ORIGINAL ARTICLE

INFLUENCE OF THE AMOUNT OF COMPRESSION ON VENOUS AND ARTERIAL BLOOD FLOW VELOCITY AND SKIN MICROCIRCULATION OF THE LOWER EXTREMITY

DOI: 10.36740/WLek202308112

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ABSTRACT

The aim: To determine the effect of compression on the venous and arterial velocity of the main blood flow of the lower limb and the skin microcirculation of the rear part of the foot.

Materials and methods: 20 healthy subjects participated in this study: 11 men 11 (55%) men and 9 (45%) girls. The ankle brachial index (ABI), femoropopliteal index, femoral arterial blood flow velocity (AFV), venous blood flow velocity (VFV), transcutaneous oxygen pressure (tcPO2) and carbon dioxide pressure (tcPCO2) were measured. After the general measurements were taken, the tire was inflated to 10 mm Hg under general basic conditions and kept for three minutes. The experiment ended when no decrease in tcPO2 was observed between two consecutive pressure levels.

Results: The average tire pressure to reach physiological zero was 80 mm Hg. for all participants. At 10 mmHg significant changes in indicators were found by 19% ($p=0.0001$). tcPCO2 values increased significantly at 10 mmHg ($p=0.0319$) and continued to increase until the end of the study. It was established that its values increased by 14% compared to the input data ($p=0.0005$).

Conclusions: At the maximum compression of 60 mmHg the arterial blood flow rate decreased by 5.5 times ($p=0.0001$). TcPCO2 increases significantly when compressed by 10 mm Hg also in parallel with the decrease in the regional perfusion index, which begins at an external compression of 40 mm Hg, which is evidence of the deterioration of the perfusion of the skin of the anterior part of the foot in healthy subjects.

KEY WORDS: microcirculation, tcp02, tcpC02, blood velocity, angiosom

Wiad Lek. 2023;76(8):1783-1789

INTRODUCTION

External compression on the lower extremities is mostly implemented by elastic compression and is used to prevent or limit the formation of edema of various origins, and in case of chronic venous insufficiency in the stage of decompensation, as a proven treatment procedure with the class of evidence «B» [1-3].

The pressure created by medical elastic products should decrease from the distal to the proximal parts, requiring a vertical position of the patient, and for chronic venous insufficiency in the stage of decompensation, it was recommended to use III class compression, where the pressure level at the level of the ankle is >35 mmHg. In an attempt to find an explanation for the beneficial effect of compression on venous function due to the improvement of the pumping function of the calf muscle with an increase in the venous blood flow rate and a decrease in venous reflux, the researchers focused the main attention on the blood flow in the deep and superficial venous system, not taking into account the changes in the microcirculation of the skin of the lower leg and foot [2] .

Although it is known for certain that a local external pressure of 20 mm Hg leads to a decrease in blood circulation in the skin, where in the stage of decompensation with chronic venous insufficiency, we already have a trophic disorder in the form of an open trophic ulcer [3, 4].

Therefore, it should be expected that the imbalance between the beneficial effect on venous blood circulation and the risk of progression of tissue ischemia must be evaluated in each specific case.

THE AIM

The aim of the study was to determine the effect of compression on the venous and arterial velocity of the main blood flow of the lower limb and the skin microcirculation of the rear part of the foot.

