Vol. 01, Iss. 2 (2023) 92-96, DOI: 10.61552/JME.2023.02.006

Journal of Materials and Engineering

www.jme.aspur.rs

Research article

Simulation of Mechanical Processes at the Contact Region of a Dental Implant with Bone Tissues Under Shock Wave Treatment

Alexey Smolin[a,*], Galina Eremina[a], Irina Martyshina[a]

[a]*Institute of Strength Physics and Materials Science SB RAS, Tomsk, Russia.*

Keywords:

Dental implant
Contact region
Osseointegration
Bone tissue
Shock-wave therapy

* Corresponding author:

Alexey Smolin
E-mail: asmolin@ispms.ru

Received: 18 January 2023
Revised: 5 March 2023
Accepted: 18 April 2023

A B S T R A C T

Dental implants are becoming an increasingly important part of modern dental treatment. Developing an optimal implant surface design can improve osseointegration. Promising to increase the rate of osseointegration is the use of external shock wave therapy, which has proven itself for the treatment of fractures, bone defects, and bone tissue regeneration during surgery and arthroplasty. This work aims at a numerical investigation of the effects of low-energy shock wave therapy of various ranges on the mechanical behaviour of bone tissues, taking into account the physiological characteristics in the area of dental implant placement. Modelling was carried out using the method of movable cellular automata. Using computer simulation, it was found that the conditions for the regeneration of bone tissues at the near-contact zone with the implant of the jaw segment are created by a shock wave with an intensity of greater than 0.1 mJ/mm2.

1. INTRODUCTION

Dental implants are becoming an increasingly common part of modern dental treatment, with long-term success exceeding 90 %. Dental implants are most commonly placed on patients over the age of 40. The most common material for implants (or pins, the basis of a dental prosthesis) is Ti-6Al-4V titanium alloy, which provides the necessary mechanical strength. The longest and most important stage in the installation of a dental prosthesis is the osseointegration of its metal implant. Improvements in osseointegration are achieved by developing an optimal implant surface design [1, 2]. Their clinical goal is to contribute to the even greater long-term success of implantation as well as reduce the risk of complications, especially in patients with medical disorders. In addition, to accelerate the process of osseointegration and enhance its quality, non-invasive methods are currently being developed, which are divided into drug therapy and external mechanical exposure. Promising to increase the rate of osseointegration is the use of external shock wave therapy, which has proven itself for the treatment of fractures, bone defects, and bone tissue regeneration during surgery and arthroplasty [3]. The interface zone of the implant with the bone should have a highly porous structure or a rough surface to allow the bone tissue to grow into the implant material. According to experimental data, the mechanical response of the surrounding biological tissues to the applied load largely depends on the design and physical and mechanical properties of the interface zone.

This work aims at a numerical investigation of the effects of low-energy shock wave therapy on the mechanical behaviour of bone tissues in the area of dental implants. For this purpose, a numerical model of the jaw segment in the area of the tooth with the implant was developed.

2. METHODS AND MODELS

2.1 Method of movable cellular automata

The need to vary the characteristic loading rates over a wide range and the need to take into account the fracture of solid-phase components determined the choice of computer simulation by the particle method as the main method for development of the numerical model. Namely, we used the method of movable cellular automata (MCA). This is an efficient, discrete method for modelling the mechanical behaviour of heterogeneous materials. It has been established that such methods have demonstrated themselves extremely well for modelling the mechanical behaviour of biomaterials and metals under dynamic loading at micro- and mesoscales [4-7]. In MCA, the simulated material is represented as a packing of cellular automata (discrete elements of the same size) interacting with neighbours according to certain rules, which makes it possible to describe its mechanical behaviour as that of an isotropic elastic–plastic body within the framework of the particle approach. The translations and rotations of automata are governed by the Newton-Euler equations. The main advantages of this method are the possibility of explicitly taking into account a complex hierarchical structure, modelling the failure of the material, and the possibility of implicitly taking into account the fluid in the internal pores and channels. The interstitial fluid is taken into account by dividing the problem to be solved into two sub-problems: 1) description of the mechanical behaviour of the solid matrix; 2) description of the fluid transfer in a porous solid matrix [6]. The solid matrix contains a system of interconnected channels and pores, which are implicitly taken into account. The description of the influence of the interstitial fluid on the stress state of the medium is carried out on the basis of the Biot linear model of poroelasticity. In addition, the possibilities of the MCA software allow modelling complex objects with real geometric parameters.

