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Influence of composition and surface roughness of titanium alloys on vital activity of mesenchymal stem cells

M. A. Sudarchikova[1] ✉, E. O. Nasakina[1], G. A. Davydova[2], L. R. Valiullin[3], Ya. A. Morozova[1], S. Yu. Kottsov[4], P. A. Prokofiev[1], S. V. Konushkin[1], K. V. Sergienko[1], M. A.Sevostyanov[1], A. G. Kolmakov[1]

[1] **Baykov Institute of Metallurgy and Materials Science, Russian Academy of Sciences**
49 Leninskiy Prosp., Moscow 119334, Russia
[2] **Institute of Theoretical and Experimental Biophysics, Russian Academy of Sciences**
3 Institutskaya Str., Pushchino, Moscow region 142290, Russia
[3] **Federal Center for Toxicological, Radiation and Biological Safety**
2 Nauchny Town, Kazan, Republic of Tatarstan 420075, Russia
[4] **Kurnakov Institute of General and Inorganic Chemistry, Russian Academy of Sciences**
31 Leninskiy Prosp., Moscow 119071, Russia

✉ mariahsudar@yandex.ru

Abstract. The study focused on titanium-based alloys for medical applications, including commercially available grades VT1-0 and VT6, and a newly developed alloy with the composition (wt. %): Ti–23Nb–5Zr. The surfaces of all samples underwent sandblasting using six different sand fractions, mechanical grinding, polishing by tumbling, tumbling polishing, and, in the case of the Ti–Nb–Zr alloy, electrolytic plasma polishing. The effects of surface treatment methods and the chemical composition of medical-grade titanium alloys on surface roughness, microhardness, wettability, and interaction with mesenchymal stem cells (MSCs) was investigated. Surface microhardness was measured using the micro-Vickers method with a diamond indenter under varying loads, while surface roughness was determined using a contact profilometer. It was found that electrolytic plasma polishing enhanced both the microhardness and roughness of the alloy compared to tumbling polishing. Wettability was characterized by the contact angle of deionized water, measured using a specialized setup, with the droplet shape described by a 5-point ellipse model. All treated surfaces exhibited wettability; the contact angle increased as surface roughness decreased. However, sandblasting with mixtures containing a wide particle size distribution increased the contact angle due to the more complex surface relief. To evaluate the biological properties of implants made from VT6, VT1-0, and Ti–23Nb–5Zr alloys after the described surface treatments, their effects on cell viability and the adhesive characteristics of the materials were studied using a direct contact method with two types of mesenchymal stem cells. The newly developed alloy, which potentially offers superior biomechanical compatibility compared to commercial materials, demonstrated no compromise in surface characteristics or adverse effects on cell viability.

Keywords: titanium alloys, medical-grade alloys, surface microhardness, surface roughness, surface wettability, mesenchymal stem cells (MSCs)

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Влияние состава и шероховатости поверхности титановых сплавов на жизнедеятельность мезенхимальных стволовых клеток

М. А. Сударчикова[1], Е. О. Насакина[1], Г. А. Давыдова[2], Л. Р. Валиуллин[3], Я. А. Морозова[1], С. Ю. Котцов[4], П. А. Прокофьев[1], С. В. Конушкин[1], К. В. Сергиенко[1], М. А. Севостьянов[1], А. Г. Колмаков[1]

[1] **Институт металлургии и материаловедения им. А. А. Байкова Российской академии наук**
Россия, 119334, г. Москва, Ленинский пр-т, 49
[2] **Институт теоретической и экспериментальной биофизики Российской академии наук**
Россия, 142290, Московская обл., г. Пущино, ул. Институтская, 3
[3] **Федеральный центр токсикологической, радиационной и биологической безопасности**
Россия, 420075, Республика Татарстан, г. Казань, г-к Научный, 2
[4] **Институт общей и неорганической химии имени Н.С. Курнакова Российской академии наук**
Россия, 119071, г. Москва, Ленинский пр-т, 31

mariahsudar@yandex.ru

Аннотация. В работе исследовались сплавы на основе титана медицинского назначения: коммерческие марки ВТ1-0, ВТ6 и разрабатываемый сплав, мас. %: Ti–23Nb–5Zr. Поверхности всех образцов подвергались струйной обработке с применением 6 видов различных фракций песка, механической шлифовке и полировке методом галтовки, а также, дополнительно, электролитно-плазменной полировке (для сплава системы Ti–Nb–Zr). Исследовалось влияние метода поверхностной обработки титановых сплавов медицинского назначения и их химического состава на шероховатость, микротвердость, смачиваемость поверхности и ее взаимодействие с мезенхимальными стволовыми клетками. Микротвердость поверхности определялась по схеме «микро-Виккерс» с применением алмазного индентора при различной нагрузке. Измерения шероховатости поверхности проводились с помощью контактного профилометра. Отмечено, что электролитно-плазменная полировка повышает микротвердость и шероховатость поверхности сплава по сравнению с галтовкой. Краевой угол смачивания образцов деионизированной водой измерялся при помощи специальной установки. При этом форма капли описывалась моделью эллипса по 5 точкам. Установлено, что все созданные поверхности смачиваемы, угол смачивания возрастает с понижением шероховатости поверхности, однако струйная обработка смесями с широким разбросом частиц по размеру приводит к его повышению за счет усложнения рельефа поверхности. Для изучения биологических свойств имплантатов из сплавов ВТ6, ВТ1-0 и Ti–23Nb–5Zr после указанных видов поверхностной обработки, а также их влияния на выживаемость клеток и адгезивные характеристики материалов использовался метод прямого контакта с двумя типами мезенхимальных стволовых клеток. Разрабатываемый сплав, потенциально обладающий лучшей биомеханической совместимостью, чем коммерческие, не вызвал ухудшения поверхностных характеристик и отрицательно не повлиял на жизнедеятельность клеток.

