УДК 616.727.2-008.63-089.843:616-089.2Latarjet]:004.942](045)

DOI: http://dx.doi.org/10.15674/0030-59872021318-26

Mathematical modeling of graft fixation variants to the anterior margin of the glenoid performing Latarjet procedure

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Latarjet procedure is a common standard in the treatment of anterior and anterior-inferior shoulder instability with a significant glenoid defect. However, like any other surgical technique, it has a list of certain intra- and postoperative complications, including mistakes in the positioning of the bone block. A necessary guarantee of prevention and reduction of the frequency of possible complications associated with graft positioning is a well-performed preoperative planning with an understanding of the biomechanical functioning of the shoulder joint with the translated bone block. Objective. According to the mathematical modelling we studied the changes that occur in the stress-strain state of the shoulder joint model depending on the options for graft fixation and may occur during the Latarjet procedure. Methods. To solve this problem, a finite element model of the shoulder was created. The simulations were performed using the SolidWorks computer-aided design system. The following situations were simulated: variants of fixing screws relative to the plane of the articular surface of the glenoid (parallel to the plane, at an angle of 10° and 20°) and variants of graft fixation height at the anterior edge of the glenoid (at the lower edge of the glenoid, 10 mm and 20 mm upper edge). Calculations of the stress-strain state of the models were performed with the CosmosM software package. Results and conclusions. The presence of a bone graft fixed with metal screws at the area of the defect at the anterior edge of the glenoid, leads to an increase in stress levels in the bone elements of the model. Changes in the stress-strain state of the shoulder model also occur, depending on the angle of the screws that secure the graft. The highest stress level was determined when providing the fixing screws at an angle of 10°, the lowest — when providing the screws parallel to the articular surface of the glenoid. The stresses on the locking screws increased slightly with increasing angle of the screws. When studying the height of graft fixation, the most favorable option, in terms of stress distribution on the articular surface of the glenoid and fixing screws, is its location in the lower part of the anterior edge of the glenoid. Key words. Shoulder joint instability, Latarjet procedure, finite element model of shoulder joint, biomechanical modeling.

Операція за Латарже є загальноприйнятою для лікування передньої та передньонижньої нестабільності плечового суглоба зі значним дефектом гленоїда. Проте вона має певні інтра- та післяопераційні ускладнення, пов'язані в тому числі з помилками розміщення кісткового блока. Ретельне передопераційне планування з розумінням біомеханічного функціонування плечового суглоба з перенесеним кістковим блоком є запорукою запобігання та зменшення частоти можливих ускладнень. Мета. На математичній моделі вивчити зміни напружено-деформованого стану (НДС) моделі плечового суглоба залежно від варіантів фіксації трансплантата та під час виконання операції Латарже. Методи. Розроблено скінченно-елементну модель плеча за допомогою системи автоматизованого проєктування SolidWorks. Відтворено варіанти проведення фіксувальних гвинтів відносно площини суглобової поверхні гленоїда (паралельно площині, під кутом 10° та 20°) та висоти фіксації трансплантата на передньому краю гленоїда (на рівні нижнього краю гленоїда, на 10 і 20 мм вище нього). Вивчено НДС моделей за допомогою програмного комплексу CosmosM. Результати. Найбільший рівень напружень визначено за проведення гвинтів під кутом 10°, найнижчий — паралельно суглобовій поверхні гленоїда. Максимальне зниження висоти фіксації трансплантата привело до наближення величин напружень у контрольних точках на суглобовій поверхні гленоїда до показників моделі в нормі. Висновки. Наявність кісткового трансплантата, фіксованого металевими гвинтами в зоні дефекту на передньому краю гленоїда, призводить до підвищення рівня напружень у кісткових елементах моделі. Зміни в НДС моделі плеча відбуваються залежно від кута проведення гвинтів, які фіксують трансплантат. Напруження на фіксувальних гвинтах незначно підвищувалися зі збільшенням кута їхнього проведення. Найбільш сприятливим з огляду на розподіл напружень на суглобовій поверхні гленоїда та фіксувальних гвинтах виявилося розташування трансплантата в нижній частині переднього краю гленоїда.

Key words. Shoulder joint instability, Latarjet procedure, finite element model of shoulder joint, biomechanical modeling

Introduction

Latarjet surgery is a common standard for the treatment of anterior and anterior-inferior shoulder instability with a severe glenoid defect. The probable mechanism of stabilization in the shoulder joint in such surgical treatment contains three components [1]: dynamic sling effect transmitted through the split of the subscapular muscle and capsule of the tendon of the short head of the biceps and coraco-brachial muscles, bone effect of glenoid surface increase and «Bankart effect» — the restoration of the capsular-labial complex to the bone or the stump of the coraco-clavicular ligament to the capsule of the joint.

