

Three-dimensional finite element analysis of maxillary sinus floor augmentation with optimal positioning of a bone graft block

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Abstract

Purpose: The aim of the present experimental 3D-finite element study was to evaluate the influence of an augmented sinus lift with an additional inserted bone graft block. The bone graft block stabilizes the implant in addition to conventional augmented bone. We placed the block in three different positions. The implants were loaded with axial force and forces secondary to laterotrusion and protrusion.

Material and Methods: A simplified U-shaped 3D finite element model of the upper jaw and a more complex anatomical model of the left maxilla were created. The bone graft block was placed in three positions: in the lower third in contact with the sinus floor, the middle, and the upper third of the implant. Van Mises' stress distribution was calculated and analyzed for the different models. We also compared the complex anatomical model with the simplified one.

Results: The position of the bone graft block significantly influences the magnitude of stress distribution. A bone graft block positioned in the upper third or middle of the implant reduces the quantity of stress compared to the reference model without a bone graft block. The low bone graft block position is clearly associated with lower stress distribution in compact bone. We registered no significant differences in stress in compact bone with regard to laterotrusion or protrusion.

Conclusions: Maximum values of von Mises stresses in compact bone can be reduced significantly by using a bone graft block. The reduction of stress is nearly the same for positions in the upper third and the middle of the implant. It is much more pronounced when the bone graft block is in the lower third of the implant near the sinus floor, which appeared to be the best position in the present study.

Keywords: sinus lift, graft bone, finite element analysis, 3D modeling, dental implant

Introduction

Finite element (FE) analysis is an engineering and mathematical tool for structural analysis of bone morphology, implants, and load transfer in order to optimize surgical methods, design, and the fixation of implants. Recent developments in the generation of finite element models, the quality of computed tomography (CT) imaging and segmentation algorithms, faster computers, and the accuracy of finite element modeling have greatly enhanced the simulation of the individual patient's anatomy [1,2].

Successful dental implant rehabilitation of the molars in a partly edentulous or completely edentulous maxilla depends on the quantity and quality of available alveolar bone. Low bone height may result from several factors, such as alveolar bone resorption after tooth extraction, periodontal disease, pneumatization of the sinus, or sinus morphology. Conventional implant insertion may not be feasible in cases of bone thickness below 3 or 2 mm. The patients may require bone augmentation procedures. Sinus lift with elevation of the Schneiderian membrane and augmentation of the subantral space are commonly used in this setting [3, 4].

As sufficient primary stability could not be achieved in patients with alveolar bone less than 2 mm thick, we used a modified procedure in these cases. A cortical bone graft block from the retromolar region of the mandible was inserted into the sinus during sinus lift augmentation from a lateral window, using granulated autogenous/xenogeneic bone material. The bone graft block was anchored with two fixation screws (Figure 1). The latter permitted placement of the bone graft block in different positions in the sinus. The screws can be removed after four months; the screw holes serve as guidance for the insertion of dental implants. The method involves a two-step procedure: the first is augmentation while the second is the insertion of the implants after four months [5].

The procedure provides double anchorage of the implants in crestal bone and the cortical bone graft block [6, 7], thus ensuring ideal stabilization and fixation of the implants and better

integration of the implants into bone. It also minimizes loss rates during post-surgical implant healing.

The aim of the present study was to evaluate the different positions of the bone graft block with regard to the stability of the implants in the augmented maxillary sinus, using 3D-FE models. We investigated the implants in the healing phase and after osseointegration.

The results of FE analysis depend significantly on the complexity and quality of the underlying models. One of the aims of the study was to analyze whether complex anatomical models are necessary or whether simplified 3D FE models are sufficient to obtain answers to the main questions of the study. Does one need to design an anatomical model? Two models - a simplified 3D U-shaped FE model and an anatomical 3D-FE model [8] – were generated to obtain results independent of geometric irregularities. The main purpose was to determine the most suitable position of the bone graft block with regard to compact bone, load directions as simulated by central, lateral and protrusive loading, and boundary conditions with a minimum of surrounding stresses. Three different positions of the bone graft block were studied.

Material and Methods

Finite element analyses were performed using two geometric models. **M1** is a simplified U-shaped model with a compact bone thickness of 2 mm (Figure 2) while **M2** is a 3D anatomical model based on CT data (Figure 3). Each model contains a bone graft block (2.0 x 6.0 x 8.0 mm) of compact bone with surrounding bone augmentation, and an implant of 4 mm diameter and 10 mm length (titanium grade 4, blueSky 4010, Bredent Medical, Germany). Three positions of the bone graft block were used: 2.60 mm, 5.27 mm, and 7.93 mm from the implant neck.

A so-called reference model was analyzed additionally, omitting the bone graft in both geometric models (Table 1).

Contact definition

Two types of contact between the implant and compact bone were used in the simplified M1 model. First, the contact between the implant and compact bone was bonded. This contact definition is used to simulate the osseointegrated state. Second, frictional contact (as in nature) with a friction coefficient of 0.3 was employed [9]. The friction coefficient was used according to previous studies [9]; it simulates the contact of the implant after insertion, at the beginning of the osseointegration process [10,11,12].

Young's modulus for cancellous bone and bone augmentation is 1.4 GPa; Poisson's ratio μ is 0.30. For cortical bone, compact bone and bone grafts, Young's modulus is 14 GPa and Poisson's ratio $\mu = 0.30$. For titanium alloy, Young's modulus is 103.4 GPa and Poisson's ratio $\mu = 0.35$ [21].

The implant was loaded mechanically (masticatory, protrusive and laterotrusive load at abutment position), 9.0 mm away from the implant neck, at the level of crestal bone.

Loads applied on the dental implant at the end of the simplified abutment, as measured by Mericske-Stern [13] were as follows:

- $F_z = 96$ N in the z-axis representing masticatory force,
- $P_y = 36$ N in the y-axis presumed from protrusion, and
- $L_x = 13$ N in the x-axis from laterotrusion.

One load situation was defined for each load, as combinations can be easily calculated by superposition. This was done to analyze the effect of different bone graft positions on different load directions. The boundary conditions were defined as fixed supports in the cross-sectional areas of compact bone and augmentation – four surfaces in all – that constrain all vertical and translational degrees of freedom.