2.2 Model of jaw segment in tooth area at prosthetics

At the first stage, a simplified numerical model of the jaw in the region of chewing teeth was built, which is depicted in Fig. 1. We used a real CAD solid model only for the implant; it was converted to STL format, which was then imported into the pre-processor of the software package that implements the MCA method (see the central green part in Fig. 1). All other components of the model were assumed to be of cylindrical shape (in Fig. 1,a only a half of their real geometry is shown in semi-transparent mode).

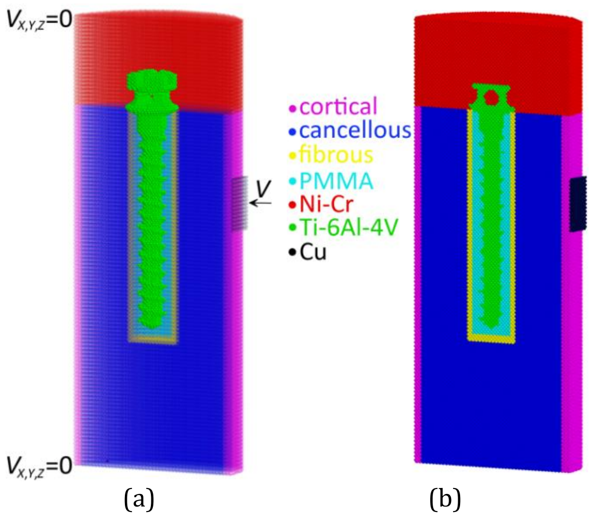

Fig. 1. A half of the model of the jaw segment with an implant shown as a packing of automata with loading conditions (a) and the model cross-section with list of materials (b).

In particular, the implant was covered by bone cement (PMMA), which, in turn, was covered by a thin layer of fibrous tissue. The main part of the model was a cylinder of cancellous bone tissue (shown in blue in Fig. 1) covered by a thin layer of cortical bone tissue. The upper part of the model (shown in red in Fig. 1) mimicked the crown of the dental prosthesis made of Ni-Cr alloy, which was rigidly connected to the implant.

To simulate shock wave exposure on the jaw segment, the applicator was introduced to the model as a thin, square copper plate measuring 5×5 mm in size and was located in the gum area (black plate in Fig. 1). The velocity V of the automata of the applicator was changed in time according to the specified energy flux density (EFD) of the shock wave (see [7] for the detailed description of the loading velocity computation). The upper and bottom layers of the automata were fixed (their velocities were kept to be zero).

The poroelastic model of biological tissues and bone cement was characterised by the following parameters: density of matrix (ρ_m), shear modulus of matrix (G_m), bulk modulus of matrix (K_m), porosity (φ), and permeability (k). The properties of biological tissues and bone cement are presented in Table 1 and correspond to the data found in the literature [8-11]. The biological fluid inside the tissues in this model had the properties of salt water with the bulk modulus K_f = 2.4 GPa, the density ρ_f = 1000 kg/m³, the viscosity η_f = 1 mPa·s [9].

Table 1. Mechanical properties of biomaterials.

Tissue (material)	ρ_m, kg/m³	G_m, GPa	K_m, GPa	φ	k, m²
cortical	1850	5.5	14.0	0.04	3.6 10^{-15}
cancellous	700	3.3	1.32	0.7	1.0 10^{-11}
fibrous	800	2.3	1.12	0.8	1.0 10^{-11}
PMMA	1000	2.3	1.87	0.1	1.0 10^{-12}

Table 2. Mechanical properties of the metal parts.

Material	ρ, kg/m³	G, GPa	K, GPa
Ni-Cr	8400	76.0	167
Ti-6Al-4V	4500	41.0	100
Copper	8950	41.6	115

The elastic model of the mechanical behaviour of the Ni-Cr alloy, titanium alloy Ti-6Al-4V, and copper was characterised by the following parameters: density (ρ), shear modulus (G), bulk modulus (K); their values are presented in Table 2 and correspond to the data available in the literature [12-14].

3. RESULTS

In the works [15,16], it was shown that the regenerative effect of shock wave therapy on bone remodelling around the tooth is observed at an exposure with the energy flux density of 0.1 mJ/mm². Therefore, herein, we studied the low-intensity acoustic effect of the shock wave with the following values of EFD: 0.025, 0.1, 0.2, and 0.3 mJ/mm².

