 10-node tetrahedron with a quadratic approximation was chosen as a finite element. The mechanical properties of the materials were selected from literature sources [12–15]. The used characteristics (E — Young's modulus of elasticity, ν — Poisson's ratio) are given in Table 1.

The models were loaded with a distributed force of 100 N applied to the sternum. The model had a rigid attachment on the upper surface of the body of the S_I vertebra and on the lower surface of the body of the L_V vertebra. Such a fastening scheme was chosen so that the model does not tip over in the case of a one-sided load on the sternum. The loading scheme of the models is shown in Fig. 7.

Table 1

Mechanical characteristics of the materials used

Tissue	Young's modulus of elasticity E, MPa	Poisson's ratio, ν
Cortical substance	18 350.0	0.30
Spongy substance	330.0	0.30
Sternum	11 500.0	0.30
Cartilage	24.5	0.40
Intervertebral disc	4.2	0.45

Comparison of the values of stresses in the elements of the models implied selection of control points, the layout of which is shown in Fig. 8.

The model was built in the SolidWorks software [16]. Calculations of the stress-strain state of the models were performed using the ANSYS environment. To evaluate the stress-strain state, the stress according to Mises [17] was chosen as the most informative.

Results and their discussion

The first stage of the study involved modeling of the scheme of correction of the funnel-shaped chest deformity using one short plate. The stress-strain state of the model is shown in Fig. 9.

With the help of the conducted modeling, it was determined that in the case of using a short plate to correct the funnel-shaped deformity of the sternum, the greatest stress of 22.0 Mpa occurs precisely in the sternum. Among the ribs, the most loaded are the fifth, where the indicators reach 11.4 MPa, because the ends of the plate rest on these ribs. Also, a high stress level of 8.2 MPa is observed on the first ribs, but this

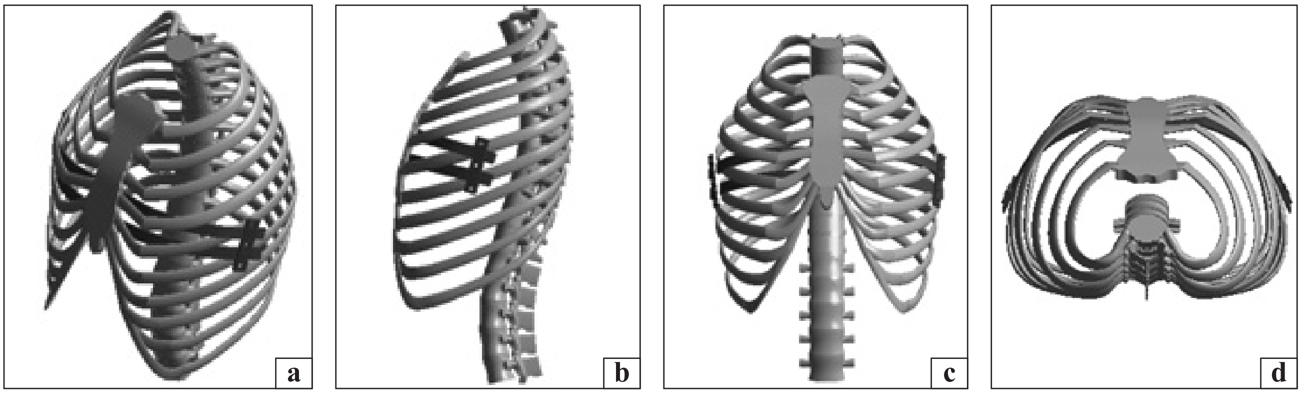

Fig. 6. Scheme of correction of the funnel-shaped deformity of the chest using a long bridge-type fixator, view: a — general; b — in sagittal plane; c — in front; d — from above

