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Mathematical Modeling of the „Bone-Fixator“ System during the Treatment of Intertrochanteric Fractures

V.E. Dubrov [1], I.M. Shcherbakov [1], K.A. Saprykina [1], I.A. Kuzkin [2], D.A. Zyuzin [1], D.V. Yashin [1]

[1] *Lomonosov Moscow State University, Moscow, Russian Federation*

[2] *Hexa LLC, Moscow, Russian Federation*

Abstract

Relevance — the need for an objective justification in choosing the type of fixation in the treatment patients with pertrochanteric hip fractures. ***Objective*** — to study the changes in the properties of a consolidating trochanteric fracture fixed by a dynamic cephalomedullary nail when subjected to cyclic dynamic loads. ***Materials and methods.*** A mathematical model was developed for trochanteric fracture of the femur (A1 according to AO classification) when fixed with a dynamic cephalomedullary nail. Then, the properties of the system were studied (pressure between fragments, mechanical stress in the bone and fixation device, displacement amplitude, neck-diaphysis angle) under a virtual load of a 80 kg body at various amount of insertion of the dynamic screw (from 10 mm to 0 mm). ***Results.*** In the process of shortening the femoral neck axis by 1 cm, the stability of the „bone-fixator“ system increases, as indicated by a decrease in the maximum amplitude of displacements in the system under load by 16.8%, a decrease in the maximum stress in the fixation elements by 20.2%, a decrease in pressure at the site of contact of fragments by 19.8%. In addition, there was a decrease in the neck-diaphysis angle by 2.8%. ***Conclusion.*** The mathematical modeling of the „bone-fixator“ system simulating conditions of dynamic osteosynthesis showed that there is a potential increase in the stability of the cephalomedullary system and that favorable conditions are created for the consolidation of the fracture when subjected to cyclic load of body mass.

Keywords: dynamic cephalomedullary osteosynthesis, finite element analysis, trochanteric fractures.

Introduction

The pertrochanteric hip fractures impair the function of the hip joint and lead to a significant limitation of patient activity and the need for help and care from others [1]. The increase in the segment of the older population and the greater incidence of osteoporosis are accompanied by an increase in the total number of these injuries [2]. At the same time, the treatment of pertrochanteric hip fractures and their consequences is a difficult and still unsolved problem, since each treatment method has its own advantages and disadvantages [3].

In recent decades, osteosynthesis of fragments of the femur has been used more often while treating pertrochanteric hip fractures, allowing for a load on the limb before the fracture consolidates [4]. The fixation devices used in this case are either static (rigid structures that completely unload the fracture site) or dynamic (structures enabling displacement of elements, which transmit a part of the load on the fracture site). In the

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Ivan M. Shcherbakov; e-mail: imscherbackov@yandex.ru

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older age group, early mobilization is considered as a measure to prevent hypostatic complications and reduce mortality. However, among older people, many patients cannot limit the load of their body mass on the operated limb while walking.

One of the possible consequences of a regular cyclic load on the operated limb may be an increase in bone tissue resorption at the fracture site. Under conditions of dynamic fixation of fragments, this resorption leads to a decrease in the distance (so-called offset) between the center of rotation of the femoral head and the longitudinal axis of the diaphysis of the femur, which, according to the literature, ranges from 0 to 19 mm with an average value of 6 mm [5]. In the case of consolidation of the fracture with a pronounced decrease in offset, there is a decrease in muscle strength in the proximal femur region due to the convergence of their points of attachment, which leads to the occurrence of chronic pain and an abnormal gait. Under conditions of static fixation, which excludes the displacement of fixation elements and fragments, uncontrolled resorption can disrupt the course of fracture consolidation and lead to migration or deformation of fixation elements with secondary loss of reposition [4].

Therefore, it remains unclear whether to consider the above-described phenomenon as a complication after use of dynamic fixation devices or as an adaptive process which accompanies the consolidation of fracture and indirectly excludes the migration of fixation elements, the formation of deformations and nonunions.

The purpose of the study — to examine the changes in biomechanical properties of the femur for different amounts of shortening of the femur offset, when an pertrochanteric fracture is fixed by a dynamic cephalomedullary nail.