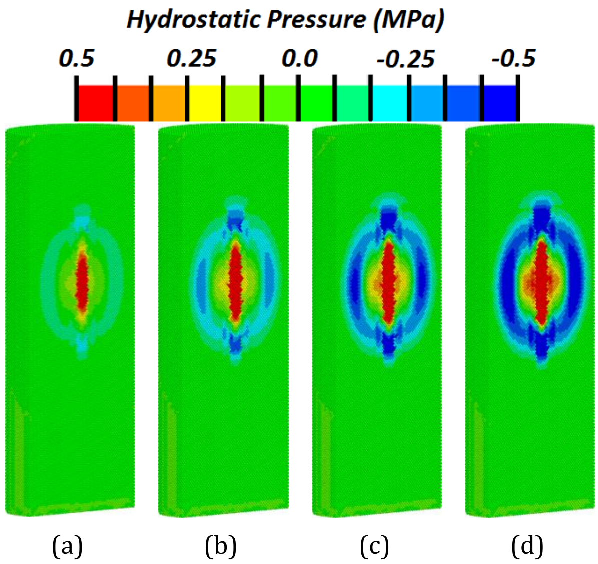

Fig. 2. Fields of hydrostatic pressure (MPa) at SW exposure with different EFD (mJ/mm²): 0.025 (a), 0.1 (b), 0.2 (c), 0.3 (d).

Under shock-wave loading of the model sample, along the implant in the near-contact area in the cement layer, tensile stresses with magnitudes in the range of 0.15 to 0.7 MPa were observed at an EFD value of 0.025 mJ/mm² (Fig. 2, a). With an increase in the energy flux density, an increase in the area of tensile stresses was observed. In the fibrous layer, tensile stresses with a magnitude of up to 0.2 MPa were observed. Compressive stresses ranging from 0.05 to 0.2 MPa were observed in the bone tissue in the contact area (Fig. 2, b, c). However, when loading at an EFD value of 0.3 mJ/mm² (Fig. 2, d), in the cancellous tissue near the contact zone, stresses above 5 MPa were observed, which, in the case of age-related changes in the bone tissue of the jaw, can lead to its resorption. Such a level of tensile stresses promotes the ingrowth of fibrous tissue into the cement material, differentiation and growth of fibrocartilage tissue in the fibrous layer, and the magnitude of compressive stresses contributes to the regeneration of bone tissue according to mechanobiological principles [17-18].

Analysis of distribution of fluid pressure in pores (Fig. 3) allowed to reveal that in local areas around the implant, the necessary level (more than 30 kPa) was reached to start the processes of bone tissue regeneration under SW with an energy flux density of more than 0.025 mJ/mm^2 (Fig. 3, a). However, the optimal level for the transfer of biological cells was observed at a level of SW exposure greater than 0.1 mJ/mm^2 (Fig. 3, b, c, d).

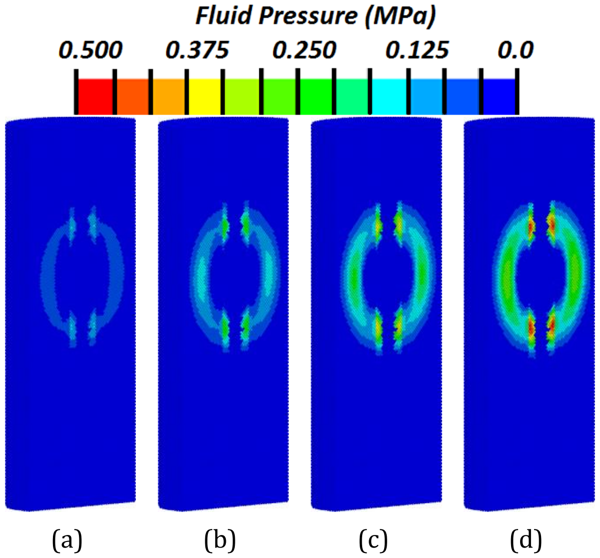

Fig. 3. Fields of fluid pressure (MPa) at SW exposure with different EFD (mJ/mm^2): 0.025 (a), 0.1 (b), 0.2 (c), 0.3 (d).

4. CONCLUSION

This paper presents a numerical model of shock wave exposure from a single source on the jaw segment with the dental implant. For the first time, with the help of computer simulations in a wide range, studies were carried out on the therapeutic effect of the shock wave exposure on the jaw segment.

Analysis of the distribution of hydrostatic pressure and fluid pressure showed that for tissue regeneration in the near-contact area with an implant in the case of endoprosthesis replacement of chewing teeth, it is necessary to apply shock wave exposure with energy flux density in the range of 0.025 to 0.2 mJ/mm^2.

Acknowledgement

The investigation has been carried out with the financial support of the Russian Science Foundation, grant No. 23-29-00212.