The software products *3-matic* (Materialise GmbH) and *SolidWorks* (Dassault Systèmes SolidWorks Corp.) were used for 3D modeling, and the *ANSYS* software (CADFEM GmbH) for FE analysis. The FE model structure was meshed with 3D continuum tetrahedron elements.

A local area net refinement around the shoulder of the implant was defined for meshing compact bone and augmentation. The number of nodes in compact bone were 41,700 in Model 1 and 88,400 in Model 2.

Results

Bone graft position

1.) Equivalent von Mises stresses for compact bone

The diagrams in Figure 4 show cumulative distribution functions plots (CDF plots) of von Mises stress distribution values in compact bone, evaluated for masticatory force F_z and protrusion load P_y for the models M1 and M2. CDF plots serve as a simple method to visualize significant shifts in distribution. Principally the stresses should be below 20 MPa because higher stresses cause resorption of the bone [24,25]. A shift of the CDF curve to the left indicates lower stresses in the augmented bone.

In comparison to Figure 4, the CDF plots for the models M1 and M2 with laterotrusion loading L_x qualitatively show the same behavior as for protrusion loading.

Model M1 – compact bone thickness 2 mm

For masticatory force F_z , the lowest bone graft block position had the lowest von Mises stress distribution. The difference between the reference model and the M1 model is notable. In addition, there is a slight difference between the center and the top bone graft block position.

The analysis with loads of protrusion P_y and laterotrusion L_x revealed no significant differences with regard to the distribution of von Mises stress in compact bone due to the position of the bone graft block. Von Mises stresses were higher for P_y and L_x (up to 56.2 MPa for P_y and 19.4 MPa for L_x) than for masticatory force F_z (max 15.3 MPa).

Model M2 – anatomical model with variable compact bone from CT data (Figure 1)

For masticatory force F_z , placing the bone graft block in the lowest position again resulted in the lowest stress distribution for compact bone. Due to the more complex and larger geometry of compact bone – resulting in more numerous elements – the difference is not as significant as it is in the M1 model.

For P_y (protrusion) and L_x (laterotrusion), we again registered non-significant differences in the distribution of von Mises stress in compact bone due to the position of the bone graft block.

Figure 5 shows representative von Mises stresses for the M2_c model (bone graft block in the center of the implant) that result from masticatory force F_z and protrusion load P_y . Maximum von Mises stresses occur in the lower part of compact bone for both loads. The stress values for F_z are approximately three times lower than those for P_y . In Figure 8 the von Mises stresses increase to 15.5 MPa for masticatory force F_z , and reach 52.8 MPa for protrusion load P_y . The differently scaled color plots in Figure 5 show a smaller red area for F_z , which signals stresses greater than 8 MPa compared to P_y , where the red area represents stresses greater than 22 MPa. The M1 and M2 models show the same trends for P_y and L_x .

2.) Strain energy in model M1 – compact bone thickness of 2 mm

Subsequent strain energy in the bone graft block, in compact bone, the augmentation, and the implant are shown in the M1 model for masticatory load F_z (Figure 6, Table 2) and for protrusion load P_y (Figure 7, Table 3). For masticatory force F_z , the strain energy of compact bone is reduced because of the bone graft block compared to the reference model. This occurs relatively independent of bone graft block position. Furthermore, a low bone graft block position reduces strain density for the implant and the augmentation to a slight extent.

For protrusion load P_y , a low bone graft position is able to reduce the strain energy of compact bone in the M1_b model while the bone graft block achieves its highest strain energy. The augmentation shows similar ranges of strain energy, independent of the position of the bone

graft block. The bone graft block and its position directly influence strain energy in compact bone for P_y in the M1 model. The implant strain energy is slightly higher in the M1 model with the bone graft block on the top, and slightly lower in the M1 model with the bone graft block below, compared to the reference model without a bone graft block. There is a slight decrease in the strain energy of the implant in the M1_t model with the bone graft block on the top compared to the M1_b model with the low bone graft block position. Figure 6 and Figure 7 show that the system turns stiffer in the presence of the bone graft block compared to the reference model for masticatory and protrusion loads F_z and P_y .

The strain energy values of M1 are shown in Table 2 and Table 3.

Consideration of the friction coefficient in contact between the implant and compact bone

In the simplified M1 model, we defined a friction coefficient between the surfaces of the implant and compact bone in order to prevent high tensile stresses in this area. Further, the stress distribution is more realistic when using this contact definition, as shown in Figure 8.

M1_f - compact bone thickness of 2 mm

The stress gradient in compact bone for F_z shows very similar behavior as it does in bonded contact. The consideration of a friction coefficient results in lower von Mises stresses in compact bone. An interesting difference is noted for P_y compared to bonded contact. In terms of bone graft block position, there is a gradual reduction of von Mises stresses starting from the reference model M1_{f_r} without a bone graft block, to the top bone graft block position, to the center position, and finally to the low position in the M1_{f_b} model. Meanwhile, no difference was observed in the M1 model with bonded contact (Figure 4).

Strain energy in the M1_f model

For masticatory force F_z , the strain energy distribution is similar in the bonded situation and under consideration of a defined friction coefficient (Figure 10). The strain energy of compact bone was reduced because of the bone graft block compared to the reference model, while different bone graft block positions did not influence the strain energy of compact bone. Furthermore, a low bone graft block position slightly reduced the strain density for the implant and the augmentation, but did not affect the strain energy of compact bone. Figure 10 shows that the system turns stiffer in the presence of the bone graft block compared to the reference model.

When P_y was applied, the overall strain energy was higher for a defined friction coefficient than it was for bonded contact (compare Figure 7 with Figure 11). In other words, for P_y the M1_f system is less stiff when using the definition of a friction coefficient. Implant deformation does not increase due to the presence of the bone graft block.

Additional information

Maximum von Mises stresses in the bone graft block and in compact bone are listed for the M1_{f_c} model in Table 4.

For masticatory force F_z , the maximum von Mises stress is considerably higher in compact bone (17.92 N/mm²) than in the bone graft (8.29 N/mm²). High stress values occur in the area of transition between the bone graft block, the augmentation, and the implant. Maximum von Mises stresses for P_y and for L_x may be regarded as local peak stress values. Neglecting the peak values results in greater von Mises stresses in compact bone (71.74 N/mm² for P_y and 25.14 N/mm² for L_x) than in the bone graft block (5.66 N/mm² for P_y and 1.79 N/mm² for L_x). Figure 12 shows equal-scaled von Mises stresses in compact bone and the bone graft block due to masticatory force F_z in the M1_{f_c} model while Figure 13 shows von Mises stresses due to

protrusion load P_y in the same model. Both figures were used to determine the values shown in Table 4 above.