Materials and Methods

At the first stage of the research, a mathematical volumetric model of the pertrochanteric fractures of the proximal femur classified as 31-A1.1, according to the AO/ASIF classification [6], or as type I, according to Evans classification [7], was developed in the Abaqus/CAE module of the Abaqus software complex. To develop it, we used generalized results of multispiral computed tomography (Toshiba Aquilion Multi 64, Japan), performed in 12 patients (8 — 66.7% — women, 4 — 33.3% — men, ages from 37 to 77 years, mean age is 66 years) with the aim of differential diagnosis of the nature of damage to the femur in the cases when X-rays were unclear. MSCT data were used to form the shape of the proximal femur model, the distribution in the volume of cortical and cancellous bone tissue, and the location of the fracture plane.

The fracture was virtually repaired with a Targon PF titanium dynamic cephalomedullary fixation device. The model used a 180 mm shaft with a diameter of 14 mm, an angle of 130° with a 100 mm fixation device sleeve, a dynamic screw with length of 70 mm and an anti-rotation pin with the length of 110 mm. A feature of this fixation device is the possibility of free sliding of the femoral neck screw in the sleeve fixed in the shaft [5].

In the model, the initial position was assumed as an accurate anatomical reposition of the fracture achieved with a cephalomedullary fixation device, wherein the dynamic screw protruded from the sleeve by 10 mm.

The elastic properties of the material are completely determined by two values — Young's modulus of elasticity and Poisson's ratio (Table 1). In developing a model of the bone, we considered the cancellous and cortical components to have different physical-mechanical properties.

At the second stage, the analysis of the „bone-fixator“ system was performed using the finite element analysis. With the Abaqus finite element analysis software packages (version 6.10, 2010), a computational mathematical model was developed using ten-node isoparametric tetrahedra with three degrees of freedom at each node. The total number of elements in the system was 242 thousand, nodes — 112 thousand.

The lower end of the model, which corresponds to the middle third of the femur diaphysis, was virtually fixed relative to all six degrees of freedom. A force equivalent to 80 kg, corresponding to the average body mass [8], was applied to the femoral head in a virtual manner. Six variants of insertion of a dynamic screw were analyzed during modeling: offset by 0, 2, 4, 6, 8, 10 mm relative to the screw sleeve, which corresponded to different amounts of shortening of the femoral neck axis in the process of fracture consolidation. For each variant of insertion of a dynamic screw, the measured parameters were: amplitude of displacement of system elements under load, magnitude of the neck-diaphysis angle, pressure at the site of contact of the bone fragments and the von Mises stress distribution in the region of metal fixation devices and bone (Table 2).

Table 1

Physical-mechanical properties of materials of models

Material	Young's modulus E, MPa	Poisson's ratio
Cortical bone layer	12000	0.3
Cancellous bone material	100	0.2
Implant (Titanium)	112000	0.32

Table 2

Characteristics of the measured parameters of the „bone-fixator" system

Measured parameter	Parameter characteristics
Displacement of system elements under load	The amplitude of the displacement of the proximal fragment relative to the distal, mm
Neck-diaphysis angle	The angle between the axis of the femoral neck and the anatomical axis of the diaphysis of the femur, degrees
Pressure at the site of contact of the bone fragments	The pressure between the proximal and distal fragments created in the plane of the fracture under load, MPa
The von Mises stress distribution in system elements	Internal stress occurring in the elements of the system during deformations caused by external load, MPa

To assess the stress-strain state of the material, the von Mises stress calculation was used, taking into account the data on the basic stress tensors [8]. In our study, the yield strength of the material was used as a parameter of the ultimate stress. According to the theory of Huber-Mises-Henki, when an equivalent stress exceeds the yield strength, plastic deformations occur in the material [9].

Statistical analysis

Statistical processing of the results was performed by calculating the Spearman's rank correlation coefficient (*r*) to determine whether there is a relationship between the depth of the dynamic screw insertion and changes in the measured parameters (pressure at the site of contact of the fragments, displacement of fragments, maximum stress in the metal fixation device).

Results

Graphical images of the developed mathematical models used for the calculations, and the von Mises stress distribution in them are presented in Figures 1, 2, 3.