Despite the fact that the «hammock» effect probably plays a crucial role in the stabilization mechanism among others [2], the variability of Latarjet surgery is largely determined by the position and centering of the coracoid process [3, 4] including intra- and extra-articular placement, fixation methods bone block [5–8] with or without restoration of capsular-labial structures, as well as arthroscopic techniques of Latarjet surgery [9–11]. In turn, this is due to the fact that the position of the bone graft and the method of its fixation affect the risk of recurrence, long-term results of the operation and possible complications [12]. Among all the described complications of Latarjet surgery (which can reach up to 15 % in open technique of operation [13]) we can identify recurrence of instability in 1–3 % [8, 14], neurological complications in 1–20 % [8, 15], hematoma in 1–2 % [8], postoperative wound infection in 1.5 % [8], development of shoulder joint contracture and loss of external rotation, nonunion of bone block-in 1.5–9 % [14–16] or its fracture in 1.5 % [17], bone block resorption, osteoarthritis in 20–25 % [18], development of adhesive capsulitis, as well as complications associated with fixators. Among them, recurrence of instability in case of excessively medial or excessively low position, with displacement in the axial plane relative to the surface of the glenoid and below the equator of the articular cavity in the sagittal plane can be reliably associated with errors in bone block placement [8]. This group of complications should also include nonunion of the bone block due to its low position and lack of rotational stability in case of insufficient fixation by the lower screw. Other typical complications associated with an inappropriate position of the bone block are the development of osteoarthritis due to its lateral protrusion, as well as intraoperative technical difficulties associated with the positioning and conduction of screws through the bone block to the glenoid. All these complications necessitate repeated surgical interventions and changes in treatment tactics. It should also be noted that the use of arthroscopic techniques has a significantly high percentage of positive results compared to open methods, with the same relatively low incidence of complications, but requires significant surgical skills of the surgeon and increased costs in technical support and execution time, which limits its spread. Thus, in arthroscopic techniques, the issues of preventing possible complications associated with the risks of recurrent surgery are also relevant and require attention.

A possible solution for the prevention of complications associated with errors in the placement of the bone block is careful preoperative planning, taking into account peculiarities of the biomechanical functioning of the shoulder joint with the existing graft. Given that most studies on the biomechanics of the shoulder joint with an anterior or anterior-inferior glenoid defect are based on a study of the bodies of the dead in the complex [2], it is useful to investigate the isolated effect in restoration of the bony surface of the glenoid on a mathematical model, which would justify the optimal position of the bone block.

Objective: to study on a mathematical model the changes of the stress-strain state of the shoulder joint model depending on the options of graft fixation and which may occur in Latarjet surgery.

Material and methods

The study involved mathematical modeling of the stress-strain state (SSS) of the shoulder joint with different options of graft fixation on the anterior surface of the glenoid, which may develop in Latarjet surgery at the Laboratory of Biomechanics of the State Institution «Professor M. I. Sytenko Institute of Abnormalities of the Spine and Joints of the National Academy of Medical Sciences of Ukraine». This task implied elaboration of a finite-element model of the shoulder, which contained the following elements: scapula, humerus and cartilaginous layer on the articular surfaces (Fig. 1).

The following situations were reproduced: options for conduction of fixing screws relative to the plane of the articular surface of the glenoid and the height of fixation of the graft at the anterior edge of the glenoid. Fig. 2 shows diagrams of the fixing screws used in Latarjet surgery.

These options of fixing screws were implemented on a mathematical model (Fig. 3).

Fig. 4 shows three situations that may occur in transplantation of the coracoid process to the defect area. The first one, when the lower edge of the displaced coracoid process, to which *m. coracobrachialis et caput breve m. biceps brachii* are attached, located in the lower edge of the articular surface, the second and third ones represent the bone block shifted up by 10 and 20 mm, respectively.

Fig. 5 shows models with different options for graft fixation relative to the anterior edge of the articular surface of the glenoid.

The elements of the model were given the properties of different materials by choosing the appropriate values of the Young's modulus of elasticity and the Poisson's ratio. Characteristics of biological tissues were chosen according to the literature [19, 20], those of artificial materials according to technical information [21]. The mechanical characteristics of the materials used in the calculations are given in Table 1.