Ключевые слова: титановые сплавы, сплавы медицинского назначения, микротвердость поверхности, шероховатость поверхности, смачиваемость поверхности, мезенхимальные стволовые клетки (МСК)

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Introduction

Biomaterials, designed for contact with the living organism's environment, are commonly used for manufacturing implants. These materials ensure compatibility with medical devices through a combination of properties such as superelasticity, low Young's modulus, high corrosion resistance, and either bioinertness or adhesiveness [1–3]. Typically, these include metallic alloys (titanium, cobalt, stainless steels), polymers, and ceramics. However, they exhibit certain drawbacks, such as low strength and/or high elastic modulus, which ultimately lead to the degradation of both the implants and surrounding tissues [4–8]. Besides organizational factors (e.g., small-scale production), the manufacturing of titanium-based products is constrained by technological challenges. One such issue is the mechanical strength and fatigue pro-

perties of titanium alloy blanks, which, however, can be addressed by developing methods for surface structure modification and optimizing alloy composition.

Shape memory alloys, particularly those in the Ti–Ni system, exhibit low Young's modulus and superelastic behavior, akin to that of living tissues [9–11]. However, the toxic properties of nickel and the potential for corrosion-related damage (material degradation in operating environments) limit their application [12–14].

At the same time, modern research indicates that shape memory and superelastic effects can also be observed in alloys composed exclusively of non-toxic metals [15–23]. For instance, tantalum [24] and niobium [17; 25–27], which exhibit high corrosion resistance and biocompatibility, can be employed as β-stabilizers in titanium alloys, thereby contributing to a reduction in the elastic modulus. In particular, research [23] has demonstrated that the Ti–Nb–Ta alloy has a lower elastic modulus and higher corrosion resistance compared to the Ti–6Al–4V alloy. Zirconium is typically used as a neutral strengthening element [28–31]; however, as reported by the authors of [20], it may also exhibit β-stabilizing effects in β-titanium alloys. Furthermore, titanium and niobium have similar atomic radii (0.145–0.146 nm), whereas zirconium has a slightly larger atomic radius (0.160 nm). Thus, alloying titanium with zirconium is expected to increase the interatomic distance in the alloy, reduce the bonding force between atoms, and consequently lower the Young's modulus. Conversely, alloying titanium with niobium is expected to at least maintain the lattice parameter of the β-phase.

Therefore, Ti–Nb–Zr alloys can be considered excellent candidates for biomedical applications involving implantation.

Mesenchymal stem cells (MSCs) are an optimal test system for analyzing the biological activity of materials intended for implant fabrication, as they possess a high potential for differentiation into cellular elements of various mesenchymal-derived tissues [32].

The interaction of any material with cells is largely influenced by the quality of its surface. Therefore, the aim of this study was to investigate the interaction of the Ti–Nb–Zr alloy, following various surface treatments, with mesenchymal stem cells in comparison with materials already used in medical applications.

Materials and methods

Samples for the study were fabricated from the following titanium-based biomedical materials:

– commercially available material VT1-0 (pure titanium), as per GOST 19807-91;

– commercially available alloy VT6 (titanium alloy with aluminum and vanadium), as per GOST 19807-91;

– a newly developed titanium-based alloy with the composition (at. %): Ti–23Nb–5Zr.

The starting materials used included iodide titanium, niobium grade Nb-1, and iodide zirconium. Alloy ingots were melted in an argon-arc melting furnace with a non-consumable tungsten electrode. To produce sheets, the ingots underwent homogenizing annealing in a vacuum, followed by warm rolling with intermediate annealing and subsequent quenching.

The Young's modulus of the Ti–23Nb–5Zr alloy sheet samples was determined using a universal testing machine, INSTRON 3382 (USA), at room temperature.

The interaction of any material with cells depends significantly on the quality of its surface; hence, several surface treatment options were selected for evaluation. Samples of the VT1-0, VT6, and Ti–23Nb–5Zr alloys, with a diameter of 20 mm and thickness of 4 mm, were cut from sheets using a DK 7745 ME11 electrical discharge machine by Meatec (China). Before sandblasting, the samples were pre-ground using abrasive papers with grit sizes ranging from 240 to 600 and treated by tumbling in a KT-100 electromagnetic tumbling machine (CARLO de GIORGI, Italy) with a metallic needle abrasive. Additionally, some samples were subjected to electrolytic plasma polishing (EPP) in a 5 % aqueous solution of a 20 % NH_4F + 80 % KF mixture at a voltage of 300 V and a temperature of 85–88 °C for 10 min. The sandblasting of sample surfaces was conducted in a 90 L chamber under 12 atm of high-purity argon pressure using copper slag (particle sizes ≤0.63 mm) and sand fractions of 0.63–1.0 mm, 1.0–1.5 mm, and 0.63–1.5 mm, as well as their 1:1 mixture (0.63–1.5 mm). For the treated surfaces, characteristics such as roughness and wettability were determined.

Surface roughness was evaluated according to GOST 25142-82 using a Proton profilometer model 130 (Russia). Prior to measurement, all samples were cleaned in an ultrasonic bath with a specialized soap solution, bidistilled water, and alcohol, then carefully dried.

