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Biomechanical analysis of limited-contact plate used for osteosynthesis

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This paper presents the results of numerical analysis aimed at determining the state of stresses and displacements of compression plate used in osteosynthesis of tibia, carried out by applying finite element method using the ANSYS program. The analysis took into account two variants of the osteosynthesis. Variant I included the osteosynthesis in which plate was attached directly to the bone, in variant II, the plate was moved away from the bones by about 5 mm. Biomechanical characteristics of the corrective osteotomy plate–tibia was determined for implants made of Ti-6Al-4V alloy. The boundary conditions adopted for the analysis reflect phenomena occurring in a real system. Based on the results of the analysis relative displacements and reduced stresses in various components were determined as a function of the applied load within the range of F = 500–1500 N. The maximum forces, both variant I and variant II determined during analysis, ensure that the generated stress does not exceed yield strength of the material and compressive strength of the bone, and do not exceed safety movement in the fracture gap. In addition, it was found that the locking of the compressive plate to the bone has a little effect on the distribution of displacements and stresses on the plate–tibia system in the case of a simple fracture.

Key words: *internal fixation; biomechanics, locking compression plates, fracture, titanium alloys*

1. Introduction

Fixation of bone fragments with bone plates is one of the most frequently used treatment methods of long bone fractures. Until recently, the most widely used plates for osteosynthesis of long bones were normal plates provided with round holes. These plates are slowly being replaced by the limited contact plates, which have a reduced contact surface with the bone and thus reducing the effect on bone injury, improve wound healing in the critical zone and a better circulation of sensitive locations.

On the basis of current clinical experience, biomechanical conditions of the osteosynthesis have not been fully explained. In the literature, there is a lack of considerations concerning the relation between displacement and stress in the fixation which is a basis for the optimal selection of geometric features, the selection of mechanical properties and the method of attaching the plate to the bone [1]–[10].

In most research centers the research on biomechanical analysis of corrective osteotomy plates consist mainly of experimental studies that aim to determine whether the method of attaching the plate to the bone has an impact on the stability of fixation and adequate blood supply to the periosteum. However, the aim of the analysis carried out by the authors was to determine the maximum force that ensures the generation of stress, which will not exceed the yield strength of the material from which the plate is made and the compressive strength of bone, as well as displacement of the fracture gap not exceeding 1 mm [1]–[10].

Ahmad et al. [2] presented results of mechanical stability of the LCP plate made of stainless steel to

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stabilize humerus. Three variants of fixing the plate to the bone were analyzed. In variant I plate was attached directly to the bone, in variant II plate was fixed at a distance of 2 mm from the bone, while in variant III plate was fixed at a distance of 5 mm from the humerus. Samples were subjected to cyclic compression till damage, which was observed and analyzed by the use of scanning electron microscope. The study showed that the best results in mechanical properties were observed in the case in which the plate was moved at a distance ≤ 2 mm. However, placing the plate at a distance of 5 mm from the bone, significantly reduces the axial stiffness and torsional rigidity of the system analyzed [2].

Miller and Goswami [3] analyzed the factors affecting the functionality of plate fixation (for example, types of plates, placement of screws, plate length, the distance between the bone and the plate, etc.). In the work, an overview of the literature related to biomechanics of a limited contact plates, and their use as internal stabilizers in the fractures treatment was presented [3].

Another example may be research carried out by Stöffleret et al. [4]. That paper describes the importance of biological factors in the internal fixation. In vitro studies are supported by biomechanical analysis using the finite element method using a blocking plate with limited contact (LCP) in order to determine optimal conditions of stability. In a study on stability of the plate–bone system, the following parameters were analyzed: length of the plate, location of the plate on the bone, number of screws, type of fracture and distance of the plate from the bone. On the basis of the results it was found that: the number of screws used for fracture fixation should be adapted to the type of fracture. Moreover, based on in vivo studies it was found that the distance between the plate and the bone should be small.

2. Materials and methods

The study investigates low contact compressive plate (Fig. 1) for osteosynthesis of fractured tibia. The plate has a shape adapted to the anatomical curvature of bone. The plate is fastened to the bone using bone screws. Numerical analysis was performed for a simple fracture located in the middle of the tibia having 2 variants of the fixation. In variant I the plate was fastened directly to the bone, while in variant II it was moved 5 mm away from the bone.