The material was considered homogeneous and isotropic. A 10-node tetrahedron with a quadratic approximation is chosen as a finite element.

Loading the model, we simulated the worst possible option, namely falling on the arm in the abduction position and 90° of external rotation. To do this, a rigid fixation of the model on the medial edge of the scapula was introduced, and a distributed load of 300 N was applied to the distal part of the ulna [21], which corresponds to half the body weight. The load scheme is shown in Fig. 6.

To compare the simulation results of different options of graft fixation, measurements of stress values were performed at specially selected control points (Fig. 7).

The study of SSS models was performed using the finite element method. Von Mises stress was

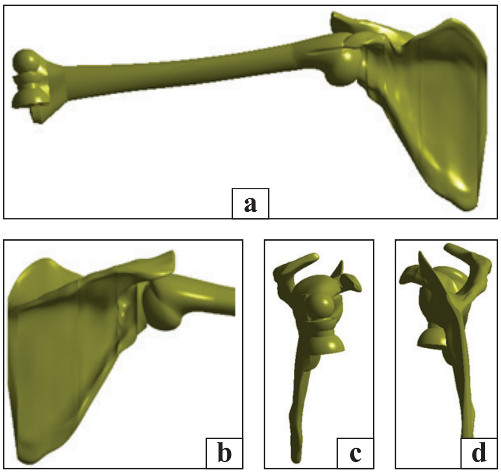


Fig. 1. Model of the shoulder joint: anterior (a), posterior (b), lateral (c) and medial (d) views

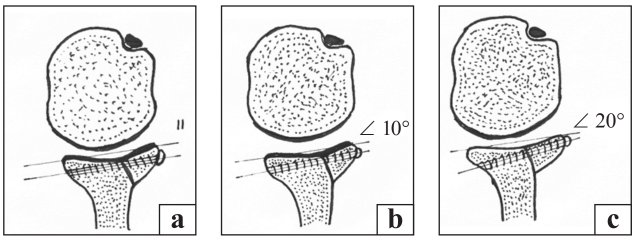


Fig. 2. Options of conduction of fixing screws in osteosynthesis of the bone block in Latarjet surgery: a) parallel to the plane of the glenoid; b) at an angle of 10°; c) at an angle of 20°

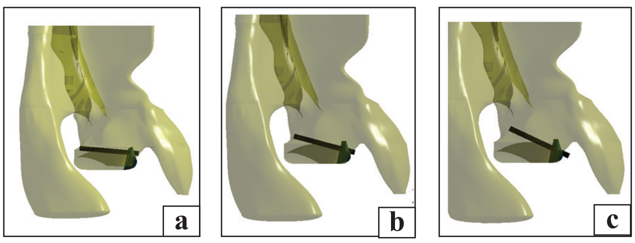


Fig. 3. Model of the shoulder joint with different options of conduction of fixing screws relative to the plane of the articular surface of the glenoid in Latarjet surgery: a) parallel to the articular surface (at an angle of 0°); b) at an angle of 10°; c) at an angle of 20°

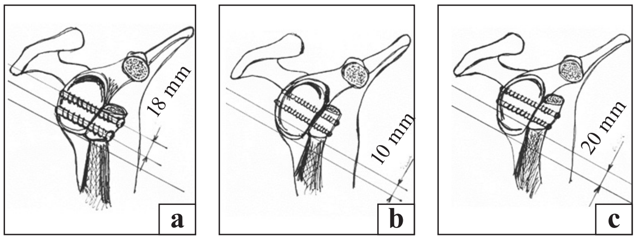


Fig. 4. Options for the location of the coracoid process on the anterior surface of the glenoid: the upper edge of the process at the level of the lower edge of the articular cavity (a), shifted to its upper edge by 10 mm (b) and 20 mm (c)

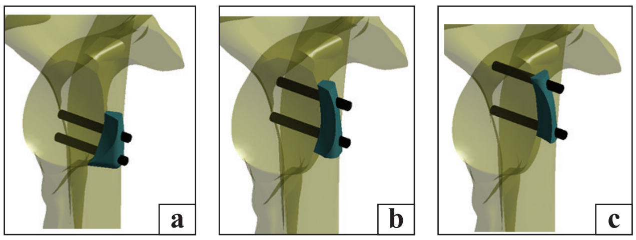


Fig. 5. Model of graft fixation on the anterior edge of the articular surface of the glenoid in Latarjet surgery: on the lower edge (a), above it by 10 mm (b) and by 20 mm (c)