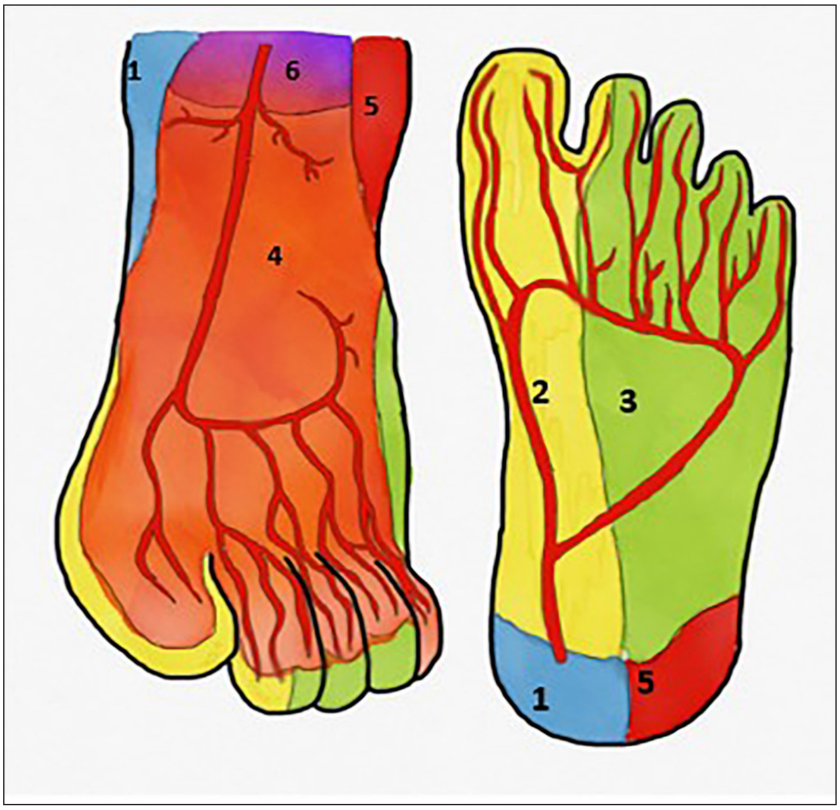

Fig.1. Simplified illustration of angiosomes of the foot: 1- medial calcaneal; 2- medial plantar; 3 - lateral plantar; 4 - dorsal angiosome of the foot; 5 - lateral calcaneal artery; 6 - angiosome of the anterior penetrating branch of the peroneal artery.

Table I. Average values of IRP indicators in different areas of angiosomes (n=20)

Angiosome	RPI (M±sd)
ATA	1.50±0.14
PTA	1.85±0.20
PA	1.70±0.15
Back surface of the foot	1.40±0.16
Sole	1.10±0.11
Lateral bone	1.4±0.31
Medial bone	1.3±0.04

MATERIALS AND METHODS

20 healthy subjects participated in this study. Among them were 11 (55%) men aged 24 (22-27), weight 66 (62-80) kg and height 175 (169-182) cm and 9 (45%) girls, whose average age was 23 (20 -26) years old, weight 58 (47-72) kg, height 165 (160-178) cm. All volunteers gave their written consent to participate in the experimental protocol, which meets all the requirements for conducting research according to the Declaration of Helsinki. All participants underwent a general physical examination.

In all subjects of the study, the ankle brachial index (ABI) was measured, which is the ratio of the systolic

Table II. Effects of positive compression on both venous and arterial femoral blood flow velocities and dorsal foot skin microcirculation in young healthy subjects (n=20).

Pressure (mm Hg)	0	10	20	40	60	80	100
VFV m/s -1 (M±sd)	0.13±0.041	0.10±0.074	0.09±0.03 **	0.07±0.041 ***	0.05±0.025 ***	0.4±0.0011 ***	0.1±0.009 **
AFV m/s -1 (M±sd)	0.22±0.019	0.18±0.013 ***	0.15±0.009 ***	0.11±0.007 ***	0.07±0.004 ***	0.05±0.005 ***	0.04±0.01 ***
tcPO2 (mm Hg) (M±sd)	76.8±15.4	75.3±16.1	71.9±11.4	72.6±9.7	63.7±11.2 **	40.5±8.8 ***	16.9±12.1 ***
tcPCO2 (mm Hg) (M±sd)	38.6±2.7	40.4±2.4*	42.0±5.7 *	42.8±6.4 **	44.1±6.2 ***	44.7±6.6 ***	44.7±12.1 *