Discussion

Performing implantation in areas of the maxilla with small quantities of alveolar bone requires different methods of augmentation. Sinus lift surgery is a common and proven method for this purpose [3,4]. One method of augmentation in the presence of alveolar bone heights below 3 mm, contrary to conventional lateral wall sinus floor elevation, is the introduction of an additional cortical bone graft block [5,7,14] for greater stabilization of the implant.

This study describes the influence of the position of the bone graft block in a simplified U-shaped model and an anatomical model, using different loads, with the aid of the 3D finite-element (FE) method. Cumulative distribution functions (CDF's) are used to interpret the results as well as visualize changes between distributions in the statistical analysis [5,11,15,16].

The finite element method is a common numerical stress analysis in engineering and biomechanics, used to resolve mechanical problems [1,10,13,17]. FE models with complex geometric structures can be easily modified to accommodate various assumptions. The quality of the FE model is determined by its concurrence with anatomical and natural conditions [2,11,18,19,20,21].

One of the debated principles of FE analysis in surgery is the physical properties of bone tissue. Bone tissue is an inhomogeneous material and cannot be defined as easily as titanium. Peterson et al. analyzed the physical behavior of bone tissue in the maxilla [22] by measuring and comparing different areas of the maxilla. Based on Peterson's data, a 3D constitutive law describing the macroscopic mechanical behavior of cortical and trabecular bone was defined [23]. As bone is living tissue, the alteration of its structure over time is very important [24,25,26,27]. Changing stress and strain are crucial factors in the healing process after bone fractures or surgery.

The main purpose of this study was to evaluate the ideal biomechanical position of the bone graft block on dental implants used for maxillary sinus floor elevation. Three positions of the bone graft block were used: the lower third, middle, and upper third of the implant. The position closest to compact bone resulted in the lowest von Mises stress distribution within compact bone. This behavior was observed for different model types (patient-specific anatomical model and simplified geometric model) as well as for different load directions and boundary conditions. Therefore, the bone graft block position closest to compact bone in the lower third of the implant is regarded as the best position.

The results indicated three global stress patterns: 1) Stress was highest in cortical bone, lower in the bone graft block, and lowest in the augmented bone (cancellous bone); 2) Stresses occurring at off-axial loads were higher in cortical bone and the bone graft block, and lower in augmented bone (cancellous bone) compared with axial loads; 3) High stress concentrations occur at the helical threads of the implant [28]. 4) The high von Mises stresses for protrusive load P_y occur at the outermost edges between compact bone and implant and should be reduced by adaption of the implant geometry to avoid first bone resorption and then bone-remodeling in these areas.

For masticatory force F_z , von Mises stresses within compact bone were significantly reduced when using a bone graft block compared to the reference model without a bone graft block. The reduction was approximately the same for the bone graft block position in the upper third and the middle of the implant. The reduction of stresses was very pronounced with the bone graft block in the lower third of the implant.

All three bone graft block positions showed the same distribution of accumulated strain energy in which the bone graft block supports the compact bone. This is obvious when the models with a bone graft block are compared to the reference models without a bone graft block.

For protrusive load P_y and laterotrusive load L_x , only those models with friction contact between the implant and compact bone showed significant differences in respect of von Mises stress distributions. A friction coefficient of 0.3 [9] was simulated for osseointegration as it occurs after implant insertion [12,29,30]. Duyck [10] reported no significant difference between higher friction coefficients. Specifically, the lowest position of the bone graft block resulted in the lowest stress distribution. There was no significant difference in the stress distribution of the bone graft block position in bonded contact models loaded with P_y and L_x . Even models with and without bone graft blocks showed no significant difference in regard of bonded contact. On the other hand, evaluating the strain energy of the individual parts shows that the bone graft block participates in load transfer to the greatest extent in the lower position and discharges maximum energy to compact bone by reducing its strain energy.

The 3D patient-specific anatomical model (M2) with geometric and natural irregularities from CT data is similar to the simplified U-shaped model (M1) for masticatory force F_z . Therefore, a simplified model is advisable for exploring the optimal bone graft block position in general. Complex patient-specific 3D FE models with a large number of nodes are not necessary to assess implants in the distal region of the maxilla. Simple models with fewer nodes can be analyzed and compared easily with the same outcome as anatomical models [6].

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FIGURE CAPTIONS

Figure 1. CT of the augmented left maxillary sinus with two fixing screws and the bone graft block. Blue indicates segmented compact bone; green indicates segmented augmented bone.

Figure 2. Simplified U-shaped 3D FE model M1. Bone graft block in the center of the dental implant. The different positions of the bone graft block are shown.

Figure 3. M2_c model. Left: compact bone, the implant and the bone graft in center position; right: compact bone with augmentation.

Figure 4. CDF plot of von Mises stress in compact bone for different models M1 and M2, masticatory force F_z compared to protrusion load P_y .

Figure 5. Von Mises stress in compact bone in the M2_c model with the bone graft positioned in the center; F_z (masticatory force) on the left and P_y (protrusion) on the right (augmentation as in Figure 2, but not shown here).

Figure 6. Strain energy in the M1 model, with F_z (masticatory force) applied.

Figure 7. Strain energy in the M1 model, with P_y (protrusion) applied.

Figure 8. Von Mises stress distribution in compact bone due to load P_y (protrusion), as seen from below; definitions of left bonded contact and right friction contact between the implant and compact bone.

Figure 9. CDF plot of von Mises stress in 2 mm compact bone for the M2_f model, using different frictions and loads.

Figure 10. Strain energy in the M1_f model, with friction and F_z (masticatory force) applied.

Figure 11. Strain energy in the M1_f model, with P_y (protrusion) applied.

Figure 12. M1f_c model: von Mises stresses in compact bone (left) and the bone graft (right), with F_z (masticatory force) applied.

Figure 13. M1f_c model: von Mises stresses in compact bone (left) and the bone graft (right), with P_y (protrusion) applied.