Table 1

Mechanical characteristics of materials used in modeling

Material	Young's modulus (E), MPa	Ποισσονэσ ρατιο, ν
Cortical bone	18400.00	0.30
Spongy bone	10000.00	0.30
Cartilaginous tissue	5.58	0.45
Titanium BT16	54000.00	0.36

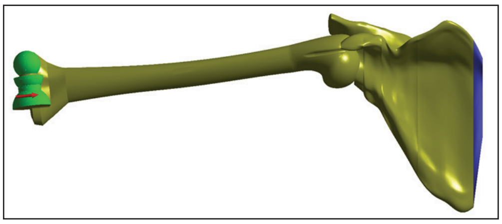


Fig. 6. Scheme of models loading

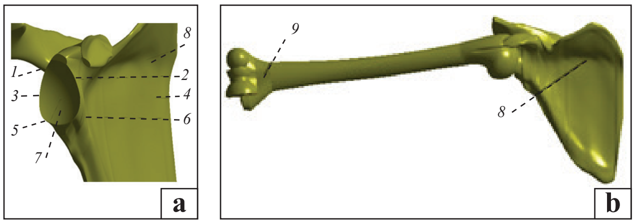
used as a criterion for estimating the SSS of the models [23]. Simulations were performed in the SolidWorks computer-aided design system, SSS calculations were performed using the CosmosM software package [24].

Results and their discussion

The first stage of the study involved assessment of the SSS model of the shoulder in the norm after the reproduction of the fall on the abducted limb. The picture of stress distribution in the model is shown in Fig. 8.

The study showed that in the case of a fall on the elbow, the maximum stresses occur in the distal part of the humerus (10.6 MPa) and on the scapula (8.9 MPa). On the glenoid, the maximum stress values were determined in the middle part at the posterior edge (7.5 MPa) and in the lower part at the anterior edge (7.4 MPa). Slightly lower stresses of 6.5 MPa were observed in the upper part of the posterior edge of the glenoid. The lower part of the posterior edge of the articular surface of the glenoid was minimally tense with the stress of 3.2 MPa. In the center of the articular surface of the glenoid stresses were determined at the level of 3.4 MPa.

The second stage of the study implied evaluation of the SSS model for different variants of fixing screws in replacement of the defect of the anterior edge of the glenoid. Fig. 9 shows stress distribution



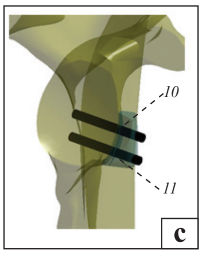


Fig. 7. Scheme of control points: the upper part of the posterior (*1*) and anterior (*2*) and the middle part of the posterior (*3*) and anterior (*4*) edges of the glenoid and the lower part of the posterior (*5*) and anterior (*6*); the center of the articular surface of the glenoid (*7*); scapula (*8*); the distal end of the humerus (*9*); upper (*10*) and lower (*11*) screws

in the model under the conditions of the screws conducted in parallel to the plane of the articular surface of the glenoid.

The presence of a free graft and metal elements on the glenoid leads to certain changes in the SSS model of the shoulder. The largest changes were found at the anterior edge of the glenoid, where the stress values doubled compared to the normal model: up to 15.3 MPa in the lower part and up to 8.6 MPa in the middle one. Stresses in the middle of the posterior edge of the glenoid and up to 7.5 MPa in its upper part also increased to 8.6 MPa. At other control points of the model, changes in stress values were insignificant, the increase did not reach 1.0 MPa. The fixing screws took on the main load, as evidenced by the values of stresses that occur in them: 53.5 MPa on the upper screw and 45.7 MPa on the lower one.

Fig.10 shows the SSS of the shoulder model in conduction of fixing screws at an angle of 10° to the plane of the articular surface of the glenoid.

Conducting the screws at an angle of 10° to the plane of the articular surface of the glenoid compared to the model in which they are held in parallel, leads to increased stresses along the posterior edge of the glenoid: up to 8.2 MPa in the upper part, 7.6 MPa in the middle and 4.7 MPa in the lower one. At the anterior edge of the glenoid, the maximum stresses of 9.7 MPa were determined in the middle part, while the lower part was found to have a slight decrease in stresses to 13.4 MPa. An increase in stress levels up to 3.6 MPa was also observed in the center of the articular surface of the glenoid and up to 10.4 MPa on the scapula. The stresses on the fixing screws also increased slightly to the level of 53.1 and 46.1 MPa at the top and bottom, respectively.