Note: * - p<0.05, ** - p<0.01, *** - p<0.0001

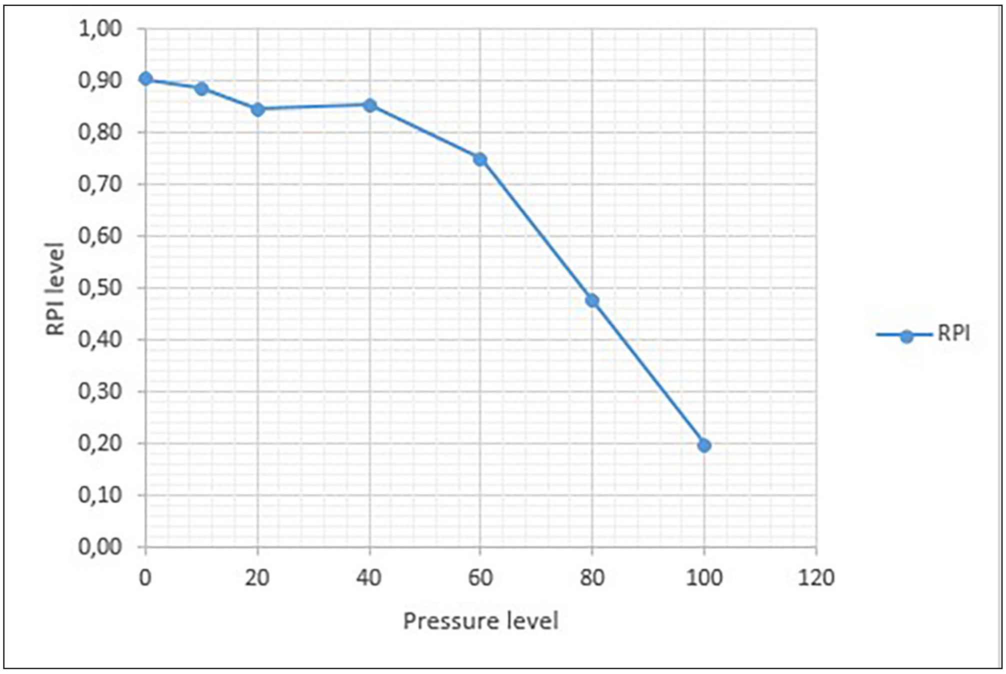

Fig. 2. Cross-inversely proportional effect of degree of compression and RPI

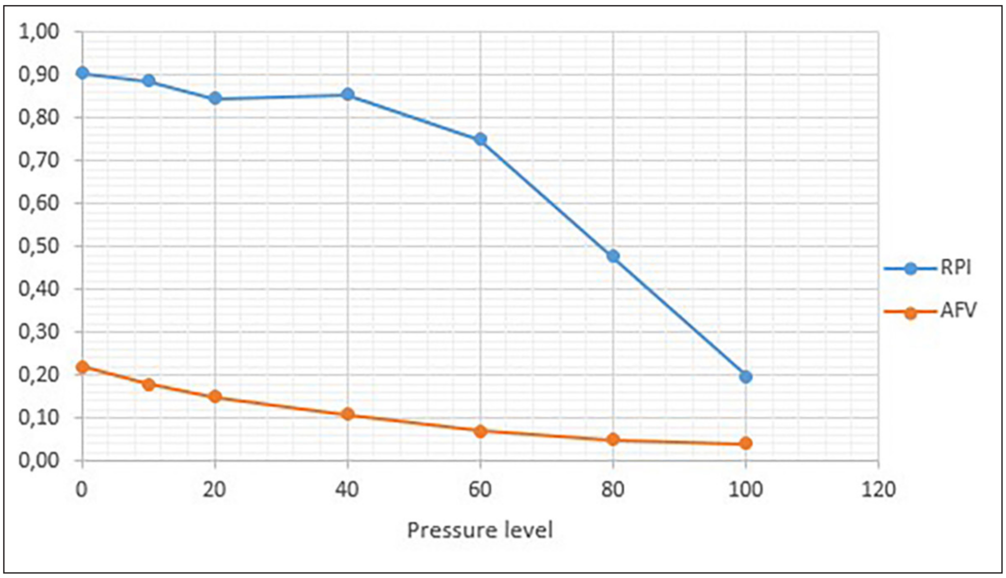

Fig. 3. Comparison of changes in AFV and changes in IPR depending on the degree of limb compression

arterial pressure on the anterior or posterior tibial artery to this indicator on the brachial artery. An ABI value of less than 0.9 indicates the presence of stenosis in the arteries of the lower extremities. To determine the functionality of the deep femoral artery, the deep femoral-popliteal index was determined, which is the ratio of the difference between the regional systolic pressure in the popliteal artery above the knee and below the knee to the regional systolic pressure above the knee. All these indicators were measured during selection for the study.

Ultrasound examination of the femoral vessels was performed using a 7 MHz linear sensor. Femoral arterial blood flow velocity (AFV) and venous blood flow velocity (VFV) distal to the saphenofemoral junction were measured.