TABLE CAPTIONS

Table 1: Twelve analyzed FE models

- M1 ... 2 mm compact bone thickness
- M2 ... model from CT data with variable compact bone thickness
- t ... position: on the **top** of the bone graft block
- c ... position: in the **center** of the bone graft block
- b ... position: **below** the bone graft block
- r ... **reference** model without the bone graft block
- f ... ‘f ‘ refers to friction contact between the implant and compact bone

Table 2: Strain energy in the M2 model, with F_z (masticatory force) applied.

Table 3: Strain energy in the M2 model, with P_y (protrusion) applied.

Table 4: Maximum von Mises stresses [N/mm²]; maximum values are given in parentheses.

* ... local stress peak value

Table 1

Model (sub-question 1)	Bone graft position (main question)			Reference model (r)	Additional information
	On the top (t)	In the center (c)	Below (b)		
M1	M1_t	M1_c	M1_b	M1_r	Compact bone 2 mm (osseointegrated phase)
	M1 _f _t	M1 _f _c	M1 _f _b	M1 _f _r	Compact bone 2 mm with friction contact (healing phase)
M2	M2_t	M2_c	M2_b	M2_r	Model from CT data (osseointegrated phase)

Table 1. Twelve analyzed FE models

M1 ... 2 mm compact bone thickness
 M2 ... model based on CT data with variable compact bone thickness
 t ... **top** position of the bone graft
 c ... **center** position of the bone graft
 b ... **lower** position of the bone graft
 r ... **reference** model without a bone graft
 f ... 'f' refers to friction contact between the implant and compact bone

Table 2

	M1_r	M1_t	M1_c	M1_b	
Bone graft		0.005	0.006	0.007	mJ
Compact bone	0.054	0.046	0.045	0.044	mJ
Augmentation	0.053	0.042	0.042	0.041	mJ
Implant	0.014	0.016	0.015	0.012	mJ

Table 2. Strain energy [mJ] in the M1 model, with F_z (masticatory force) applied.

Table 3

	M1_r	M1_t	M1_c	M1_b	
Bone graft		0.001	0.002	0.006	mJ
Compact bone	0.077	0.073	0.074	0.070	mJ
Augmentation	0.027	0.020	0.021	0.023	mJ
Implant	0.090	0.094	0.090	0.083	mJ

Table 3. Strain energy [mJ] in the M1 model, with P_y (protrusion) applied.

Table 4

M1 _f _c model	$\sigma_{v,max}$ load F_z	$\sigma_{v,max}$ load P_y	$\sigma_{v,max}$ load L_x
Compact bone	11.66 (17.92*)	35.03 (71.74*)	13.79 (25.14*)
Bone graft	7.18 (8.29*)	4.80 (5.66*)	1.53* (1.79*)

Table 4. 99.9% p-fractile von Mises stresses [N/mm²]; maximum values are given in parentheses. * ... local stress peak value

Figure 1

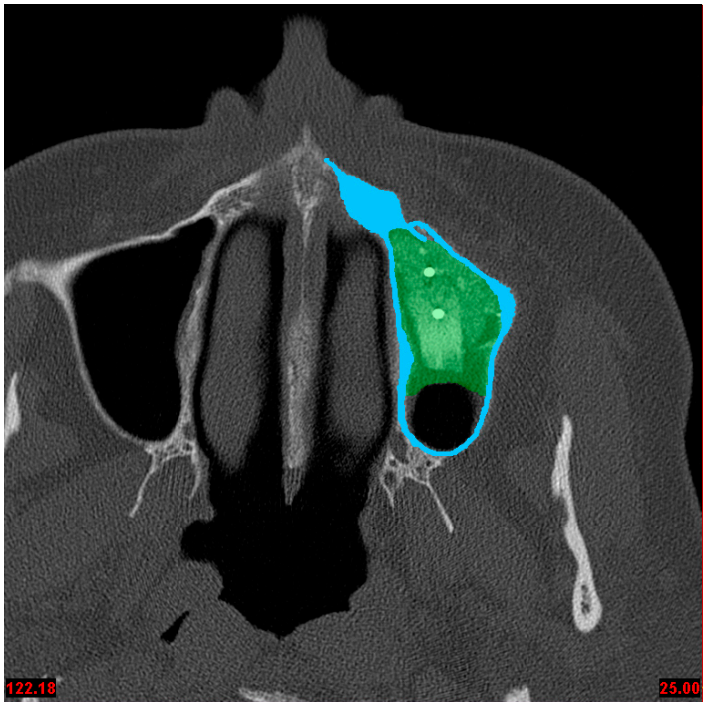


Figure 1. CT of the augmented left maxillary sinus with two fixing screws and the bone graft block. Blue indicates segmented compact bone; green indicates segmented augmented bone.

Figure 2

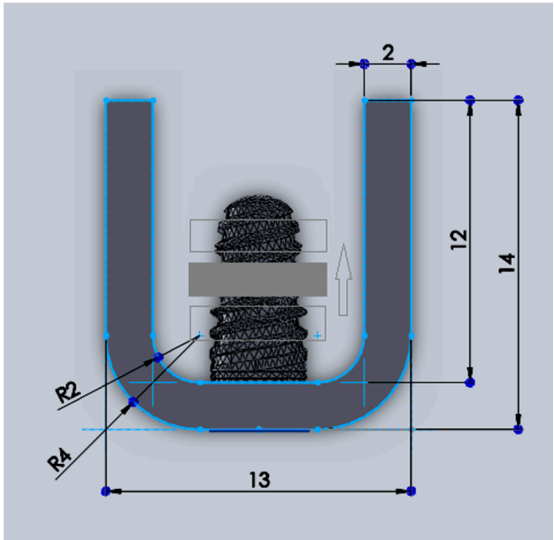


Figure 2. U-shaped 3D FE model. The bone graft block is in the center of the dental implant, M1_c model (center position of the bone graft block). The different positions of the bone graft block are shown (illustrated).