Surface microhardness (*HV*) was determined using the micro-Vickers method as per GOST 9450-76 with a 401/402-MVD device (Wolpert Group, Germany) equipped with an optical microscope. A diamond indenter with a tip size of 10 μm and test loads of 25, 100, 300, and 500 g were used.

The wettability of the samples was characterized by the contact angle of deionized water, measured using a Lonroy SDC-350 setup (Dongguan Lonroy

Equipment Co., LTD, China) at a tilt angle of 0°. A droplet with a volume of 6 μL was deposited on the sample, and an image of the droplet was taken 60 s later. When measuring the contact angle, the droplet shape was analyzed after a delay following its contact with the substrate. This delay helps eliminate dynamic effects that could distort the shape of the elastic droplet immediately upon impact with the sample. Typically, the waiting time before droplet shape analysis is 30–60 s after the start of the measurement [33–35]. When calculating the contact angle, the droplet shape was described using a 5-point ellipse model.

To evaluate the biological properties of implants made from VT6, VT1-0, and Ti–23Nb–5Zr alloys following the described surface treatments, as well as the effect of the samples on cell viability and the adhesive characteristics of the materials, a direct contact method was employed using two types of mesenchymal stem cells (MSCs): dental pulp stem cells (DPSCs) from human dental pulp (clone Th44), and immortalized fibroblast-like cells (embryonic connective tissue cells involved in regeneration and synthesis of proteins critical for dermal rejuvenation [36], skin MSCs [37]).

For cell viability assessment, the samples were sterilized with 70 % ethanol and placed in wells of a 24-well plate. DPSC cells at the 5th passage were seeded into the plate wells at a density of 30,000 cells/cm^2 in DMEM/F12 medium containing 10 % FBS and supplemented with 100 U/mL penicillin/streptomycin. The cells were cultured for 24 h at 37 °C in a humidified atmosphere with 5 % CO_2. Following the culture period, the morphology of the cells in direct contact with the samples was assessed on the surface of the culture plastic.

As a negative control, DMEM/F12 medium without cells was added to the wells. At the end of the cultivation period, the morphology of the cells on the surfaces of the tested materials was evaluated, and cell viability was assessed using fluorescent staining with SYTO 9, propidium iodide (PI), and Hoechst 33342 reagents. The fluorescent dye SYTO 9, at an excitation wavelength (λ_{exc}) of 450÷490 nm and an emission wavelength (λ_{em}) of 515÷565 nm, stains the DNA and RNA of both live and dead cells green. The intercalating reagent propidium iodide (PI), with λ_{exc} = 546 nm and λ_{em} = 575÷640 nm, stains the nuclei of dead cells red. The fluorescent dye Hoechst 33342, with λ_{exc} = 343 nm and λ_{em} = 483 nm, stains the DNA of both live and dead cells blue.

The effect of the tested materials on fibroblast cells was evaluated by culturing the cells directly in the presence of the samples. After 24 h, the cell layer was evaluated using an inverted microscope based on the following parameters: surface coverage area, cell shape, the number of cellular aggregates, and the number of floating cells. Cell counting was performed using a Goryaev chamber, and the number of viable and dead cells was determined using trypan blue staining (0.1 % solution) [38]. The influence of the Ti-based samples on the culture morphology of the cells was determined based on the following metrics:

– viability coefficient: the ratio of live cells to the total number of cells, %;

– proliferation index: the ratio of the number of grown cells to the number of seeded cells [39];

– cell death percentage: the ratio of the number of dead cells remaining after exposure to the compound to the total number of cells after exposure, %.

Statistical analysis of the obtained data was conducted using the methods of variation statistics with Student's *t*-test to assess significance.

The isolation of dental pulp stem cells (DPSCs) was performed as follows: after opening the crown, the pulp was extracted, washed with Hank's solution, minced, and incubated in a 0.1 % type I collagenase solution for 30 min at 37 °C. The resulting cell suspension was centrifuged at 1000 rpm for 5 min. The pellet was resuspended in growth medium (DMEM/F12) supplemented with 10 % fetal calf serum (FCS), 100 U/mL penicillin, 100 U/mL streptomycin, and 2 mM glutamine, and then transferred into culture flasks. After 3 days, non-adherent cells were removed, and the fraction of adherent cells was cultured until 80–90 % confluence was reached. The cells were then suspended using a mixture of 0.25 % trypsin solution and Versene solution (1:1) and reseeded at a 1:3 ratio. Passaging of cells *in-vitro* was performed using standard methods in culture flasks within a CO_2 incubator (37 °C, 5 % CO_2, 80 % humidity) with the growth medium changed every 3 days.

Results and discussion

The Young's modulus of the Ti–23Nb–5Zr alloy surface in its initial state was E = 56±5 GPa, which is significantly lower than that of the commercially available alloys VT1-0 and VT6 (E > 90 GPa) [40; 41] and is closer to the values of bone [42].

Six types of samples were prepared for each alloy, differing in the method of sandblasting and the presence of electrolytic plasma polishing (EPP). The results of roughness (R_a) and microhardness (HV) measurements for the samples are presented in Tables 1 and 2, while microphotographs of the polished samples (tumbling and EPP) are shown in Fig. 1. High surface heterogeneity after sandblasting prevented reliable results due to indenter slippage. The R_a values for the samples after tumbling were lower than those after

EPP. This can be explained by the fact that, in the first case, a kind of "smoothing" of the surface relief occurs, while in the latter, preferential etching of certain structural components and segregation zones may take place. No correlation was observed between the roughness and microhardness of the samples.