Analysis of the stress-strain state of the „bone-fixator" system under a virtual load corresponding to an average human body mass of 80 kg showed an increased von Mises stress concentration in the distal part of the fracture plane near the lesser trochanter, Adams' arch and the contact zone of the screw sleeve and the anti-rotation pin with the shaft. However, no critical von Mises stress values were discovered in the bone tissue and/or metal fixation device, which would indicate damage to them.

As a result of analyzing the mathematical model of the „bone-fixator" system, depending on the depth of insertion of the dynamic screw, we determined the limits of the displacement amplitude of the system elements under load, of pressure at the contact of bone fragments, of the maximum stresses in metal implants and the neck-diaphysis angle measure presented in Table 3 and in Figure 4. The table shows the absolute values and changes in the parameters relative to the zero level, by which is meant the total insertion of the dynamic screw. Relative values were calculated by the formula:

$$\frac{A_i - A_0}{A_0} \times 100\%,$$

where A_0 is the parameter value at full insertion of the dynamic screw, A_i is the parameter value at a given insertion value of the dynamic screw.

According to the calculation of the correlation coefficient, a direct linear relationship was found between the amount of shortening of the femoral neck axis (insertion of the dynamic screw) and the decrease in measured parameters: the maximum displacement amplitude in the „bone-fixator" system, the pressure between fragments and the maximum stress in the fixation elements. This correlation is strong — the Spearman's rank correlation coefficient is $r = 0.99$ ($p<0.05$) (Fig. 4).

Table 3

The results of the calculations of the parameters presented in Table 2 depending on the dynamization of the fracture in the process of consolidation (the value of the Spearman's rank correlation coefficient *r* for all parameters is 0.99)

Parameter	Leverage length					
	0	2	4	6	8	10
Displacement of system elements under load, mm	1.88	1.91	2.0	2.07	2.13	2.2
Pressure at the contact of bone fragments, MPa	9.1	9.5	10.0	10.4	10.6	10.9
Maximum stress in metal implants, MPa	226.3	228.2	237.8	250.5	261.4	272.0
Neck-diaphysis angle, °	126.5	127.0	127.4	128.1	129.7	130.0

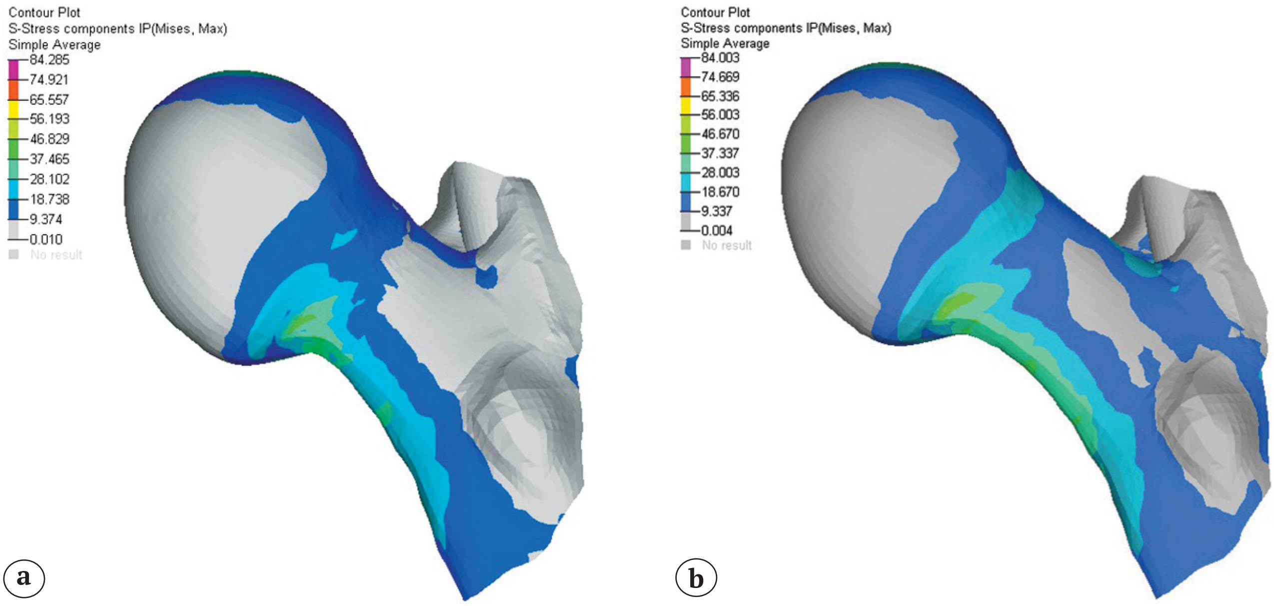

Fig. 1. The distribution of the maximum von Mises stresses in the proximal fragment with a leverage length of 10 mm (a) and 0 mm (b)