Figure 3

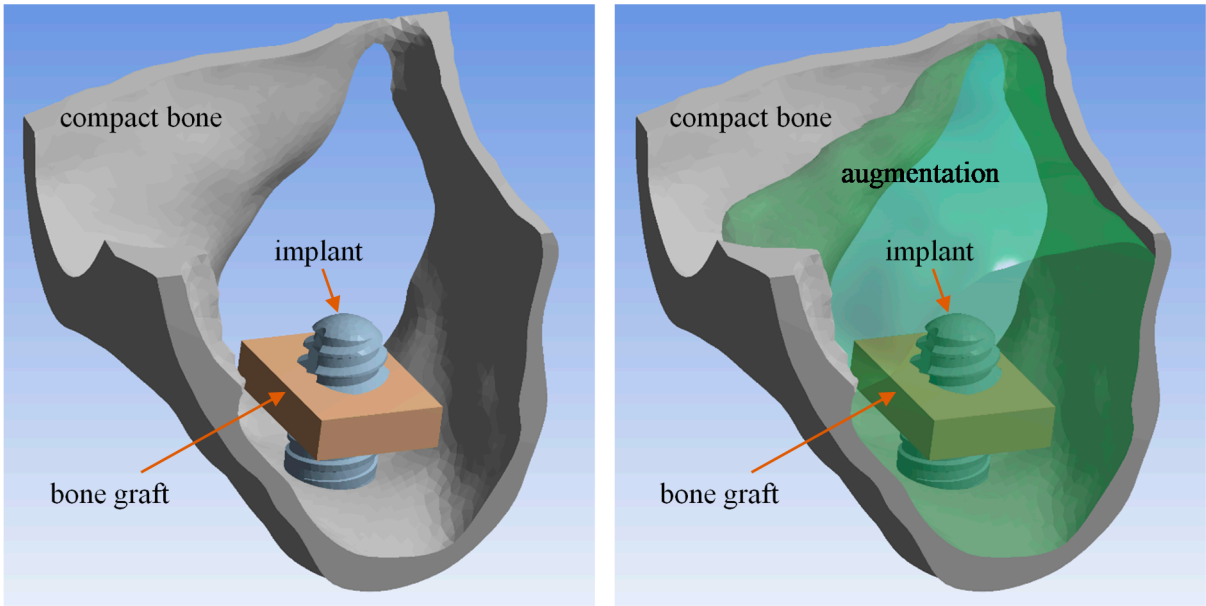
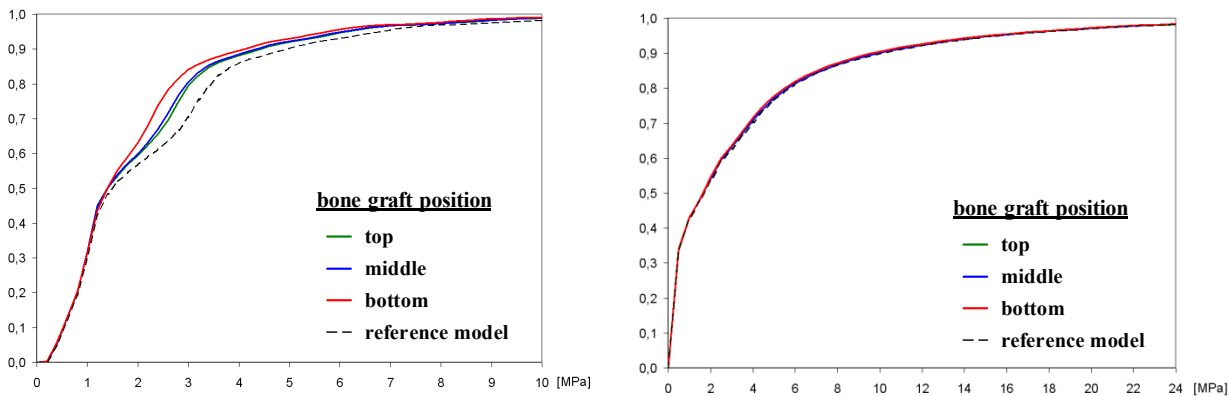


Figure 3. M2_c model – left: compact bone, the implant and the bone graft in middle position; right: compact bone with augmentation.

Figure 4



(a): Model M1, masticatory force F_z

(b): Model M1, protrusion P_y

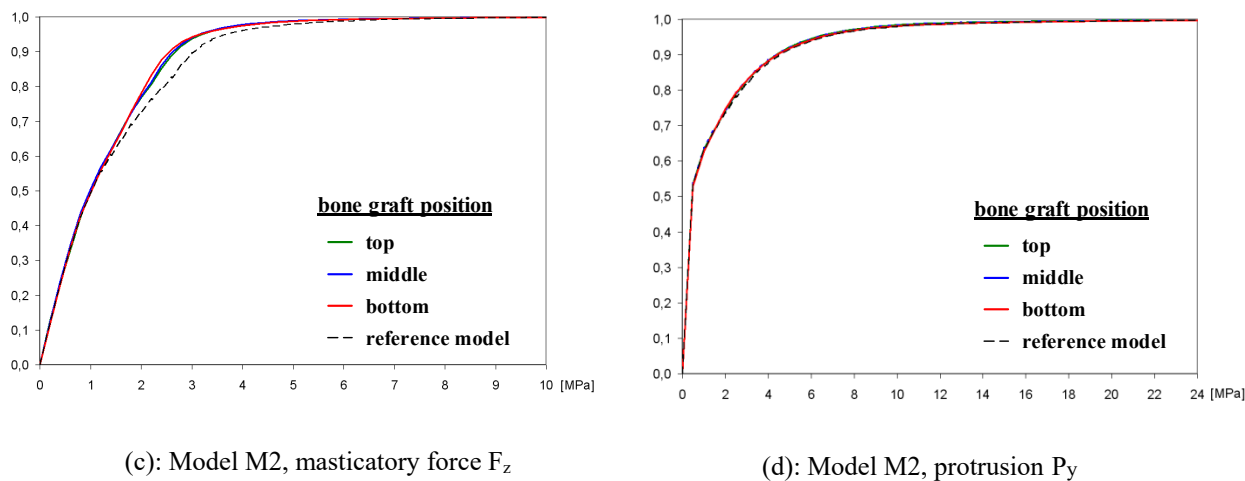


Figure 4. CDF plot of von Mises stress in compact bone for the M1 and M2 models; masticatory force F_z compared to protrusion load P_y .