At the same time, electrolytic plasma polishing contributes to an increase in the hardness of the surface layer (see Tables 1 and 2). This is presumably due to structural changes in the surface layer of the metallic materials, which influence their mechanical properties [43]. Notably, as the load decreases, microhardness increases, since the contribution of the surface itself becomes more significant compared to the bulk material (Table 2). No correlation was observed between surface roughness and microhardness of the samples.

The effect of treatment on surface roughness is consistent with the results of contact angle measurements (see Table 1, Fig. 2). A typical trend observed for solid materials wetted by liquid is that the contact angle increases (wettability decreases) as surface roughness decreases [44]. Minimum wettability was observed

Table 1. **Results of roughness and Vickers microhardness at 500 g load, and wettability depending on material surface treatment**

Таблица 1. **Результаты исследования шероховатости, микротвердости по Виккерсу при нагрузке 500 г и смачиваемости в зависимости от обработки материалов**

Material	Sample No.	Surface treatment	R_a, μm	Microhardness, HV	Contact angle, deg
VT1-0	*1*	Copper slag	1.90 ± 0.10	–	46 ± 2
	2	Sand (1.0–1.5 mm)	5.40 ± 0.20	–	31 ± 2
	3	Sand (<1.0 mm)	3.10 ± 0.20	–	43 ± 2
	4	Original sand	5.10 ± 0.20	–	49 ± 2
	5	Copper slag + original sand	4.30 ± 0.20	–	53 ± 2
	6	Tumbling	0.46 ± 0.04	245 ± 28	72 ± 2
VT6	*1*	Copper slag	2.50 ± 0.20	–	41 ± 2
	2	Sand (1.0–1.5 mm)	5.70 ± 0.20	–	35 ± 2
	3	Sand (<1.0 mm)	3.30 ± 0.20	–	43 ± 2
	4	Original sand	5.10 ± 0.20	–	48 ± 2
	5	Copper slag + original sand	4.20 ± 0.20	–	54 ± 2
	6	Tumbling	0.27 ± 0.02	219 ± 19	73 ± 2
Ti–23Nb–5Zr	*1*	Copper slag	2.60 ± 0.20	–	43 ± 2
	2	Sand (1.0–1.5 mm)	5.50 ± 0.20	–	32 ± 2
	3	Sand (<1.0 mm)	3.70 ± 0.30	–	44 ± 2
	4	Original sand	5.10 ± 0.20	–	49 ± 2
	5	Copper slag + original sand	4.10 ± 0.30	–	55 ± 2
	6	Tumbling	0.17 ± 0.01	269 ± 15	74 ± 2
	7	Electrolytic plasma polishing	0.75 ± 0.06	297 ± 17	57 ± 2

Table 2. **Results of studies of microhardness of polished samples depending on the load**

Таблица 2. **Результаты исследования микротвердости полированных образцов в зависимости от нагрузки**

Sample No.	Material	Treatment	Microhardness, HV, at load		
			25 g	100 g	300 g
6	Ti–23Nb–5Zr	Tumbling	306 ± 61	271 ± 45	276 ± 21
7	Ti–23Nb–5Zr	EPP	363 ± 42	313 ± 35	301 ± 13
6	VT1-0	Tumbling	313 ± 64	269 ± 32	238 ± 31
6	VT6	Tumbling	358 ± 158	282 ± 74	232 ± 26

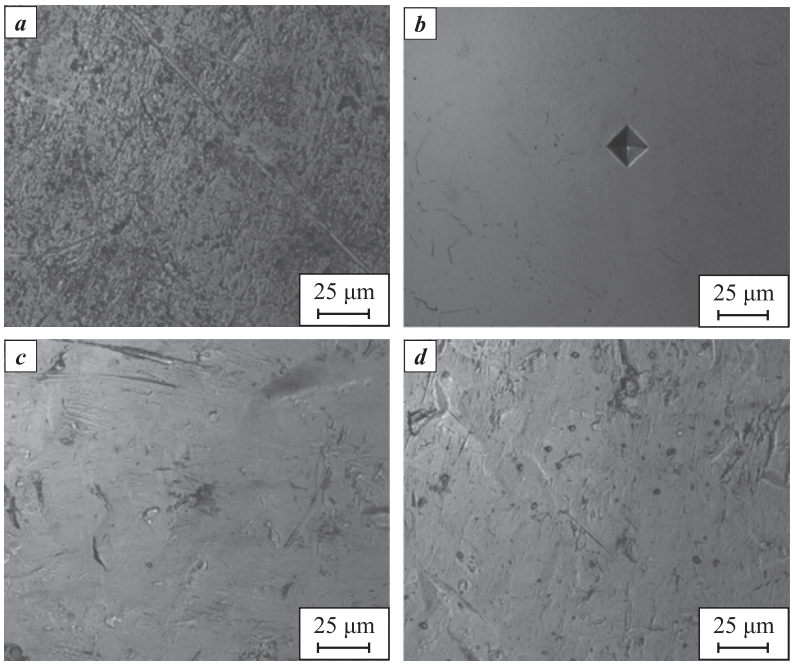

Fig. 1. Microphotographs of samples with smooth surfaces
a – Ti–23Nb–5Zr after tumbling, ***b*** – Ti–23Nb–5Zr after EPP, ***c*** – VT1-0, ***d*** – VT6

Рис. 1. Микрофотографии образцов с гладкой поверхностью
a – Ti–23Nb–5Zr после галтовки, ***b*** – Ti–23Nb–5Zr после ЭПП, ***c*** – ВТ1-0, ***d*** – ВТ6

after tumbling. However, a deviation from the direct relationship occurred for all materials treated with a mixture of copper slag and original (non-fractionated) sand. This is likely due to the wide range of particle sizes impacting the surface, resulting in many small cavities among the larger ones, which locally increased the contact angle. For a similar reason, albeit to a lesser extent, the contact angle for samples treated with original sand also deviates from the trend, as the range of particle sizes is narrower. All three alloys demonstrated similar surface characteristics after each type of treatment.