The changes that occurred in the SSS model of the shoulder as a result of the screws at an angle of 20° to the plane of the articular surface of the glenoid are shown in Fig. 11.

Increasing the value of the angle of the screws to 20° resulted in a slight decrease in the amount of stress at almost all control points of the model. The exception was the upper part of the posterior edge of the glenoid, where the stresses rose to 9.7 MPa. Besides, a slight increase in the stress level was observed on the fixing screws: 54.8 and 4.9 MPa on the upper and lower ones, respectively.

The absolute values of stress values in the control points of the model in the norm and at different angles of the fixing screws are given in Table 2.

Fig. 12 shows a diagram elaborated for comparison of values of stresses on the fixing screws in the models at different angles of their conduction.

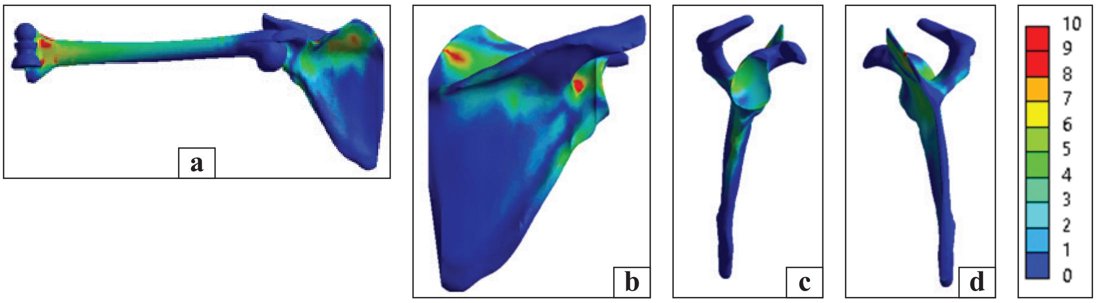


Fig. 8. Representation of the SSS model in norm: anterior (a), posterior (b), lateral (c) and medial (d) views

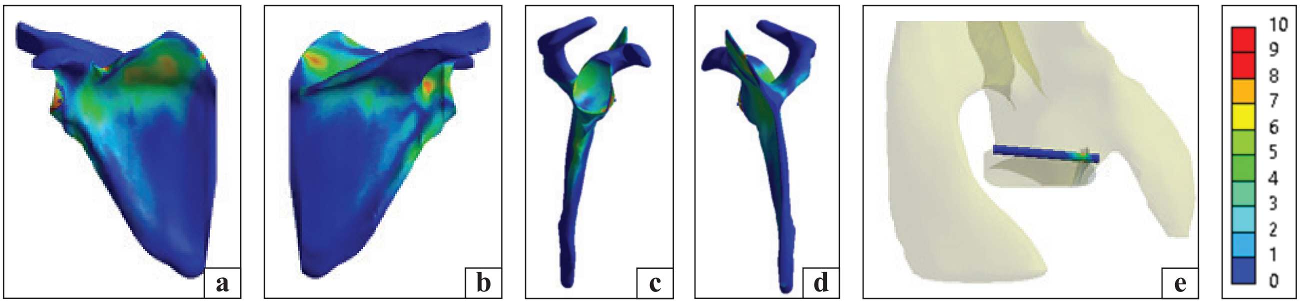


Fig. 9. Representation of the SSS of the shoulder model in conduction of the screws parallel to the plane of the articular surface of the glenoid: anterior (a), posterior (b), lateral (c) and medial (d) views, fixing screws (e)

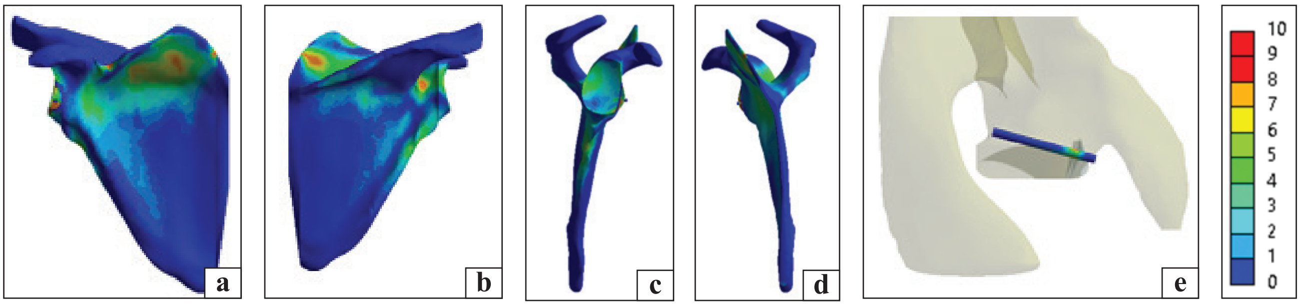


Fig. 10. Representation of the SSS in conduction of screws at an angle of 10° to the plane of the articular surface of the glenoid: anterior (a), posterior (b), lateral (c) and medial (d) views, fixing screws (e)