Figure 5

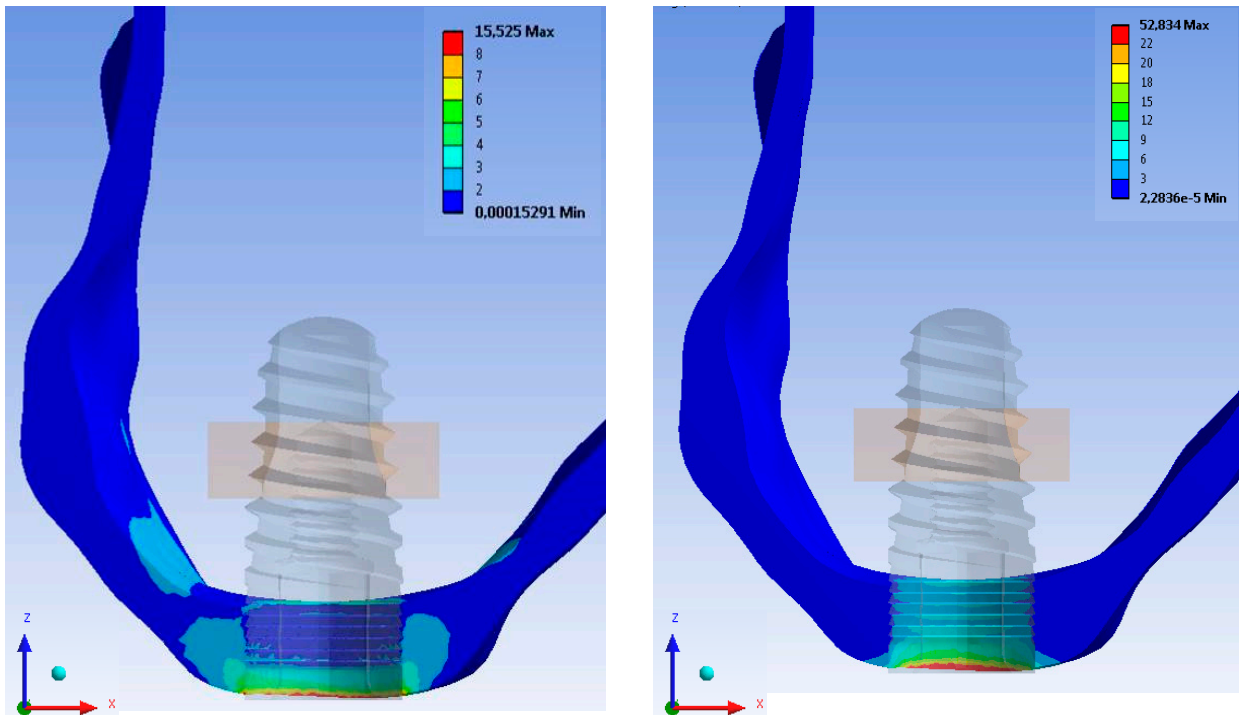


Figure 5. Von Mises stress [MPa] in compact bone in the M2_c model, with the bone graft positioned in the center; F_z (masticatory force) on the left and P_y (protrusion) on the right (augmentation as in Fig. 2, but not shown here).

Figure 6

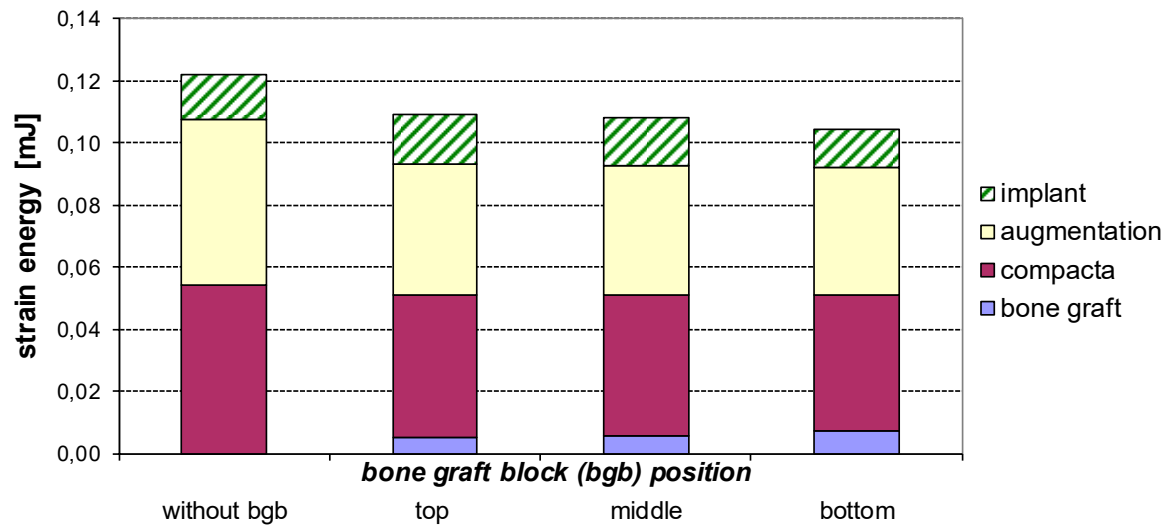


Figure 6. Strain energy in the M1 model, with F_z (masticatory force) applied.

Figure 7

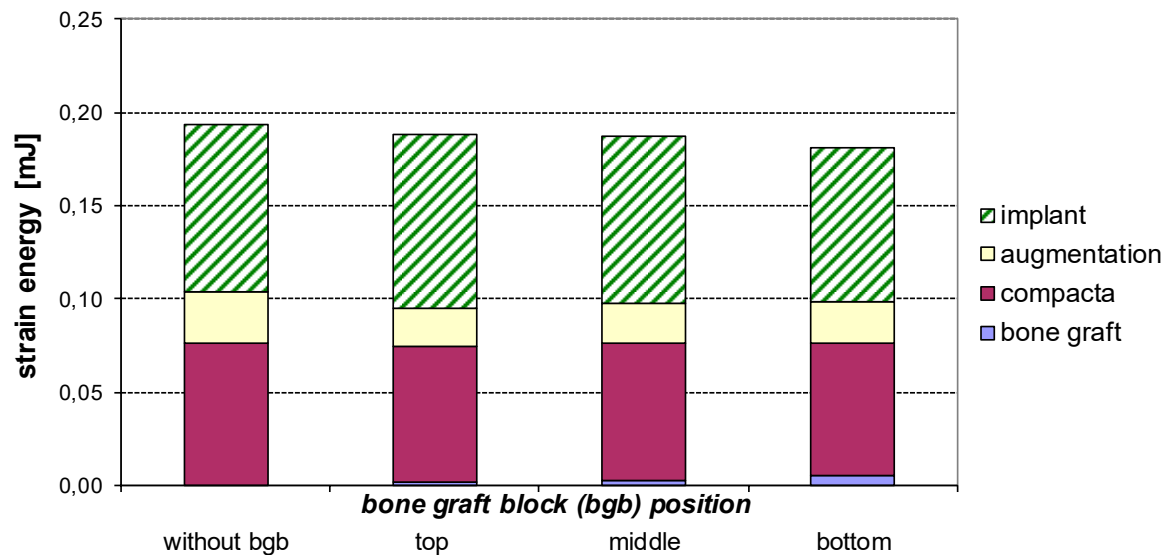


Figure 7. Strain energy in the M1 model, with P_y (protrusion) applied.