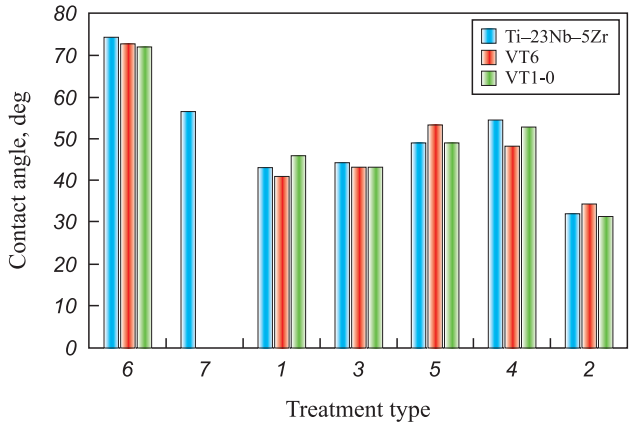

Fig. 2. Dependence of wettability on surface treatment (see Table 1)
1 – cooper slag, ***2*** – sand (1.0–1.5 mm), ***3*** – sand (<1.0 mm), ***4*** – original sand (0.63–1.5 mm), ***5*** – cooper slag + original sand, ***6*** – tumbling, ***7*** – EPP

Рис. 2. Зависимость смачиваемости от обработки поверхности (см. табл. 1)
1 – купершлак, ***2*** – песок (1,0–1,5 мм), ***3*** – песок (<1,0 мм), ***4*** – песок исходный (0,63–1,5 мм), ***5*** – купершлак + песок исходный, ***6*** – галтовка, ***7*** – ЭПП

The images in Fig. 3 show the appearance of DPSC cells at the contact area with the tested materials after 24 h of cultivation. It is evident that none of the materials inhibit cell growth, demonstrating their biocompatibility[1]. No differences were observed depending on the alloy composition or treatment type.

Characteristic microphotographs from the first day of cultivation for samples treated with copper slag and sand (1.0–1.5 mm) are shown in Fig. 4 and 5, respectively. The surfaces displayed a large number of "spread-out" cells, evenly distributed with only a few non-viable ones. This demonstrates that all sample types were adhesive to cells.

Table 3 presents the culture-morphological properties of fibroblast cells in contact with the alloys after sandblasting treatments. All materials showed low cytotoxicity, highlighting their suitability for medical applications. No correlation was found between the cytotoxic properties of the alloys and their composition or surface treatment methods.

[1] The study of extracts from these materials is deemed impractical.

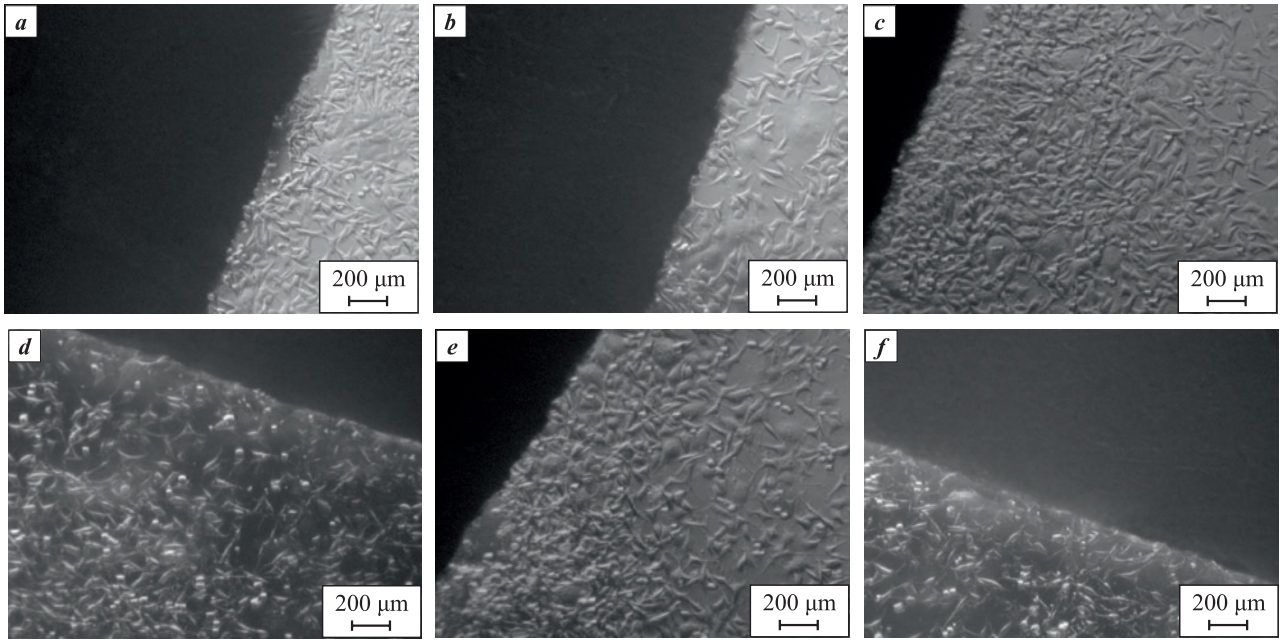

Fig. 3. Appearance of DPSC cells at the contact area with tested materials 24 h after seeding
a–c: Ti–23Nb–5Zr after EPP (***a***), treatment with original sand (non-fractionated) (***b***), and sand with a grain size of 1.0–1.5 mm (***c***);
d and ***f***: VT1-0 after tumbling (***d***) and treatment with sand (<1.0 mm) (***f***);
e – VT6 after treatment with sand (1.0–1.5 mm)