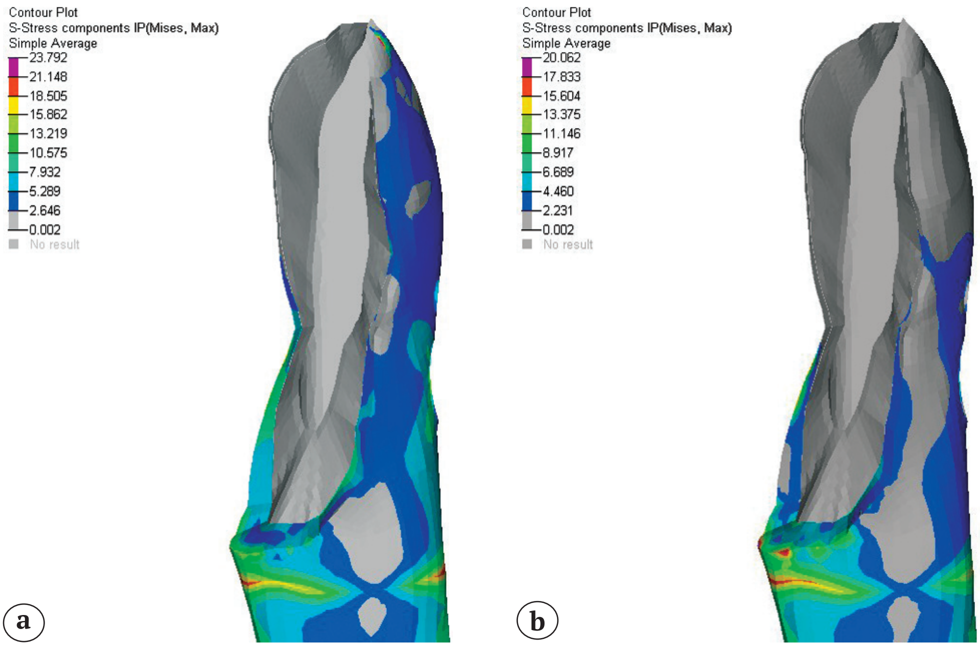

Fig. 2. The distribution of the maximum von Mises stresses in the distal fragment with a leverage length of 10 mm (a) and 0 mm (b)