Figure 8

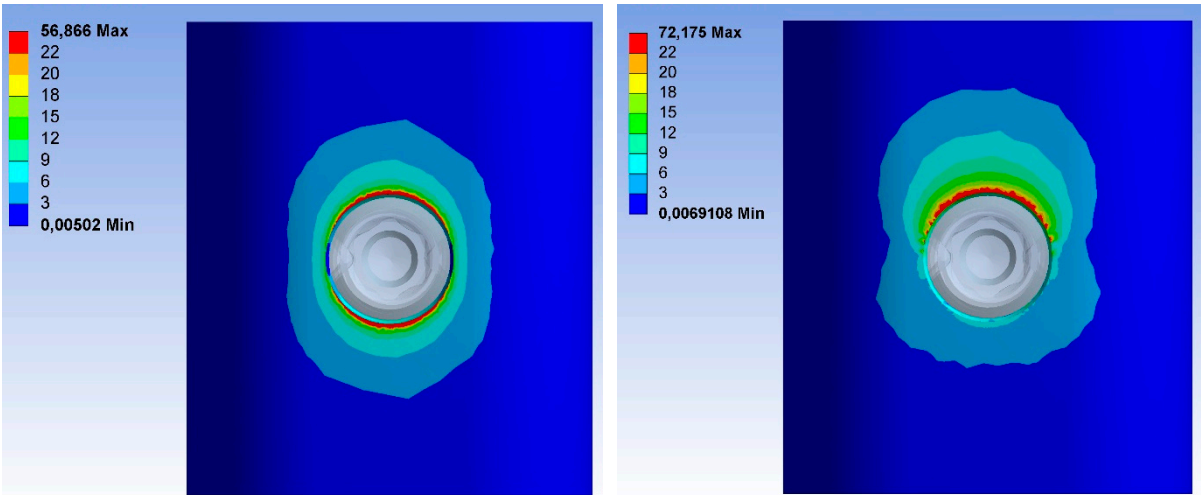
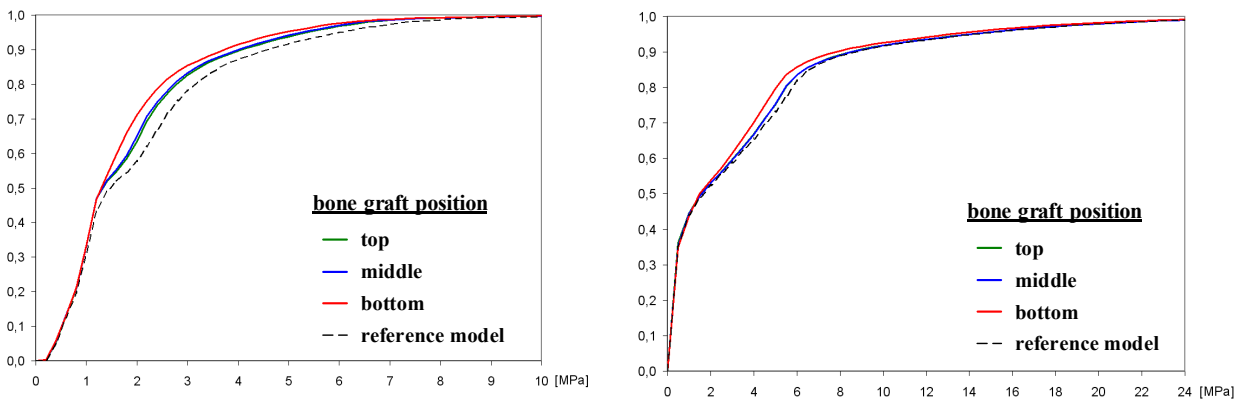


Figure 8. von Mises stress distribution [MPa] in compact bone due to load P_y (protrusion), as seen from below; left bonded contact $M1_r$ and right friction contact $M1_f_r$ between the implant and compact bone.

Figure 9



(a): $M1_f$ model with masticatory force F_z applied (b): $M1_f$ model with protrusion P_y applied

Figure 9. CDF plot of von Mises stress in 2 mm compact bone for the $M1_f$ model, with friction and different loads applied.

Figure 10

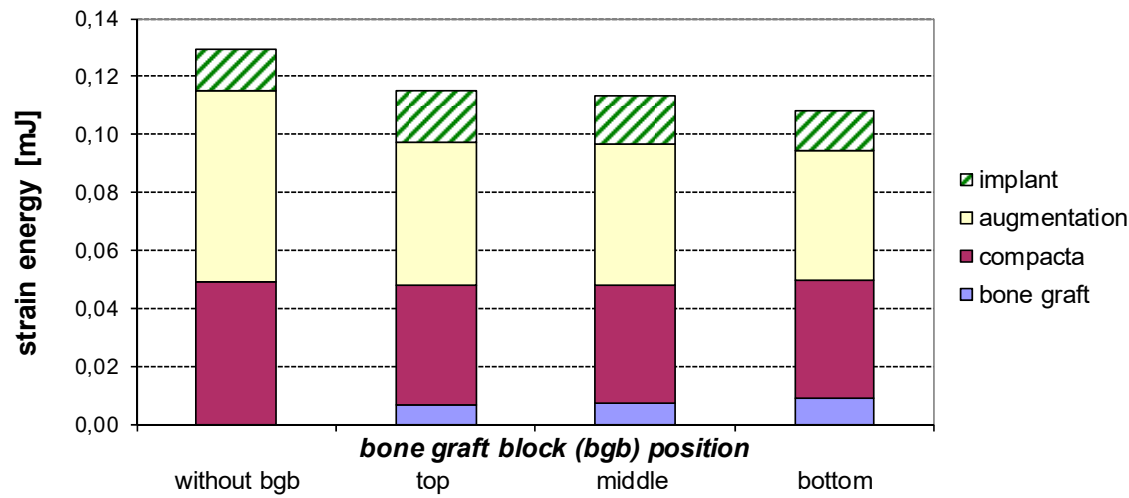


Figure 10. Strain energy in the $M1_f$ model, with friction and F_z (masticatory force) applied.