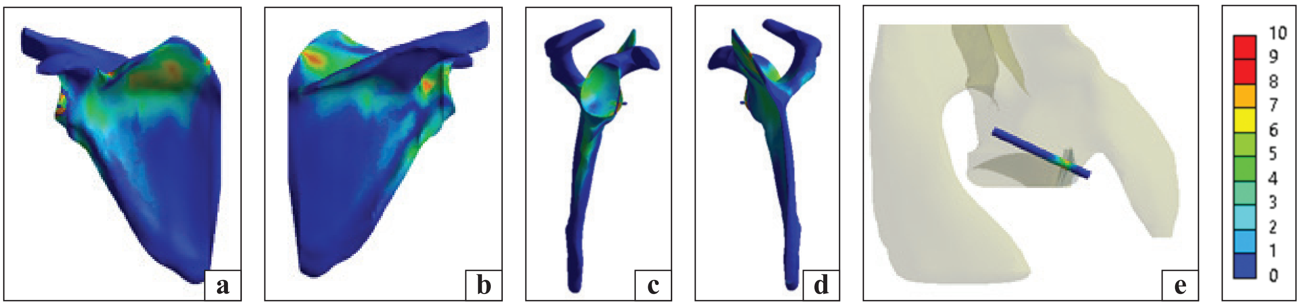


Fig. 11. Representation of the SSS in conduction of screws at an angle of 20° to the plane of the articular surface of the glenoid: anterior (a), posterior (b), lateral (c) and medial (d) views, fixing screws (e)

Thus, the presence of a bone graft fixed with metal screws in the defect area at the anterior edge of the glenoid, leads to an increase in stress levels in the bone elements of the model. The highest stress level was determined by holding the screws at an angle of 10°, the lowest in parallel to the articular surface of the glenoid. The stresses on the screws increased slightly with increasing angle of conduction, and on the upper screw were determined to be slightly greater than on the lower one.

The last stage of the study simulated different options for graft fixation at the height of the anterior edge of the glenoid. The distribution of stresses in the shoulder model under the conditions of graft fixation along the lower edge of the glenoid is shown in Fig. 13.

The maximum decrease in the height of graft fixation led to the approximation of stress values at control points on the articular surface of the glenoid to the normal values of the model. A high stress level

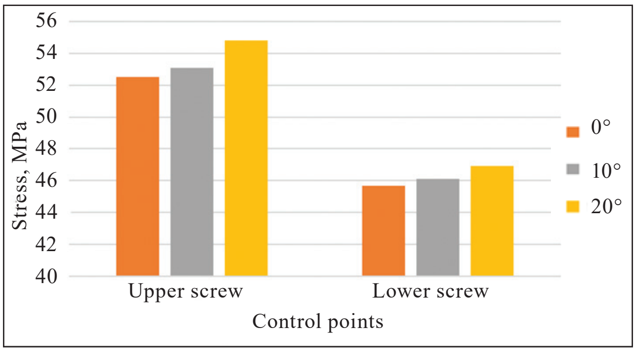


Fig. 12. Diagram of stress values of fixing screws of shoulder models at different angles of their conduction

of 9.6 MPa was maintained on the scapula. The largest changes in stress values were determined on the screws, where they fall to 17.0 and 20.8 MPa at the top and bottom, respectively.

Increasing the height of graft fixation by 10 mm caused changes in the SSS of the shoulder model (Fig. 14).