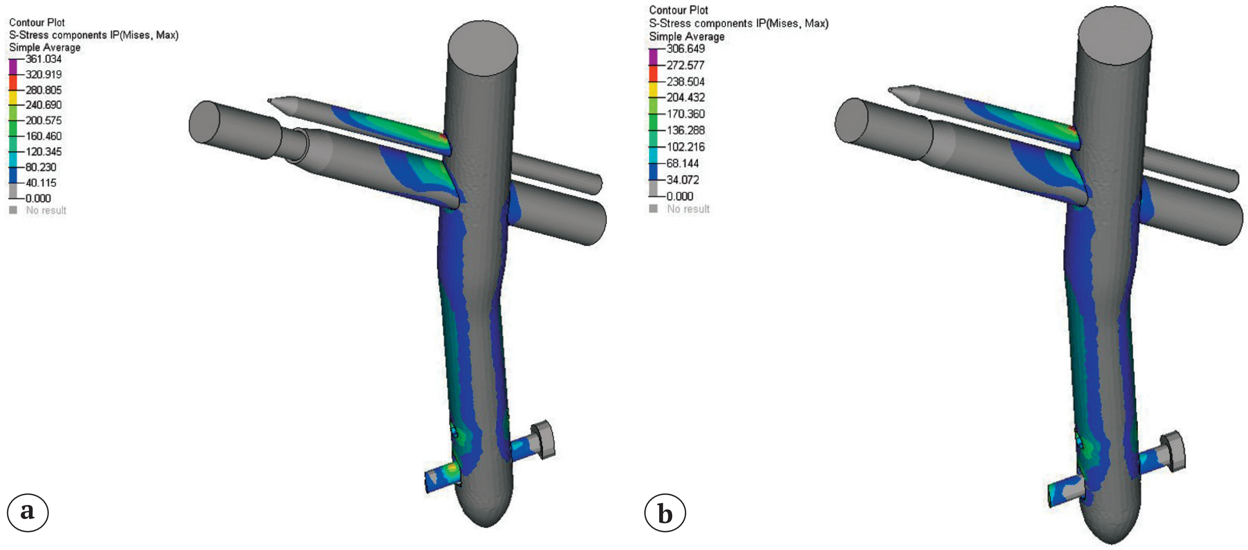

Fig. 3. The distribution of the maximum von Mises stresses in the metal fixation device with a leverage length of 10 mm (a) and 0 mm (b)

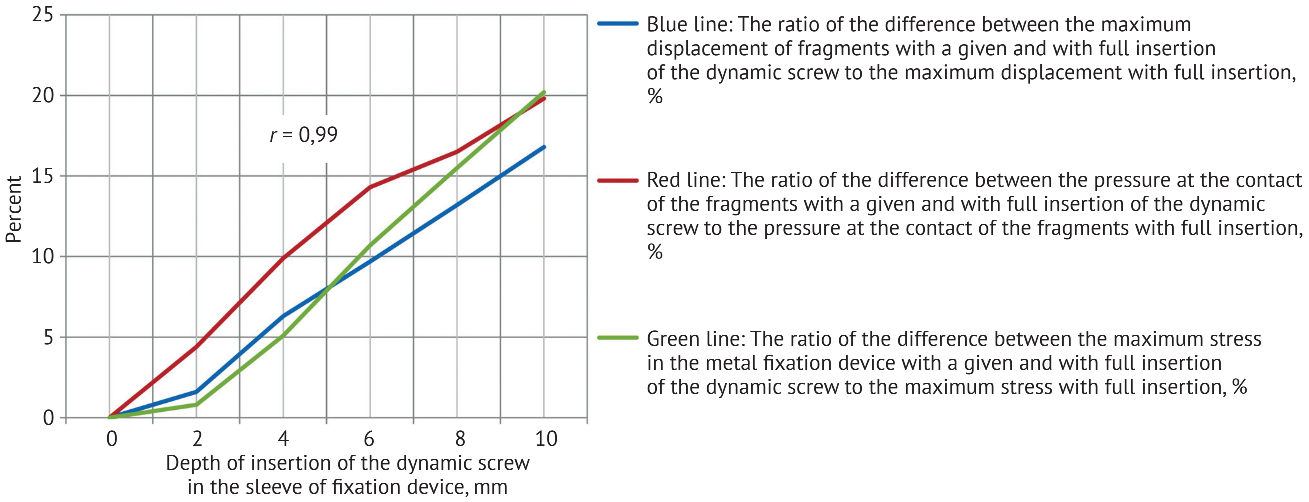

Fig. 4. Ratios of the maximum amplitude of the fragment displacement, the pressure at the contact of the fragments and the maximum stress in the metal fixation device to the value at the depth of insertion of the dynamic screw (the value of the Spearman's correlation coefficient *r* for all parameters is 0.99)

Discussion

The occurrence of complications after surgical treatment of pertrochanteric hip fractures is determined by a combination of both biological (the process of fracture consolidation, quality of bone tissue) and mechanical (type of implant, quality of reposition, mutual positioning of fixation device and bone fragments at the time of implantation, loading on the limb after surgery) factors. These factors ultimately affect the geometry of the application of forces and the distribution of loads in the bone and fixation device. Although explaining and predicting the development of these complications is often discussed in the specialized literature, a mutual approach to the choice of treatment in patients with pertrochanteric hip fractures has not been determined [10–12].

To predict the strength of any system, a sample similar in bone properties (a physical model such as a cadaveric human bone, animal bone or plastic bone model) can be subjected to appropriate loads. However, in all these experiments there is a significant disadvantage — they do not take into account bone resorption and changes in the relative positions of the proximal femur fragments during fracture consolidation. This is because it is almost impossible to accurately simulate the process of shortening the femoral bone axis on the same model [13–21].