Figure 11

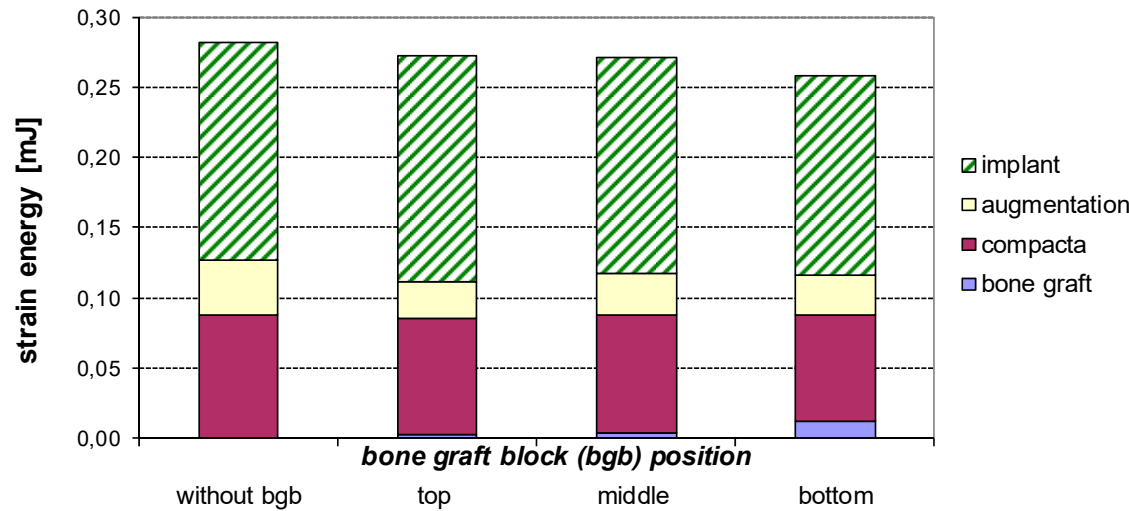


Figure 11. Strain energy in the $M1_f$ model, with P_y (protrusion) applied.

Figure 12

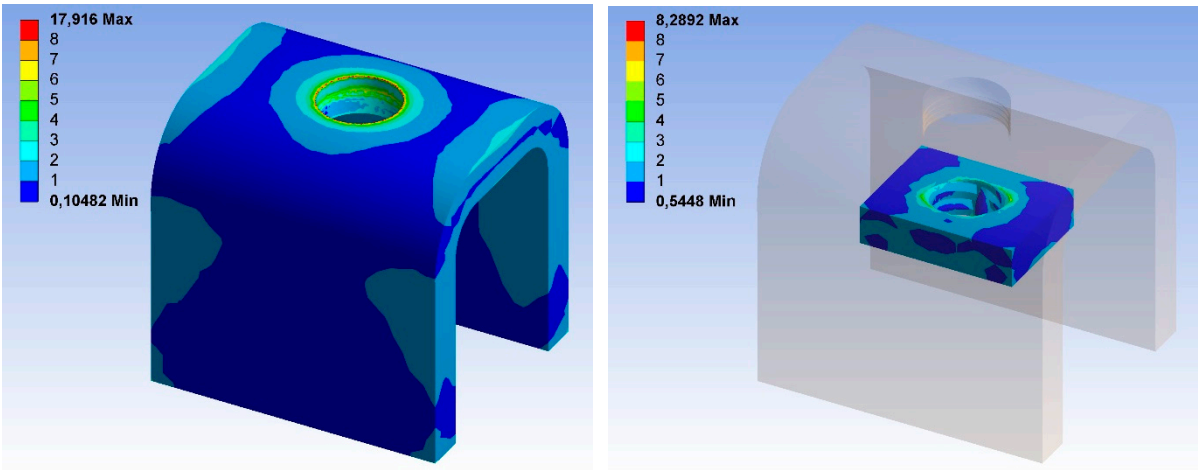


Figure 12. M1f_c model: von Mises stresses [MPa] in compact bone (left) and the bone graft (right), with F_z (masticatory force) applied.

Figure 13

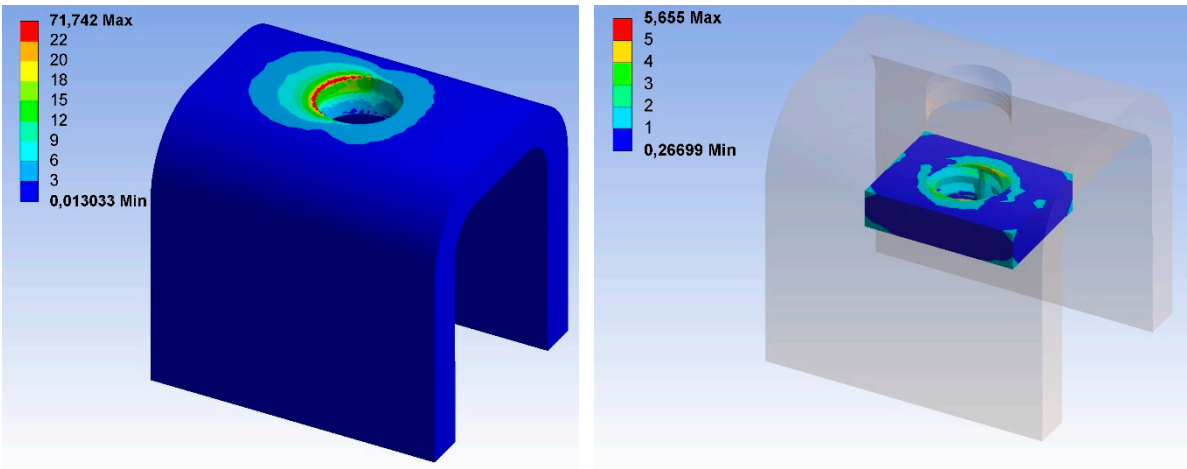


Figure 13. M1f_c model: von Mises stresses [MPa] in compact bone (left) and the bone graft (right), with P_y (protrusion) applied.