The movement of the graft to the middle part of the anterior edge of the glenoid caused multidirectional changes in the stress distribution in the shoulder model. In particular, an increase in stress levels was observed at two control points of the model: at the upper part of the posterior edge of the glenoid (up to 6.5 MPa) and in the middle part of the anterior edge (up to 5.2 MPa). In the middle part of the posterior edge of the glenoid, the amount of stress remained unchanged compared to the previous version

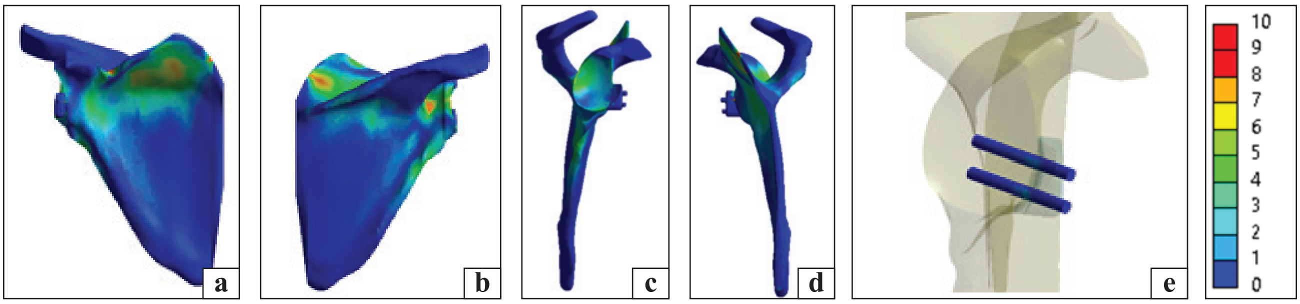


Fig. 13. Representation of the SSS in graft fixation on the lower edge of the glenoid: anterior (a), posterior (b), lateral (c) and medial (d) views

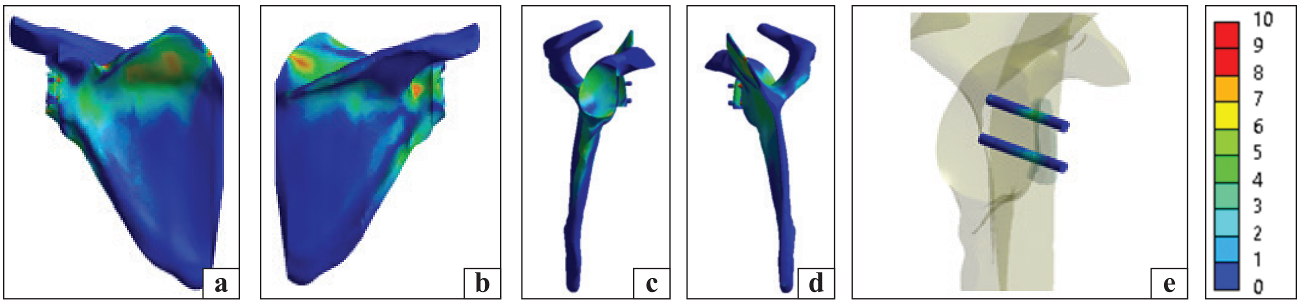


Fig. 14. Representation of the SSS in graft fixation 10 mm above the lower edge of the glenoid: posterior (b), lateral (c) and medial (d) views

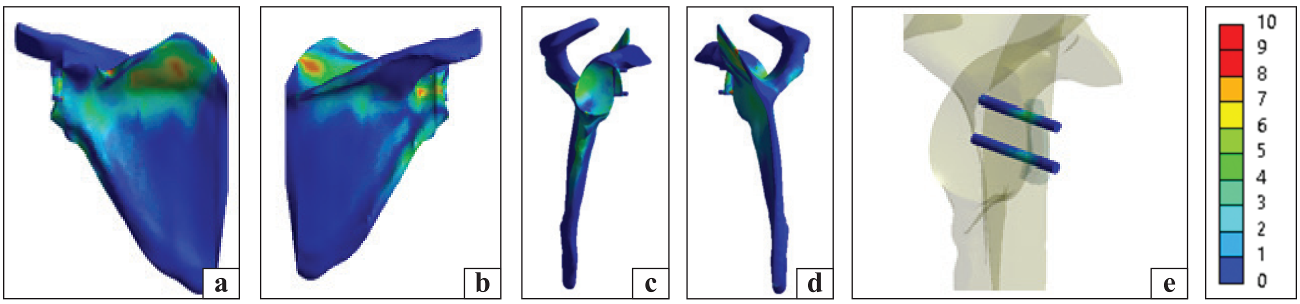


Fig. 15. Representation of the SSS in graft fixation 20 mm above the lower edge of the glenoid: posterior (b), lateral (c) and medial (d) views

Table 2

Stress values at the control points of the model at different angles of the fixing screws