Рис. 3. Внешний вид клеток DPSC в месте контакта с исследуемыми материалами через 24 ч после посева
a–c: Ti–23Nb–5Zr после ЭПП (***a***), обработки песком – исходным (не разделенным на фракции) (***b***) и зернистостью 1,0–1,5 мм (***c***);
d и ***f***: ВТ1-0 после галтовки (***d***) и обработки песком зернистостью до 1,0 мм (***f***);
e – ВТ6 после обработки песком (1,0–1,5 мм)

Table 3. **Cytotoxic properties of alloys depending on surface treatment**

Таблица 3. **Цитотоксические свойства сплавов в зависимости от обработки поверхности**

Material	Sample No.	Surface treatment	Proliferative activity, %	Viability, %	Cytotoxicity index IC_{50}
VT1-0	*1*	Copper slag	80	83	0,90 ± 0,04
	2	Sand (1.0–1.5 mm)	82	84	0,90 ± 0,02
	3	Sand (<1.0 mm)	82	82	0,90 ± 0,04
	4	Original sand	49	74	0,80 ± 0,03
	5	Copper slag + original sand	82	85	0,90 ± 0,03
	6	Tumbling	83	86	0,90 ± 0,02
VT6	*1*	Copper slag	60	80	0,90 ± 0,04
	2	Sand (1.0–1.5 mm)	65	74	0,80 ± 0,03
	3	Sand (<1.0 mm)	51	62	0,70 ± 0,01
	4	Original sand	81	85	0,90 ± 0,02
	5	Copper slag + original sand	79	80	0,90 ± 0,03
	6	Tumbling	68	72	0,60 ± 0,02
Ti–23Nb–5Zr	*1*	Copper slag	79	80	0,90 ± 0,02
	2	Sand (1.0–1.5 mm)	49	56	0,50 ± 0,01
	3	Sand (<1.0 mm)	81	76	0,90 ± 0,04
	4	Original sand	75	80	0,80 ± 0,03
	5	Copper slag + original sand	53	67	0,60 ± 0,01
	6	Tumbling	80	76	0,80 ± 0,03

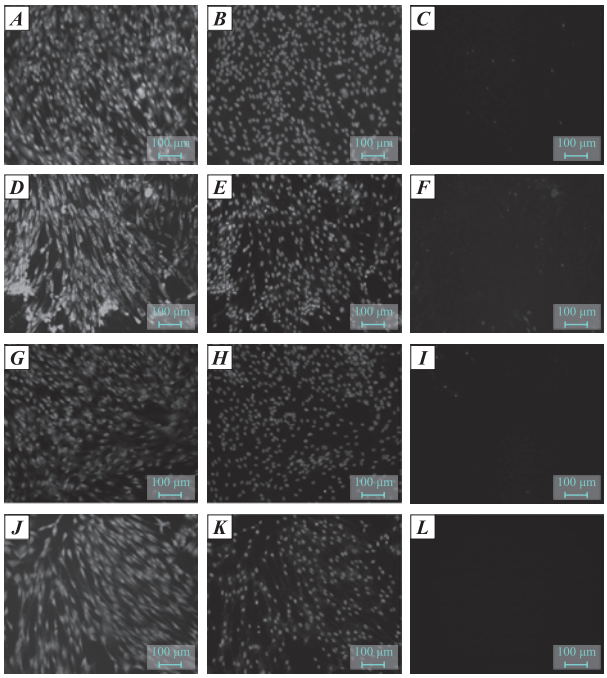

Fig. 4. Appearance of DPSC cells incubated on the surface of titanium alloy samples: TiNbZr (***A***–***C***), VT1-0 (***D***–***F***), VT6 (***G***–***I***), and control (***J***–***L***), after sandblasting with cooper slag 24 h post-seeding

a – Staining with SYTO 9, ***b*** – staining with Hoechst 33342, ***c*** – staining with PI

Рис. 4. Внешний вид клеток DPSC при инкубации на поверхности образцов титановых сплавов: TiNbZr (***A***–***C***), ВТ1-0 (***D***–***F***), ВТ6 (***G***–***I***) и контрольного (***J***–***L***), после струйной обработки купершлаком через 24 ч после посева