In order to determine the state of stress and deformations of the plate for different displacement values (range of forces 500–1500 N) a numerical analysis using ANSYS enviroment was performed. The results obtained are significant for selecting structure and mechanical properties of metallic biomaterials for bone plates.

Geometrical model of the limited contact plates was developed based on the initial concept design, Fig. 2. In addition, geometric model of tibia used has

Fig. 1. Low contact compressive plate being analyzed

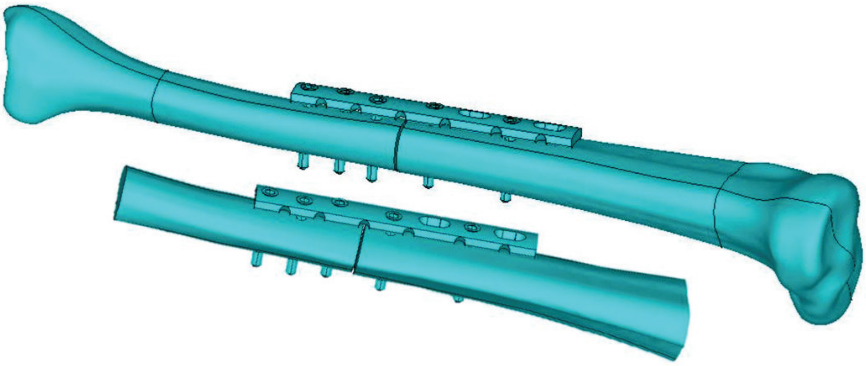

Fig. 2. Geometric model of the tibia–locking compressive plate

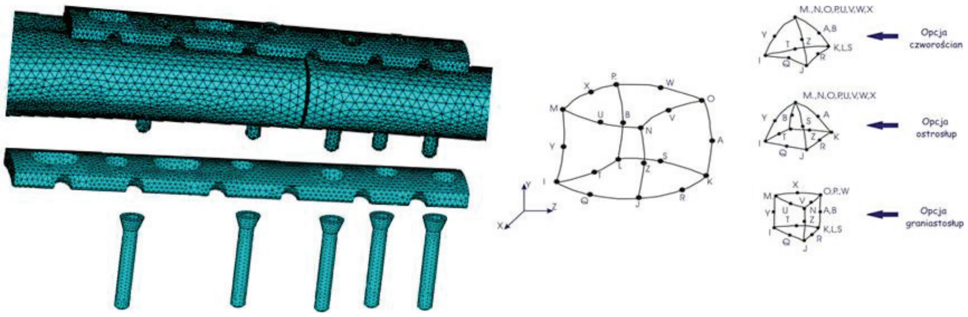

Fig. 3. The geometrical model discretized by the SOLID95 elements

been simplified by removing the condyles. To develop geometrical models the Inventor software was used. Subsequently, geometric plate–tibia model was developed.

On the basis of geometric models finite element meshes were generated, as shown in Fig. 3. For model discretization a SOLID95 type finite element was used, which is typically used in spatial analysis of solids. This element type is parametric solid element having 20 nodes with three degrees of freedom in each of them (moving in the x, y, z directions). The choice of this element allows one to include during analysis the physical nonlinearity, large displacements and rotations. Computational model of the plate had 675 elements.

Fig. 4. Adopted boundary conditions: (a) distal fixation, (b) applied axial load, (c) the model of the load

For discretization of the elements ANSYS software was used. For the calculations it was necessary to identify and give the initial and boundary conditions, which reflect the accuracy of the corresponding phenomena in a real system. The following assumptions were set:

- the lower part of the bone is immobilized by taking away the nodes lying in the plane all degrees of freedom, the location of the support made it impossible to move the bones along the assumed X, Y and Z axis, at the same time blocking the possible rotation, Fig. 4b,
- the upper base of tibia was loaded axially with the forces in the range of 500 N to 1500 N, with load increasing every 100 N, Fig. 4a. The center of gravity of the sagittal plane is positioned on the line formed by the geometric centers of the knee and ankle joints, so it makes it possible to apply axial load.