We performed a study of the microcirculation of the skin of the lower extremities taking into account the angiosomal approach using the TCM 400 Radiometer device (Denmark). Transcutaneous oxygen pressure (tcPO2) was measured using a Clark type electrode. Transcutaneous carbon dioxide pressure (tcPCO2) was measured using a Severinhaus type carbon dioxide electrode. A combined transcutaneous oxygen and carbon dioxide pressure electrode was used, which was placed distally from the cuff. The electrode was attached to the skin of the back of the foot with adhesive tape. All measurements were carried out in room air conditions.

In order to achieve statistically reliable results, not absolute values were used, but the ratio of the obtained value in the first interdigital space of the investigated lower limb to the same value in the chest area. The norm of oxygen tension for the skin of the chest is 85 mm Hg, for the interdigital space 60 mm Hg. The resulting index of two values was called the regional perfusion index (RPI). Further, RPI was calculated in relation to the value of perfusion in the studied angiosome to the same in a normal point of a specific patient (ulnar fossa).

The regional perfusion index is used to exclude the influence of cardiopulmonary disorders and simplify the interpretation of tcPO2, which is correlated with the values obtained on the chest.

To determine tcPO2, angiosomes of the anterior tibial artery (ATA), posterior tibial artery (PTA), and peroneal artery (PA) were used, since the corresponding arteries participate in the perfusion of the corresponding skin-muscle flaps (Fig. 1).

As can be seen from the given illustration, the medial calcaneal angiosome, medial plantar and lateral plantar angiosome correspond to PTA. ATA is responsible for the dorsal angiosome of the foot. In the blood supply of the lateral calcaneal angiosome and the angiosome of the anterior penetrating branch of the peroneal artery, mainly PA.

Heart rate and systolic and diastolic blood pressure on the arm were also measured throughout the study usingautomatic cuff inflation system with a diameter of 16 cm to control the general hemodynamic parameters of the study subjects. All subjects were in a horizontal position in the same climatic conditions with the exception of the previous load.

After the general measurements were taken, the tire was inflated to 10 mm Hg under general basic conditions and kept for three minutes. Sonographic parameters were measured in the last two minutes. The total duration of each subsequent approach was 3 minutes. After the first approach, the pressure in the tire was increased to 20 mm Hg, then the pressure was gradually increased in steps of 20 mm Hg. The experiment ended when no decrease in tcPO2 was observed between two consecutive pressure levels. The minimum values were defined as the physiological zero of the participant, which was observed when the individual maximum value of the tire pressure was reached.

The criteria for inclusion in the study were: the absence of any cardiovascular pathology, the absence of any concomitant diseases on the part of other organs and systems, written consent to conduct the study, ankle-brachial pressure index >1.1, femoral-popliteal index < 0.35 .

Results are shown as mean and standard deviation. Analysis of differences between paired values was performed using a one-sample Student's T test to determine differences within subjects. The p-values were calculated taking into account the number of participants at each pressure, significant results were registered at a value of $p<0.05$. Correlation analysis was performed using the Pearson correlation test. Statistical processing and analysis of the obtained results was performed using Jamovi and Exel2019.

RESULTS

Each subject had a stable heart rate and systolic and diastolic blood pressure on the arm throughout the experiment. These indicators did not change significantly and averaged 62±13.0 per minute and 106±15.0 mm Hg, 60±7.0 mm Hg.

Before conducting the study, tcPO2 norms were measured in healthy subjects depending on the angiosomes of the foot (Table I).

According to the resultsshown in table 1, it can be stated that each angiosome has its own level of blood supply depending on the atria and its diameter.

To investigate the statistical hypothesis that when the positive pressure in the cuff increases, the transcutaneous oxygen tension in the limb will decrease and, conversely, the transcutaneous carbon dioxide tension will increase, a statistical comparison of the tcpO2, tcpCO2, AFV and VFV indicators, which characterize the blood supply and microcirculation of the limb between the norm, when the pressure of the cuff is equal to zero and indicators at each subsequent increase in pressure.

The results of the tcpO2, tcpCO2, AFV and VFV measurements and their statistical comparison are presented in Table II.

As can be seen from Table II, the minimum values were reached at 80 mm Hg. in 12 subjects. Therefore, further measurements with a pressure of 100 mm Hg. was conducted only in 8 subjects. The average tire pressure to reach physiological zero was 80 mm Hg for all participants.