This disadvantage can be overcome by using mathematical modeling, in particular, the finite element analysis, which takes into account changes in the magnitude and direction of loads in the „bone-fixator" system [14, 20]. However, in the majority of works devoted to the finite-element modeling of the „bone-fixator" system, their characteristics are studied after the fixation devices are installed, and the subsequent change in the geometry of the system is not considered [21–27]. For example, in the study [27], similar parameters were used to develop and test the model. At the same time, similar results were obtained for the distribution of loads and deformations in the proximal femur and metal fixation device. However, the difference between this work and ours is the modeling of fractures with different sizes of the posterior-medial fragment with a lesser trochanter, which, according to the authors of the article, increased fracture instability, but the spatial changes that occurred with the fracture during consolidation were not factored in.

The simulation of the natural process of shortening the femoral neck axis during fracture consolidation while assessing the changes in the mechanical properties of the „bone-fixator" system under these conditions (Table 3, Fig. 5) showed that the decrease of the von Mises stress in the region of the „bone-fixator" indicates reducing the risk of damage to elements of this region while reducing the offset of the femur. A decrease in pressure between fragments may indicate a potential self-limiting of the shortening process if we consider the cyclic increase in the load on the fracture site as the cause of accelerated resorption. A decrease in the amplitude of fragment displacements can be considered as a possible equivalent of increasing the stability of the „bone-fixator" system. This fact may indirectly contribute to consolidation, since excessive mobility disrupts vascularization and bone maturation at the fracture site. The identified reduction of the neck-diaphysis angle may be associated with accelerated bone resorption in areas of increased load in the lesser trochanter and Adams' arch.

The obtained data as a whole can testify to the theoretical advantage of using dynamic cephalomedullary osteosynthesis for pertrochanteric hip fractures under conditions of early full loading. The positive effect of this use ensures the autocompression at the fracture site by changing the position of the system elements, and consequently, creating constant contact of the bone fragments with each other in spite of bone resorption, [5, 21].

But it should be kept in mind the negative consequences of shortening the femoral neck axis — reducing the neck-diaphysis angle with the formation of the varus deformity of the proximal femur and shortening the distance between the femoral diaphysis axis and the hip joint rotation center (hip offset). Together, all this can lead to a biomechanical dysfunction in the hip, the most prominent manifestation of which is the development of the Trendelenburg symptom.

Comparative studies with models of intertrochanteric femur fractures under static fixation conditions have not been conducted since the possibility of dynamization was not considered in their design. If excessive bone resorption develops, it will be uncontrollable and a complication.

Therefore, the facts obtained in this study suggest that dynamic fixation can reduce the incidence of complications in managing pertrochanteric hip fractures in elderly patients who find it difficult to follow the orthopedic regimen for various reasons (loss of intellect, sarcopenia, etc.). This leads to increased stress at the fracture site and more shortening of the femoral neck axis. However, clinical studies are required to confirm this fact.

Mathematical modeling of the dynamics of the positioning of elements of the 'bone-metal fixation device' system under conditions of dynamic osteosynthesis showed the possibility of reducing the maximum displacement amplitude of the fragments, decreasing the pressure between them, and reducing the stress in the fixation elements while lessening the offset of the femur. This fact can be considered equivalent to increasing the stability of the cephalomedullary system and creating favorable conditions for fracture consolidation under a cyclic load with body mass.

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INFORMATION ABOUT AUTHORS:

Vadim E. Dubrov — Dr. Sci. (Med.), Professor, Chairman, Department of General and Specialized Surgery, School of Medicine, Lomonosov Moscow State University, Moscow, Russian Federation

Ivan M. Shcherbakov — PhD Student, Department of General and Specialized Surgery, School of Medicine, Lomonosov Moscow State University, Moscow, Russian Federation

Kseniya A. Saprykina — PhD Student, Department of General and Specialized Surgery, School of Medicine, Lomonosov Moscow State University, Moscow, Russian Federation

Ivan A. Kuz'kin — Principal Engineer, «Hexa» Company, Moscow, Russian Federation

Dmitrii A. Zyuzin — PhD Student, Department of General and Specialized Surgery, School of Medicine, Lomonosov Moscow State University, Moscow, Russian Federation

Dmitrii V. Yashin — Resident, Department of General and Specialized Surgery, School of Medicine, Lomonosov Moscow State University, Moscow, Russian Federation