For analysis purposes material properties corresponding to alloy Ti-6Al-4V were established: Young's modulus equal to $E = 1.06 \cdot 105$ MPa, Poisson's ratio $\upsilon = 0.33$. The scope of the analysis included determination of displacements and stresses in elements of the plate–tibia system depending on the applied osteosynthesis variant.

3. Results

The results of the analysis of displacement and stress states conducted for the tibia–limited contact plate system for load range $F = 500–1500$ N are shown in Table 1. The analysis showed that the maximum stress occurring in the plate (Fig. 5), as a result of application of force $F = 1500$ N was equal to $\sigma_{\max} = 1118$ MPa (for variant I) and $\sigma_{\max} = 832$ MPa (variant II). These stresses were generated in the area of the first hole below the fracture gap.

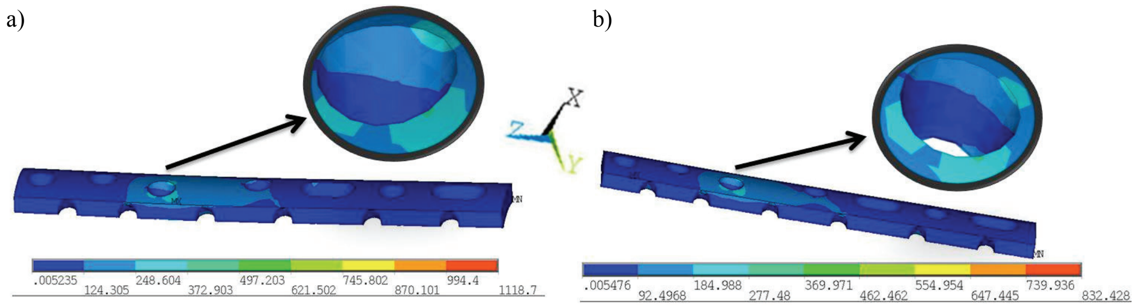

Fig. 5. Distribution of equivalent stresses in the plate, resulting from loading the model with the force $F = 1500$ N: (a) variant I, (b) variant II

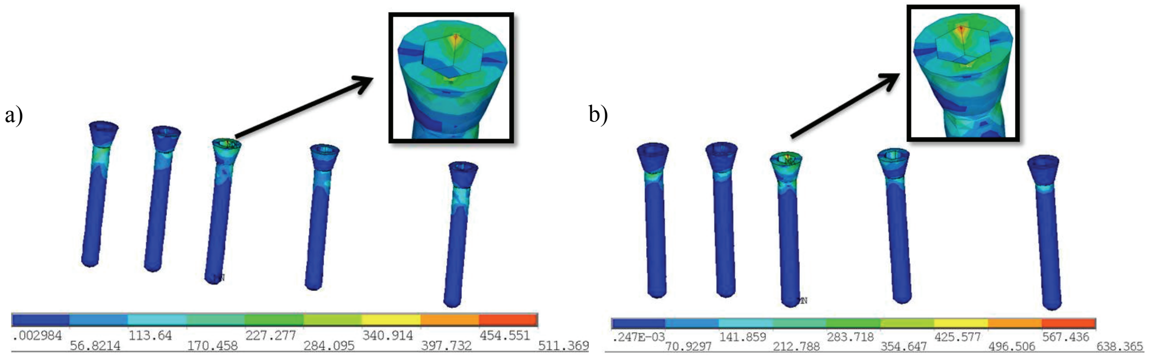

Fig. 6. Distribution of equivalent stresses in the screws, resulting from loading the model with the force $F = 1500$ N: (a) variant I, (b) variant II