Studying the speed of femoral arterial blood flow already at 10 mmHg. significant changes in indicators were found by 19% (p=0.0001). The higher the tire pressure, the more the AFV value decreased with each step. The arterial blood flow rate decreased by 5.5 times compared to the input data at the maximum pressure in the tire (p=0.0001).

No significant changes in VFV were registered at a tire pressure of 10 mm Hg. Compression at 20 mm Hg caused a decrease in VFV relative to the initial level (p=0.0011). Venous femoral blood flow velocity decreased significantly, on average by 31% compared to baseline conditions. At individual maximum tire pressure, the maximum decrease in venous velocity compared to the resting value was 83.8% (p=0.0028).

Turning to tcPO2, although it tended to decrease, no significant changes were detected until the tire pressure reached 60 mmHg. ($p=0.0039$). The value of transcutaneous oxygen pressure further decreased with increasing pressure in the tire. The lowest value registered in the subjects was 16.9±12.1 mm Hg which means a decrease in tcPO2 by 4.5 times ($p=0.0001$).

When checking statistical indicators according to FDR and FWER, statistically significant results can be considered those with $p<0.0001$, other indicators, despite their values, did not pass statistical verification.

To establish the influence of the level of external compression on changes in the main blood flow and microcirculation, a Pearson correlation test was performed. A strong inverse correlation was established between the increase in pressure in the cuff and the change in the transcutaneous pressure tension in the limb ($r= -0.9$, $p=0.0002$), when analyzing the correlation between the cuff pressure and the change in the transcutaneous tension of carbon dioxide, a direct strong correlation was established connection ($r= 0.9$, $p=0.0001$). According to the data of the correlation test, it can be concluded that when the pressure in the cuff increases, there are changes in the microcirculation in the limb in the form of an increase in carbon dioxide pressure and a decrease in oxygen tension in the tissues, which subsequently leads to ischemia of the limb. When analyzing the correlation, the indicator of 100 mmHg was not taken into account, since at this value there is practically no blood flow in the limb.

On the other hand, tcPCO2 values increased significantly at 10 mmHg ($p=0.0319$) and continued to increase until the end of the study. Analyzing changes in the transcutaneous pressure of carbon dioxide, it was established that its values increased by 14% compared to the input data ($p=0.0005$).

To compare the changes in tcPO2, the value of RPI was calculated, which normally ranges from 0.8 to 1.4 for the back of the foot. The results of the changes are shown in Fig. 2.

As can be seen from the graph shown, similarly, the RPI values significantly decrease starting from a pressure level of 40 mmHg. as well as the tcPO2 indicator, therefore, the use of RPI can serve as a criterion of choice for diagnosing the degree of ischemia.

The dependence of AVF and RPI changes on the degree of compression is shown in fig. 3.

Analyzing the changes in AFV and RPI, we came to the conclusion that tissue oxygen saturation does not change as dramatically as the degree of arterial blood flow speed, because AFV changed sharply with each step of increasing the pressure in the tire, and as you can see RPI, it decreased smoothly, and its sharp decrease is noted at 60 mm Hg ($p<0.01$).

If we analyze the obtained results, the first indicators that respond to the degree of compression were AFV and tcPCO2, which already at a value of 10 mmHg. varied significantly with a significant difference.

DISCUSSION

The results of this study demonstrate significant deterioration of AFV, tcPCO2 with a compression value of only 10 mmHg. Art., although VFV and tcPO2 did not decrease. On the other hand, in our experimental conditions, tcPO2 seems to be less relevant than tcPCO2 for the assessment of local microcirculation impairment.

Very little information is known about the effect of external compression on general venous blood flow [5]. On the other hand, few results are available on the effect of uniform limb compression and the effect on arterial blood flow [6]. Even less is known about the influence of external pressure on venous and arterial blood flow and distal microcirculation.

The pressure created by elastic compression or bandages can be classified according to the amount of compression [7]. But on the other hand, the pressure values used in the management of patients are in the range from 14 to 17 mmHg. for light compression bandages, and for moderate ones, these values are from 25 to 35 mmHg and can even be 60 mmHg, but as can be seen from the results of our research, even at a pressure of 10 mmHg there are changes in microcirculation in the lower limb.

A 2009 Cochrane review comparing compression with primary bandaging (non-compression bandages) in usual care concluded that venous ulcers healed faster with any form of compression therapy than without. It is better to give the patient knitwear of a deliberately lower compression class or one that does not correspond to the scale of the lesion (for example, stockings instead of pantyhose), than to leave it without elastic compression at all.