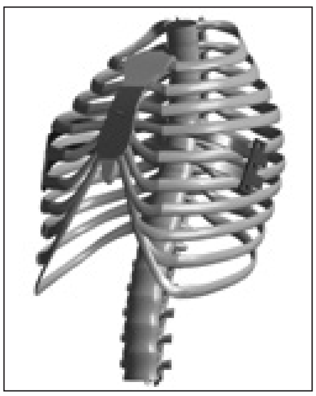

Fig. 7. Model loading scheme

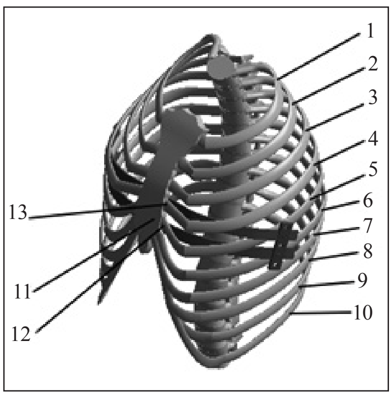

Fig. 8. Layout of control points: 1–10 — ribs; 11 — sternum; 12 — lower plate; 13 — upper plate

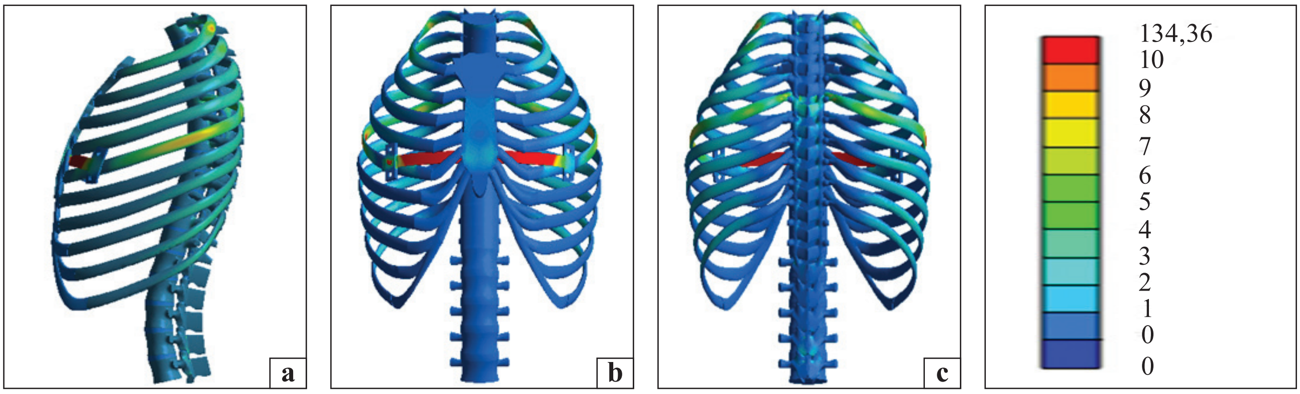

Fig. 9. Stress distribution in the chest model with correction of the funnel-shaped deformity of the sternum with a short plate, view: a — in sagittal plane; b — from the front; c — behind