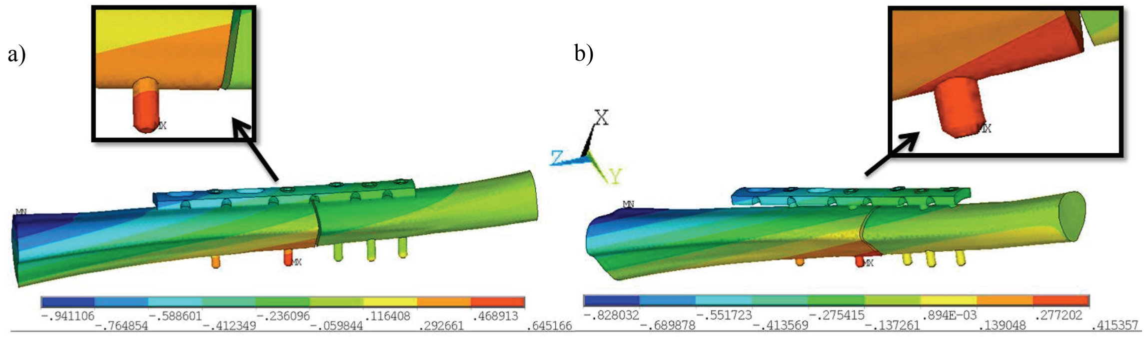

Fig. 7. Distribution of equivalent displacements in *OZ* axis formed by loading the model with given forces: (a) variant I, (b) variant II

The maximum equivalent stresses for screws as a result of the applied force $F = 1500$ N were lower and were equal to $\sigma_{\max} = 638$ MPa (variant I) and $\sigma_{\max} = 511$ MPa (variant II). The stresses were located in the first screw directly under the fracture gap, Fig. 6. They were uniformly distributed over its entire surface. Maximum values were in the area of direct impact on the screw plate.

In addition, it was also found that the maximum stress in the bone was respectively $\sigma_{\max} = 193$ MPa and $\sigma_{\max} = 204$ MPa. The obtained values of reduced stress should not exceed the yield strength of the material from which the plate is made ($Rp_{0,2} = 780$ MPa) and a compressive strength of bone ($Rc = 160$ MPa). Therefore, on the basis of the analysis it was found that the maximum load of the plate–tibia should not exceed the value of $F = 1000$ N for variant I and $F = 1100$ N for variant II. In addition, for the given load values F, maximum displacements in the fracture gap, do not exceed the value of $u = 0.7$ mm, Fig. 7.

Biomechanical analysis of the solution proposed shows that for the assumed boundary conditions, determined on the basis of clinical recommendations (loading force $F = 1000$ N for variant I and $F = 1100$ N for variant II) and the experimentally determined mechanical properties of the alloy Ti-6Al-4V, this type of fixation can be successfully used for the treatment of tibia fractures.

Table 1. The results of the analysis of the stresses and displacements in the elements of the tibia-limited contact plate system

Force F, N	Max. reduced stresses in the plate, σw, MPa	Max. reduced stresses in the screws, σp, MPa	Max. reduced stresses in bone-plate system, τ, MPa	Max. reduced stresses in bone σk, MPa	Displacement in fracture gap (OZ axis) u, mm
I VARIANT – the plate was attached directly to the bone					
500	372	212	315	64	0,32
600	447	255	378	77	0,38
700	522	297	441	90	0,45
800	596	340	504	103	0,51
900	671	383	567	115	0,58
1000*	745	425	630	128	0,64
1100	820	468	693	141	0,70
1200	894	510	756	154	0,77
1300	969	553	819	167	0,83
1400	1044	595	882	181	0,90
1500	1118	638	945	193	0,96
II VARIANT – the plate was moved away from the bones by about 5 mm					
500	277	170	178	68	0,18
600	332	204	214	81	0,22
700	388	238	250	95	0,26
800	443	272	285	109	0,30
900	499	306	321	122	0,33
1000	554	340	357	136	0,37
1100*	610	375	393	150	0,41
1200	665	409	428	163	0,45
1300	730	445	464	177	0,49
1400	776	477	500	191	0,52
1500	832	511	535	204	0,56

* Loading of the analyzed model with the force F = 1000 N for variant I and F = 1100 N in the case of variant II is the extreme value of the load for which the yield strength of Ti alloy was not exceeded.