Control point		Stress, MPa			
		norm	angle of the screws to the plane of the articular surface		
			0°	10°	20°
Bony tissue	1	6.5	7.5	8.2	9.7
	2	3.6	4.5	4.5	4.4
	3	7.5	8.6	7.6	7.2
	4	4.4	8.6	9.7	9.6
	5	3.2	4.0	4.7	4.1
	6	7.4	15.3	13.4	12.8
	7	3.4	3.2	3.6	3.1
	8	8.9	8.8	10.4	9.3
	9	10.6	10.6	10.6	10.6
Screw	10	—	52.5	53.1	54.8
	11	—	45.7	46.1	46.9

Table 3

Stress values at the control points of the model for different options of graft fixation

Control point		Stress, MPa			
		norm	зміщення вверх		
			0 мм	10 мм	20 мм
Bony tissue	1	6.5	6.5	6.2	5.5
	2	3.6	4.0	4.1	5.8
	3	7.5	8.4	8.6	8.6
	4	4.4	4.8	5.2	5.1
	5	3.2	4.4	4.2	4.9
	6	7.4	4.4	5.8	6.7
	7	3.4	3.2	3.2	3.4
	8	8,9	9.4	9.2	9.6
	9	10.6	10.6	10.6	10.6
Screw	10	—	17.0	68.5	49.5
	11	—	20.8	42.8	43.8

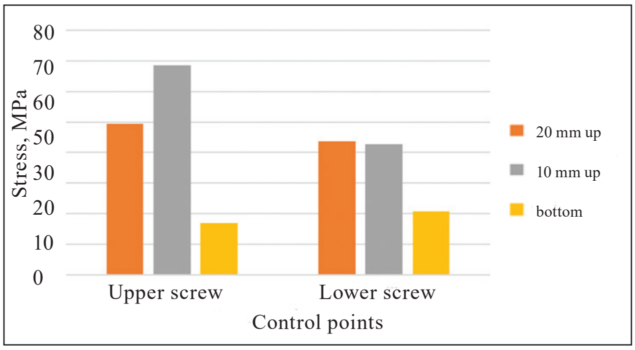


Fig. 18. Diagram of stress values at control points on the fixing screws of the shoulder models for different variants of graft fixation

of the model, namely 8.6 MPa. At other control points of the model, the stress values decreased. The same multidirectional tendency of stress redistribution was found on the fixing screws, where an increase to 68.5 MPa on the upper screw and a decrease to 42.8 MPa on the lower screw were recorded.

Fig. 15 shows a picture of the distribution of SSS in the shoulder model under the conditions of graft fixation 20 mm above the lower edge of the glenoid.

In graft fixation on the upper edge of the glenoid, the maximum stresses were found on the scapula — 9.6 MPa. On the articular surface of the glenoid, the middle part of the anterior edge was the most loaded — 8.6 MPa. In the upper and lower parts of the anterior edge of the glenoid stress was determined at 5.5 and 4.9 MPa, respectively. At the posterior edge of the glenoid, the maximum stress did not exceed the mark of 6.7 MPa in its lower part, in the middle and upper parts of the stress was equal to 5.1 and 5.8 MPa, respectively. The minimum stress value of 3.4 MPa was observed in the central part of the articular surface of the glenoid. The stresses on the fixing screws became 49.5 MPa at the top and 43.8 MPa at the bottom.

Table 3 summarizes the values of stresses in the control points of the models in norm and at different heights of graft fixation relative to the anterior edge of the glenoid.

An idea of the ratio of the stresses on the screws in the shoulder model for different options for graft fixation can be obtained using the diagram (Fig. 16).

Thus, the most favorable option for fixing the graft, given the distribution of stresses on the articular surface of the glenoid and fixing screws, is its fixation in the lower part of the anterior edge of the glenoid.

Conclusions

The presence of a bone graft fixed with metal screws in the area of the defect at the anterior edge of the glenoid leads to an increase in the level of stresses in the bone elements of the model.

Changes in the SSS of the shoulder model occur depending on the angle of the screws that secure the graft. The highest level of stresses was determined in the case of screws at an angle of 10°, the lowest in parallel to the articular surface of the glenoid. The stresses on the fixing screws increased slightly along with an increase in the angle of conduction. The location of the graft in the lower part of the anterior edge of the glenoid was the most favorable due to the distribution of stresses on the articular surface of the glenoid and fixing screws.

Conflict of interest. The authors declare the absence of conflict of interest.

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The article was received by the editors 26.08.2021

MATHEMATICAL MODELING OF GRAFT FIXATION VARIANTS TO THE ANTERIOR MARGIN OF THE GLENOID PERFORMING LATARJET PROCEDURE

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