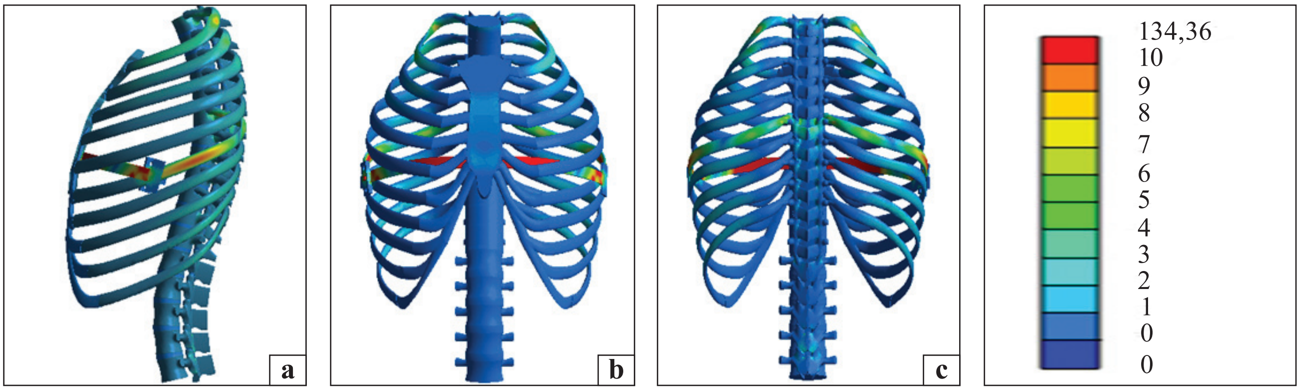

Fig. 10. Stress distribution in the model of the chest with correction of FSCD with a long plate, view: a — in sagittal plane; b — from the front; c — behind

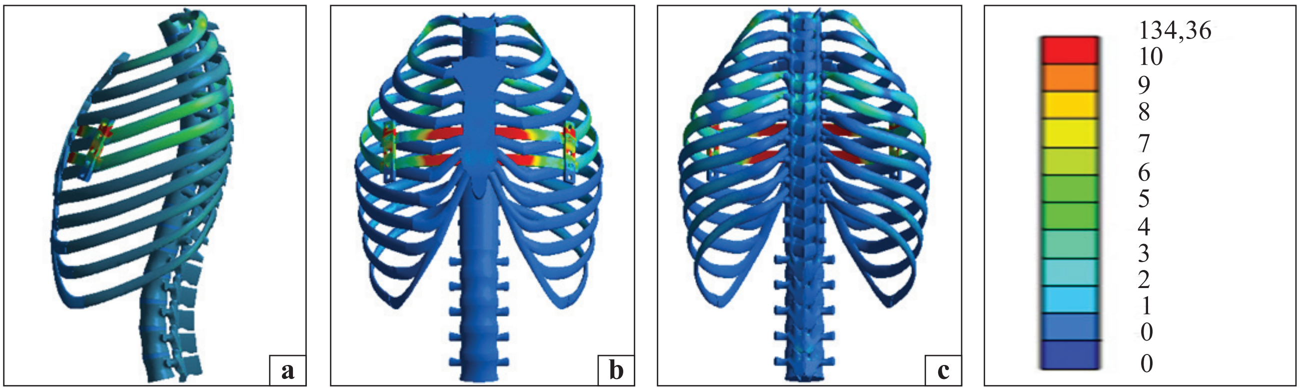

Fig. 11. Distribution of stresses in the model of the chest with correction of the funnel-shaped chest deformity with a short bridge-type fixator, view: a — in sagittal plane; b — from the front; c — behind

indicator should not be paid attention to, because it is caused by the rigid attachment of the S_I vertebra, i. e., the modeling conditions, and not by the sternum correction scheme. Further, the stress level decreases, reaching a minimum of 2.5 MPa on the third rib, and slightly increases to 3.4 MPa on the fourth. On the edges below the plate, the stresses are almost the same and are determined in the range of 2.2–2.8 MPa. The indicators on the plate reach the mark of 50.1 MPa.

Let us consider what changes in the stress-strain state of the model occur when one long plate is used. The pattern of stress distribution in the model is shown in Fig. 10.

The use of a long plate leads to a reduction in the magnitude of stresses in the sternum by half to the mark of 11.2 MPa, and also shifts the maximum level of stresses to the sixth rib, where they are determined at the level of 10.7 MPa, which is also lower than during correction with a short plate. This is due to the fact that the fulcrum of the ends of the plate is moved exactly to six ribs. On all other ribs, there is also a decrease in the stress level. On the plate itself, the stresses also decrease and are fixed at the mark of 42.7 MPa.

The next stage of the study involved assessment of the stress-deformed state of the models with a scheme for correcting the funnel-shaped deformity of the chest with the help of a short bridge-type fixator. The stress distribution in the model with two short plates is shown in Fig. 11.