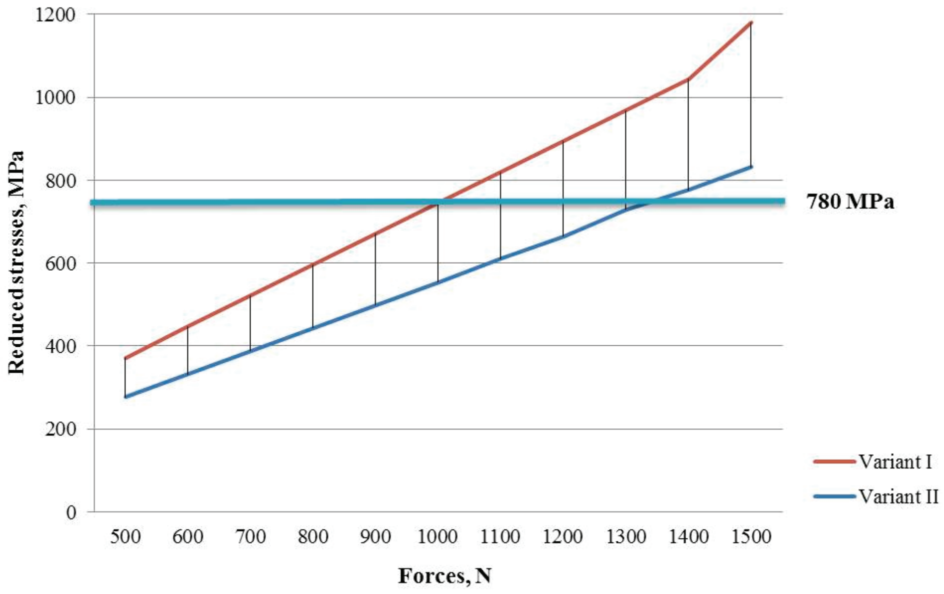

Fig. 8. The results of equivalent stresses in the plate for variant I and variant II

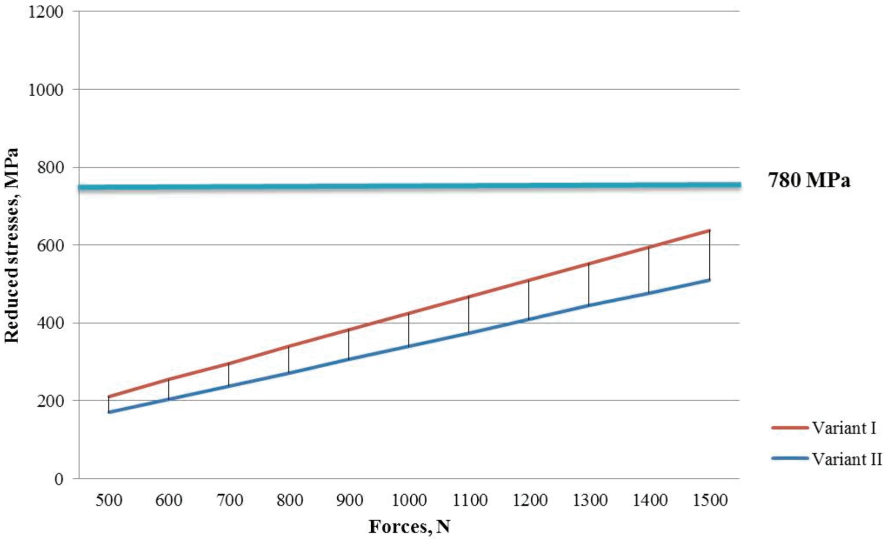

Fig. 9. The results of equivalent stresses in the screws for variant I and variant II

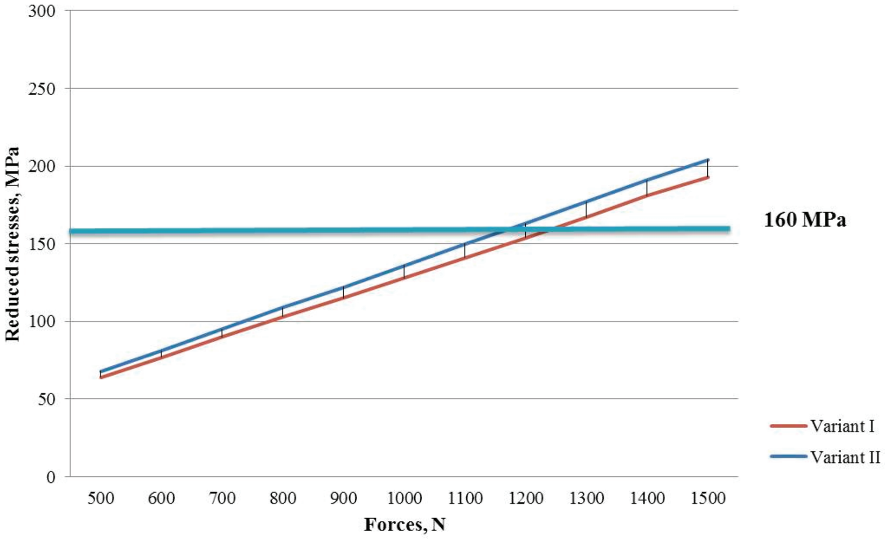

Fig. 10. The results of the analysis of the compressive strength of bone for variant I and variant II