Studies have shown that selective compression improves the results of sclerotherapy. E. Berliner and co-authors [8] analyzed eight studies, three of which showed that compression stockings can alleviate the symptoms of chronic venous insufficiency and help heal long-standing chronic ulcers (level of evidence A). However, changes in microcirculation in these studies were not described, and what effect does the different type of jersey and pressure have in a specific case, resulting from the study conducted.

Our research is consistent with the research of such scientists as Sabri and Berengere Fromy, since we showed that the femoral venous blood flow rate decreases significantly at a limb pressure of 20 mmHg [9].

Halperin and the authors drew the attention of scientists that an external pressure of 10 mm Hg. is sufficient to decrease the arterial blood flow rate in normal limbs, which fully corresponds to our research results, and is explained by a decrease in arteriovenous pressure gradients and a decrease in the caliber of small vessels in the compression zone, which causes an increase in flow resistance [10].

Also, analyzing the data of other authors, it was established that the decrease in tcPO2 with increasing pressure is consistent with the study of Silva H et al., who noted that compression of the lower limb when the subject is lying down leads to a drop in transcutaneous oxygen pressure in the tissues [11].

On the other hand, our results suggest that tcO2 alone does not interpret arterial hemodynamics adequately under our experimental conditions. It is possible that the blood flow of the skin is disturbed due to pressure on the tire up to 60 mm Hg. was not high enough.

However, for pressures as low as 10 mmHg, tcPO2 increased significantly. We assume that the pH increased and distal microcirculation was observed in the forefoot. Andreozzi and his co-authors have already demonstrated that there is a discrepancy between tcPO2 and tcPCO2 [12]. In a follow-up study, they noted that «in some cases, tsPO2 cannot provide a correct assessment of the risk of skin necrosis, whereas tsPCO2 measurement can» [13].

Therefore, the measurement of tsPO2 by itself may not be an adequate tool in our experimental conditions to control the distal microcirculation.

From this study, it can be seen that positive pressure on the entire leg did not provide a significant beneficial effect on the velocity of blood flow in the femoral veins. While we have shown that at uniform external pressure up to 10 mm Hg. in healthy young people, significant violations of both the arterial blood flow of the lower limb and the microcirculation of the front part of the foot were observed. Although this result was found in healthy volunteers, the technique used in this work is an interesting approach to understanding the effects of compression.

Compression therapy is the basis of treatment of venous trophic ulcers of the lower extremities. Most authors are of the opinion that compression of the lower extremities is one of the main pathogenetically justified methods of conservative treatment chronic venous insufficiency. At the same time, the effect of compression treatment is determined due to a decrease in the pathological venous capacity of the lower extremities. This happens in connection with the coming compression of venous intermuscular plexuses, superficial and penetrating veins, improvement in the functional activity of the valvular apparatus and in connection with a decrease in the diameter of the veins.

There is also an increase in reverse absorption of tissue fluid in the venous knee of the capillary and a decrease in its filtration in the arterial - due to an increase in tissue pressure. As a result, a reduction in swelling and an increase in the fibrinolytic activity of the blood is achieved, as the tissue activator (plasminogen) is produced more intensively and the rheology of the blood improves due to the reduction of the stagnation of the latter in the venous channel [12, 13].

According to some authors, good wound care and the use of compression therapy are sufficient to cure most short-lived and small venous ulcers [14], however, taking into account the results of various researchers that correlate with our data, we can conclude that not everything is so clear-cut and changes in perfusion should be evaluated tissue and microcirculation changes, which are accompanied by trophic disorders.

The question of conducting a study of patients with vascular diseases, both with arterial and venous pathology, is relevant. This may lead to a better understanding of the potential beneficial and harmful effects of compression in such patient populations.

CONCLUSIONS

1. At a maximum compression of 60 mmHg the arterial blood flow rate decreased by 5.5 times (p=0.0001).
2. Venous velocity of blood flow in the femoral vein at compression of 20 mmHg was 0.09±0.03 m/s^{-1}, which is 31% less than the initial data, and at the maximum pressure of the cuff, the decrease in venous velocity compared to the initial value was 0.1±0.009 m/s^{-1} (83, 8%) (p=0.0028).
3. tcpCO2 increases significantly when compressed by 10 mmHg. also in parallel with the decrease in the regional perfusion index, which begins at an external compression of 40 mm Hg, which is evidence of the deterioration of the perfusion of the skin of the back of the foot in healthy subjects.
4. A strong inverse correlation was established between the increase in pressure in the cuff and the change in the transcutaneous pressure tension in the limb (r= -0.9, p=0.0002), when analyzing the correlation between the cuff pressure and the change in the transcutaneous tension of carbon dioxide, a direct correlation was established strong correlation (r= 0.9, p=0.0001).