a – окраска SYTO 9, ***b*** – Hoechst 33342, ***c*** – PI

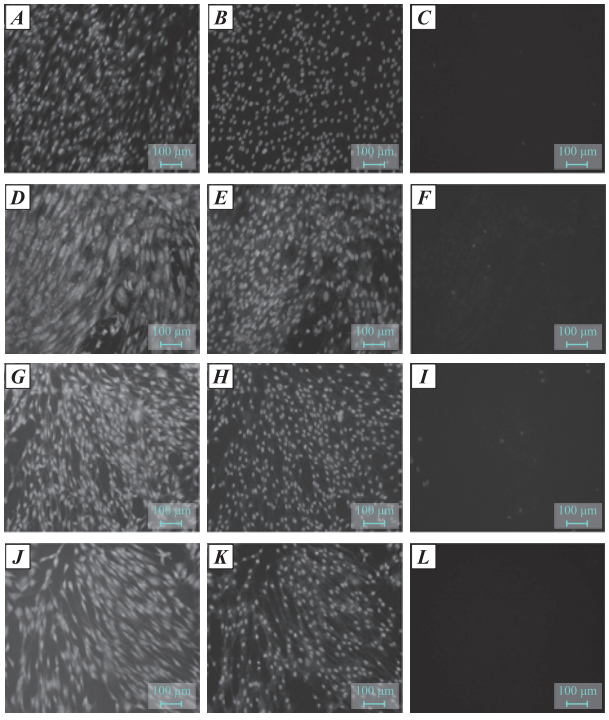

Fig. 5. Appearance of DPSC cells incubated on the surface of titanium alloy samples: Ti–Nb–Zr (***A***–***C***), VT1-0 (***D***–***F***), VT6 (***G***–***I***), and control (***J***–***L***), after sandblasting with coarse sand (1.0–1.5 mm) 24 h post-seeding

a – Staining with SYTO 9, ***b*** – staining with Hoechst 33342, ***c*** – staining with PI

Рис. 5. Внешний вид клеток DPSC при инкубации на поверхности образцов титановых сплавов: TiNbZr (***A***–***C***), ВТ1-0 (***D***–***F***), ВТ6 (***G***–***I***) и контрольного (***J***–***L***), после струйной обработки крупным песком (1,0–1,5 мм) через 24 ч после посева

a – окраска SYTO 9, ***b*** – Hoechst 33342, ***c*** – PI

Conclusion

The study examined the effects of six sandblasting techniques and electrolytic plasma polishing (EPP) on the surface properties and interaction with mesenchymal stem cells of two commercially available titanium-based alloys – VT1-0 (pure titanium) and VT6 (a titanium-aluminum-vanadium alloy) – as well as a newly developed Ti–Nb–Zr alloy.

EPP was found to enhance microhardness but reduce surface roughness compared to tumbling.

All treated surfaces exhibited wettability, with the contact angle increasing as surface roughness decreased. However, sandblasting with mixtures containing a wide range of particle sizes increased the contact angle, likely due to the creation of a more complex surface texture. Tumbling produced the highest contact angle among all alloys, resulting in the most “developed” surface relief.

All three materials exhibited low cytotoxicity, high proliferative activity, and excellent cell viability. A significant number of viable cells were evenly distributed on the sample surfaces. No definitive relationship was observed between cytotoxicity parameters and either the material composition or the surface treatment method.

The newly developed alloy Ti–23Nb–5Zr, which shows promise for improved biomechanical compatibility compared to the commercial alloys, demonstrated stable surface properties and had no adverse effects on cell viability.

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Information about the Authors

Maria A. Sudarchikova – Junior Research Scientist, Laboratory of Strength and Plasticity of Metal and Composite Materials and Nanomaterials, A.A. Baykov Institute of Metallurgy and Materials Science, Russian Academy of Sciences (IMET RAS)
ORCID: 0000-0001-9708-3284
E-mail: mariahsudar@yandex.ru

Elena O. Nasakina – Cand. Sci. (Eng.), Senior Research Scientist, Laboratory of Strength and Plasticity of Metal and Composite Materials and Nanomaterials, IMET RAS
ORCID: 0000-0002-0783-1558
E-mail: nacakina@mail.ru

Galina A. Davydova – Cand. Sci. (Phys.-Math.), Leading Research Scientist, Laboratory of Cell and Tissue Growth, Institute of Theoretical and Experimental Biophysics, Russian Academy of Sciences (ITEB RAS)
ORCID: 0000-0003-4215-7084
E-mail: davidova_g@mail.ru

Lenar R. Valiullin – Cand. Sci. (Biolog.), Head of the Laboratory of Probiotic Preparations and Enzymes, Federal Center for Toxicological, Radiation, and Biological Safety
ORCID: 0000-0002-8277-3941
E-mail: mariahsudar@yandex.ru

Yaroslava A. Morozova – Research Engineer, Laboratory of Strength and Plasticity of Metal and Composite Materials and Nanomaterials, IMET RAS
ORCID: 0000-0003-3526-5474
E-mail: yasya12987@gmail.com

Sergey Yu. Kottsov – Junior Research Scientist, Laboratory of Synthesis of Functional Materials and Processing of Mineral Raw Materials, N.S. Kurnakov Institute of General and Inorganic Chemistry, Russian Academy of Sciences
ORCID: 0000-0001-8263-889X
E-mail: mariahsudar@yandex.ru

Pavel A. Prokofiev – Cand. Sci. (Eng.), Junior Research Scientist, Laboratory of Physicochemistry of Refractory and Rare Metals and Alloys, IMET RAS
ORCID: 0000-0003-0477-0822
E-mail: nacakina@mail.ru

Sergey V. Konushkin – Cand. Sci. (Eng.), Research Scientist of the Laboratory of Strength and Plasticity of metal and composite materials and Nanomaterials, IMET RAS
ORCID: 0000-0002-4363-3604
E-mail: venev.55@mail.ru

Konstantin V. Sergienko – Junior Research Scientist, Laboratory of Strength and Plasticity of Metal and Composite Materials and Nanomaterials, IMET RAS
ORCID: 0000-0003-4018-4599
E-mail: shulf@yandex.ru

Mikhail A. Sevostyanov – Cand. Sci. (Eng.), Leading Research Scientist, Laboratory of Strength and Plasticity of Metal and Composite Materials and Nanomaterials, IMET RAS
ORCID: 0000-0003-2652-8711
E-mail: cmakp@mail.ru