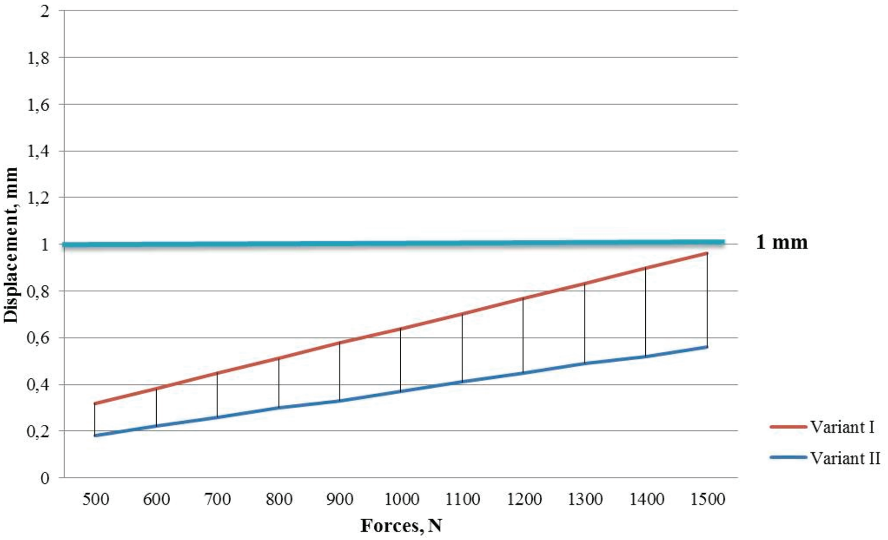

Fig. 11. Displacement in fracture gap (*OZ*) as a function of applied load for variant I and variant II

The graphs in Figs. 8 through 11 summarize the biomechanical characteristics of the bone–limited contact plate. They represent the dependence of the equivalent stress as a function of force (Figs. 8, 9 and 10) and the *OZ* axis displacement as a function of force (Fig. 11) with a fixed maximum force which can be applied to the model created.

4. Discussion

In order to determine the state of displacements and stresses in the LCP–tibia system the numerical analysis using the finite element method was performed. Based on the analysis, it was found that loading the system with the forces from the range F = 500–1500 N has created a non-uniform state of stress. The analysis showed that from the point of view of the mechanical properties of metallic material the LCP plate and analyzed bone screws are made of, the maximum force that can be loaded with the test system is $F_{\max}$ = 1000 N for variant I and $F_{\max}$ = 1100 N for variant II. This is the maximum value of the load for which the yield strength of the applied alloy ($R\mathrm{p}_{0,2}$ = 780 MPa) is not exceeded. However, from the viewpoint of the strength of the bone, the load should not exceed $F_{\max}$ = 1000 MPa. It should be noted that the numerical analysis was performed on the assumption of elastic deformation of the biomaterial and the bone. It is known that bone is in fact viscoelastic material and in contact zones, as a result of relaxation, the actual stresses and displacements are smaller.

On the basis of the analysis it was found that the implantation technique of the limited contact plates has a little impact on distribution of displacements and stresses in the plate–tibia system, in the case of a simple fracture.

Similar conclusions were reached by Ahmad et al., whose study was aimed at understanding the stability of the applied fixing fracture limited contact plate and the impact of this to increasing distance between the plate and the bone. They stated that increasing the distance of the plate to the bone by 2 mm causes greater tissue blood circulation and more stable mechanical environment at the fracture site. However, the authors in order to determine maximum values of displacement, strain and stress of experimental studies focused only on the comparison of samples subjected to cyclic compression until its destruction. They did not carry out numerical analysis in order to verify their experimental studies. They also did not take into attention such parameters as: yield strength of the plate, compressive strength of bone, and displacement in the fracture gap which should not exceed 1 mm.

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