Under the conditions of applying the FSCD correction scheme with a short bridge-type fixator, there is a decrease in the stress level on all elements of the model compared to the model with one short plate. The most significant decrease is recorded on the sternum, where the maximum stress level stops at the mark of 3.8 MPa. The stress on the fifth and sixth ribs, on which the ends of the plates rest, is 7.3 and 7.0 MPa, respectively. Also, a significant decrease in stresses is observed on the upper and lower plates, where they do not exceed the marks of 25.0 and 27.0 MPa, respectively.

Fig. 12 shows the stress-strain state of the model with FSCD correction using a long bridge-type fixator.

The conducted studies provided evidence that increasing the length of the plates and changing the points of the fixator laterally allows to reduce the stress level on all the elements of the model, but these changes are not as noticeable as with the lengthening of a single plate.

Indicators of the amount of stress in the elements of the models, depending on the scheme of correction of the funnel-shaped deformity of the sternum, are given in Table 2.

A visual representation of the ratio of the values of the maximum stresses in the bone elements of the models depending on the scheme of correction of the funnel-shaped deformity of the sternum can be obtained using the diagram shown in Fig. 13.

The use of long plates has advantages over short ones in terms of reducing stress in the ribs and sternum. The most significant changes in the stress level

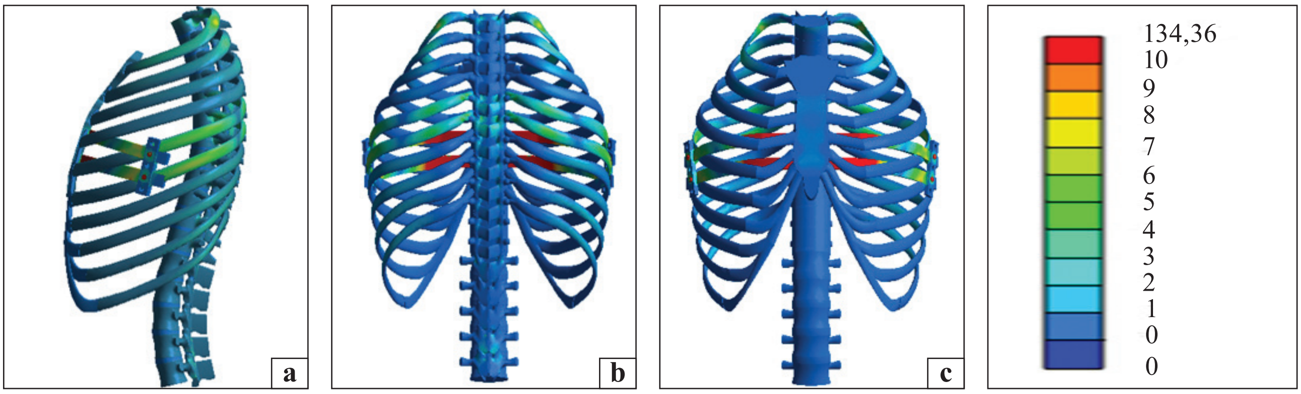

Fig. 12. Stress distribution in the model of the chest with correction of the funnel-shaped chest deformity with a long bridge-type fixator, view: a — in sagittal plane; b — from the front; c — behind

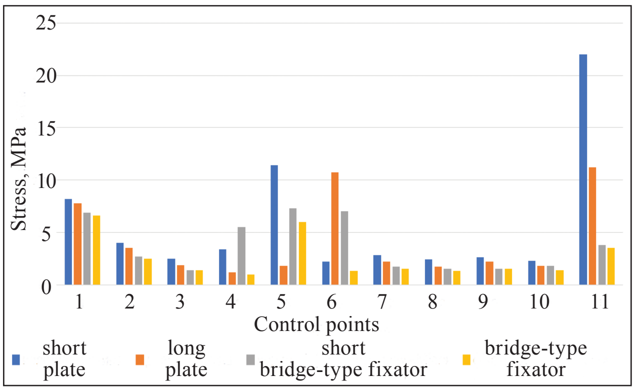

Fig. 13. Diagram of stress values in the bone elements of the models according to different schemes for the correction of the funnel-shaped chest deformity