REFERENCES

[1] J.S. Colombo, S. Satoshi, J. Okazaki, S.J. Crean, A.J. Sloan, R.J. Waddington, "In vivo monitoring of the bone healing process around different titanium alloy implant surfaces placed into fresh extraction sockets," *Dental*, vol. 40, no. 4, pp. 338-346, 2012.

[2] C.P. Hao, N.J. Cao, Y.H. Zhu, W. Wang, "The osseointegration and stability of dental implants with different surface treatments in animal models: a network meta-analysis," *Scientific Reports*, vol. 11, pp. 13849, 2021.

[3] W.P. Song, X.H. Ma, Y.X. Sun, L. Zhang, Y. Yao, X.Y. Hao, J.Y. Zeng, "Extracorporeal shock wave therapy (ESWT) may be helpful in the osseointegration of dental implants: A hypothesis," *Medical Hypotheses*, vol. 145, pp. 110294, 2020.

[4] E.V. Shilko, A.S. Grigoriev, A.Yu. Smolin, "A discrete element formalism for modelling wear particle formation in contact between sliding metals," *Facta Universitatis Series: Mechanical Engineering*, vol. 19, pp. 7-22, 2021.

[5] S.G. Psakhie, A.V. Dimaki, E.V. Shilko, S.V. Astafurov, "A coupled discrete element-finite difference approach for modeling mechanical response of fluid-saturated porous materials," *International Journal for Numerical Methods in Engineering*, vol. 106, pp. 623-643, 2016.

[6] G.M. Eremina, A.Yu. Smolin, "Risk assessment of resurfacing implant loosening and femur fracture under low-energy impacts taking into account degenerative changes in bone tissues. Computer simulation," *Computer Methods and Programs in Biomedicine*, vol. 200, pp. 105929, 2021.

[7] G.M. Eremina, A.Yu. Smolin, "Numerical study of the mechanical behavior of the hip joint under therapeutic acoustic impact," *Russian Journal of Biomechanics*, vol. 1, pp. 32-45, 2023.

[8] D.R. Carter, W.C. Hayes, "The compressive behavior of bone as a two-phase porous structure," *The Journal of Bone & Joint Surgery*, vol. 59, no. 7, pp. 954–962, 1977.

[9] S.C. Cowin, S.B. Doty, *Tissue Mechanics*, Spriger, New York, 2007.

[10] K.A. Mann, M.A. Miller, "Fluid-structure interactions in micro-interlocked regions of the cement-bone interface," *Computer Methods in Biomechanics and Biomedical Engineering*, vol. 17, no. 16, pp. 1809-1820, 2014.

[11] G. Lewis, "Properties of acrylic bone cement: State of the art review," *Journal of Biomedical Materials Research*, vol. 38, pp. 155–188, 1977.

[12] Starbond Ni, available at: https://scheftner.dental/starbond-ni-en.html, accessed: 14.04.2023.

[13] P. Krakhmalev, G. Fredriksson, I. Yadroitsava, N. Kazantseva, A. du Plessis, I Yadroitsev, "Deformation behavior and microstructure of Ti6Al4V manufactured by SLM," *Physics Procedia*, vol. 83, pp. 778-788, 2016.

[14] J. He, Z. Zeng, H. Li, S.T. Wang, "The microstructure and mechanical properties of copper in electrically assisted tension," *Materials & Design*, vol. 196, pp. 109171, 2020.

[15] S. Sathishkumar, A. Meka, D. Dawson, N. House, W. Schaden, M.J. Novak, J.L. Ebersole, L. Kesavalu, "Extracorporeal shock wave therapy induces alveolar bone regeneration," *Journal of Dental Research*, vol. 87, no. 7, pp. 687-691, 2008.

[16] H. Hazan-Molina, Y. Gabet, I. Aizenbud, N. Aizenbud, D. Aizenbud, "Orthodontic force and extracorporeal shock wave therapy: Assessment of orthodontic tooth movement and bone morphometry in a rat model," *Archives of Oral Biology*, vol. 134, pp. 105327, 2022.

[17] N.J. Giori, L. Ryd, D.R. Carter, "Mechanical influences on tissue differentiation at bone-cement interfaces," *Journal of Arthroplasty*, vol. 10, no. 4, pp. 514-522, 1995.

[18] M. Wang, N. Yang, X. Wang, "A review of computational models of bone fracture healing," *Medical & Biological Engineering & Computing*, vol. 55, no. 11, pp. 1895-1914, 2017.