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Conflict of interest:

The Authors declare no conflict of interest.

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Received: 04.11.2022
Accepted: 18.07.2023

A - Work concept and design, **B** – Data collection and analysis, **C** – Responsibility for statistical analysis, **D** – Writing the article, **E** – Critical review, **F** – Final approval of the article

ORIGINAL ARTICLE

FEATURES OF BONE REMODELING AROUND SURFACE-MODIFIED TITANIUM AND TANTALUM IMPLANTS

DOI: 10.36740/WLek202308113

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ABSTRACT
The aim: To study the osseointegrative properties of titanium and tantalum implants with different surface structures in animal experiments.
Materials and methods: The histological and morphometric study was carried out on 60 male white rats after titanium implants with different surface structures made by 3D printed technology were inserted in the distal femur bone: presented by the multilayered layers of interlacing pores of 300 microns (series 1); rough (> 2 microns) (series 2); and tantalum implants with 300 microns pores and 80% porosity (series 3) as control material.
Results: On the 30 days we found statistically significant differences in the bone-implant contact rate between the 2nd experiment series (44.77 ± 1.86)% and 1st (59.91 ± 2.86)% (p=0.000047) and 3rd (53.89 ± 2.11)% (p=0.000065), on the 90 days between the 2nd experiment series (51.26 ± 2.7)% and 1st (66.84 ± 2.63)% (p=0.000187) and 3rd (70.35 ± 4.32)% (p=0.000349). There was a difference between the indices of the bone-implant volume at day 90 between the 1st (48.43 ± 2.2)% and 2nd (36.88 ± 2.56)% series (p=0.000919), between the 2nd and 3rd series (51.2 ± 3.06)% (p=0.000107). There were no significant differences between the studied indices in the 1st and 3rd series of the experiment.
Conclusions: Titanium implants with multilayered interlaced pore layers of 300 microns and tantalum with 300 microns pore size and 80% porosity may be promising. Rough-surface titanium also has osseointegrative qualities, but they are lower compared to other materials.

KEY WORDS: Titanium, Tantalum, Bone-to-implant contact, Bone-implant volume

Wiad Lek. 2023;76(8):1790-1796

INTRODUCTION

Titanium (Ti) and its alloys have excellent corrosion resistance and high biocompatibility, which has led to their wide use as a material for orthopedic and dental implants. In recent years, along with titanium, tantalum implants have taken a leading position in orthopedics [1]. Despite the widespread use of these biomaterials, work on the improvement of implants continues. One of the directions is to modify the implant surface (roughness, porosity, etc.) and create porous frameworks, which contributes to early mechanical stability due to the possibility of direct contact of the implant with the bone, close adhesion and ingrowth of cells and vessels into the pores [2, 3]. Significant progress has been achieved by using materials with predetermined properties and surface characteristics, on which biologically active substrates can be formed. When developing implants and introducing them into clinical practice, the main evaluation criterion is osseointegration.

Osseointegration is a key concept in orthopedics and traumatology, as various non-natural biomaterials are widely used in the surgical treatment of patients. Osseointegration is viewed as a structural, mechanical, and functional relationship. which is defined as a time-dependent healing process leading to rigid fixation of alloplastic materials in bone with their capacity for functional loading [4]. Currently, the notion of osseointegration has expanded. The term has been interpreted from a new perspective, i.e., osseointegration can be seen as a demarcation reaction to a foreign body caused by immunity and classified as delayed type (type IV) hypersensitivity, which manifests itself as a reaction to drugs and foreign bodies [5, 6]. That is, the authors consider osseointegration as an immunomodulated inflammatory process, which at an early stage promotes the attraction of cells to the implant surface.

Osseointegration is a complex process that can be influenced by many factors, the osseointegration process includes material biocompatibility, implant design with particular attention to its surface and internal structure, biomechanical characteristics of the