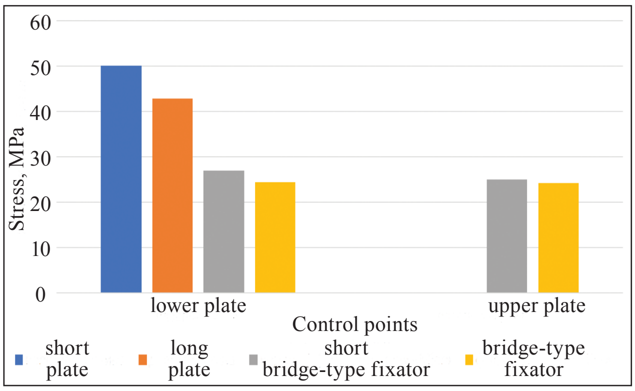

Fig. 14. Diagram of stress values in the metal elements of the models according to different schemes for the correction of the funnel-shaped deformity of the sternum

Table 2

Stress values in the elements of the models for different corrections of the funnel-shaped deformity of the sternum

Control point		Stress, MPa			
№	model element	short plate	long plate	short fixator	long fixator
1	rib 1	8.2	7.8	6.9	6.6
2	rib 2	4.0	3.5	2.7	2.5
3	rib 3	2.5	1.9	1.4	1.4
4	rib 4	3.4	1.2	5.5	1.0
5	rib 5	11.4	1.8	7.3	6.0
6	rib 6	2.2	10.7	7.0	1.3
7	rib 7	2.8	2.2	1.7	1.5
8	rib 8	2.4	1.7	1.5	1.3
9	rib 9	2.6	2.2	1.5	1.5
10	rib 10	2.3	1.8	1.8	1.4
11	sternum	22.0	11.2	3.8	3.5
12	lower plate	50.1	42.7	27.0	24.4
13	upper plate	—	—	25.0	24.2

occur precisely in the elements that are in contact with the metal plates, in the sternum and ribs 5 and 6.

The diagram shown in Fig. 14, gives an idea of the ratio of stress levels in metal plates depending on the scheme of correction of the funnel-shaped deformity of the chest.

As the diagram shows, an increase in the length and number of plates also results in a decrease in their stress level.

Analyzing the performed study, we can come to the conclusion that employment of any of the schemes for the correction of the funnel-shaped deformity of the sternum, the maximum level of stress occurs in the metal plates due to the fact that they bear the main loads from the sternum, which strives to return to its original position after correction . For the same reason, it causes the highest level of stress among the elements of the skeleton in the sternum. The fifth and sixth ribs are loaded due to the fact that the plates rest on them with their ends, which, in turn, leads to an increase in the stress level. The use of long plates contributes to a slight decrease in stress values in all elements of the model, most likely due to a more uniform distribution of the load along the length of these elements. The use of two parallel plates (bridge-type fixator) doubles the area of their contact with the bone structures, as a result of which there is a significant reduction in stress, both in the plates themselves and in the elements of the skeleton.

Conclusions

During the use of any scheme for the correction of the funnel-shaped deformity of the sternum, the maximum stress level occurs in the metal plates, the sternum, the fifth and sixth ribs, which are in direct contact with the plates.

The use of long plates with lateral points of delivery contributes to a slight reduction of stress values in all elements of the model due to a more uniform distribution of the load along the length of these elements. At the same time, with the help of two parallel plates (bridge-type), it is possible to significantly reduce the stress level, both in the plates themselves and in the elements of the skeleton due to the increase of their contact area.

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

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STUDY OF THE DISTRIBUTION OF STRESSES IN THE ELEMENTS OF THE STERNO-COSTAL COMPLEX AND METAL PLATES IN THE CASE OF MINIMALLY INVASIVE CORRECTION OF THE FUNNEL-SHAPED DEFORMATION OF THE CHEST ACCORDING TO NUSS

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