Сведения об авторах

Мария Андреевна Сударчикова – мл. науч. сотрудник лаборатории прочности и пластичности металлических и композиционных материалов и наноматериалов, Институт металлургии и материаловедения им. А.А. Байкова Российской академии наук (ИМЕТ РАН)
ORCID: 0000-0001-9708-3284
E-mail: mariahsudar@yandex.ru

Елена Олеговна Насакина – к.т.н., ст. науч. сотрудник лаборатории прочности и пластичности металлических и композиционных материалов и наноматериалов, ИМЕТ РАН
ORCID: 0000-0002-0783-1558
E-mail: nacakina@mail.ru

Галина Анатольевна Давыдова – к.ф.-м.н., вед. науч. сотрудник лаборатории роста клеток и тканей, Институт теоретической и экспериментальной биофизики Российской академии наук (ИТЭБ РАН)
ORCID: 0000-0003-4215-7084
E-mail: davidova_g@mail.ru

Ленар Рашитович Валиуллин – к.б.н., заведующий лабораторией пробиотических препаратов и ферментов, Федеральный центр токсикологической, радиационной и биологической безопасности
ORCID: 0000-0002-8277-3941
E-mail: mariahsudar@yandex.ru

Ярослава Анатольевна Морозова – инженер-исследователь лаборатории прочности и пластичности металлических и композиционных материалов и наноматериалов, ИМЕТ РАН
ORCID: 0000-0003-3526-5474
E-mail: yasya12987@gmail.com

Сергей Юрьевич Котцов – мл. науч. сотрудник лаборатории синтеза функциональных материалов и переработки минерального сырья, Институт общей и неорганической химии имени Н.С. Курнакова Российской академии наук
ORCID: 0000-0001-8263-889X
E-mail: mariahsudar@yandex.ru

Павел Александрович Прокофьев – к.т.н., мл. науч. сотрудник лаборатории физикохимии тугоплавких и редких металлов и сплавов, ИМЕТ РАН
ORCID: 0000-0003-0477-0822
E-mail: nacakina@mail.ru

Сергей Викторович Конушкин – к.т.н., науч. сотрудник лаборатории прочности и пластичности металлических и композиционных материалов и наноматериалов, ИМЕТ РАН
ORCID: 0000-0002-4363-3604
E-mail: venev.55@mail.ru

Константин Владимирович Сергиенко – мл. науч. сотрудник лаборатории прочности и пластичности металлических и композиционных материалов и наноматериалов, ИМЕТ РАН
ORCID: 0000-0003-4018-4599
E-mail: shulf@yandex.ru

Михаил Анатольевич Севостьянов – к.т.н., вед. науч. сотрудник лаборатории прочности и пластичности металлических и композиционных материалов и наноматериалов, ИМЕТ РАН
ORCID: 0000-0003-2652-8711
E-mail: cmakp@mail.ru

Alexey G. Kolmakov – Dr. Sci. (Eng.), Corresponding Member of the Russian Academy of Sciences, Head of the Laboratory of Strength and Plasticity of Metal and Composite Materials and Nanomaterials, IMET RAS
ORCID: 0000-0002-4907-951X
E-mail: imetranlab10@mail.ru

Алексей Георгиевич Колмаков – д.т.н., чл.-корр. РАН, зав. лабораторией прочности и пластичности металлических и композиционных материалов и наноматериалов, ИМЕТ РАН
ORCID: 0000-0002-4907-951X
E-mail: imetranlab10@mail.ru

Contribution of the Authors

M. A. Sudarchikova – conducted surface roughness measurements, contributed to result discussions, and prepared documentation.
E. O. Nasakina – secured project financing, defined the study objectives, and processed research results.
G. A. Davydova – conducting research on mesenchymal stem cell cultures derived from human tooth pulp (DPSC) (clone Th44) and participated in result discussions.
L. R. Valiullin – conducting research on immortalized fibroblast cell cultures and skin mesenchymal stem cells, and contributed to result discussions.
Ya. A. Morozova – performed a literature review and prepared the article layout.
S. Yu. Kottsov – studied the contact angle of wettability of surfaces and participated in result discussions.
P. A. Prokofiev – prepared samples for research and contributed to result discussions.
S. V. Konushkin – performed smelting, rolling, and heat treatment of the alloys.
K. V. Sergienko – prepared sheets and cut samples using an electric discharge machine.
M. A. Sevostyanov – selected research methodologies and equipment.
A. G. Kolmakov – participated in result discussions.

Вклад авторов

М. А. Сударчикова – измерения шероховатости поверхности, обсуждение результатов, подготовка документации.
Е. О. Насакина – привлечение финансирования проекта, определение цели работы, обработка результатов исследований.
Г. А. Давыдова – проведение исследований на культурах МСК из пульпы зуба человека (DPSC) (клон Th44), обсуждение результатов.
Л. Р. Валиуллин – проведение исследований на иммортализованных культурах клеток фибробластов, МСК кожи, обсуждение результатов.
Я. А. Морозова – обзор литературы, оформление статьи.

С. Ю. Котцов – исследование краевого угла смачивания поверхностей, обсуждение результатов.
П. А. Прокофьев – подготовка образцов к исследованиям, обсуждение результатов.
С. В. Конушкин – выплавка, прокатка и термическая обработка сплавов.
К. В. Сергиенко – подготовка листов и резка образцов на электроэрозионном станке.
М. А. Севостьянов – выбор методики исследований и подбор оборудования.
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