

Modern Approaches to The Development and Use of Biocompatible Implants: Materials, Technologies and Prospects

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ABSTRACT

Objective: This study aims to evaluate the osseointegration potential of stainless steel implants manufactured using additive technologies for tibial prosthetics in rabbits, focusing on mechanical stability and bone-implant integration. **Method:** The experimental study was conducted on six chinchilla rabbits aged 6–8 months. Under general anesthesia, each rabbit underwent leg amputation followed by the implantation of a screw-type stainless steel implant produced through additive manufacturing. The implants were stabilized using the Ilizarov apparatus for six weeks. Clinical assessments, radiological imaging, and histological analyses were performed to evaluate the extent of osseointegration. **Results:** The findings demonstrate that the screw-type implant structure successfully osseointegrated into the tubular bone, with significant new bone tissue formation observed on the implant surface after 12 weeks. This bone-implant integration formed a stable bone-implant block capable of withstanding mechanical stress, confirming the implant's mechanical stability within the bone. **Novelty:** This study highlights the promising potential of additive manufacturing technologies in producing biocompatible implants with enhanced osseointegration capabilities, paving the way for more effective and durable orthopedic prosthetics.

INTRODUCTION

Intraosseous screw implants are actively used in dentistry and orthopedics. The optimal condition for osseointegration is the mechanical stability of the implant in the bone [1, 2]. However, this process depends on many factors that affect the interaction of the implant with bone and paraosseous tissues. In particular, diseases such as osteoporosis or insufficient protein intake with food can not only negatively affect the quality of lamina compacta bone tissue, but also disrupt the process of osseointegration of implants [3]. On the contrary, systemic treatment of osteoporosis can improve osseointegration, which has a positive effect on the architecture and composition of bone tissue formed around the implants, which increases the mechanical strength of the developing bone-implant block [4-6].

In vivo mechanical loading of bone has a positive effect on bone mass, contributing to an increase in its density and strength, as confirmed by data from studies of the microarchitecture of lamellar and trabecular bones [4, 5, 7].

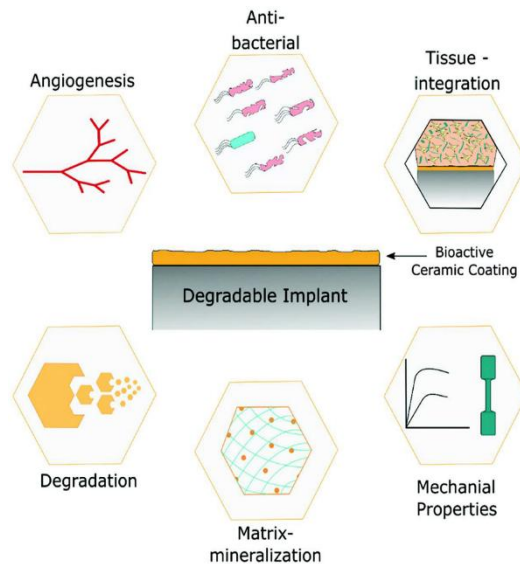


Figure 1.

The mechanical properties of the implant itself (or an adjunct), its geometry, chemical composition of the surface coating, relief, topology, etc. are of great importance for the osseointegration process [5]. The method of forming the surface relief also plays a major role. Currently, sandblasting and polishing of the surface texture are preferred, as this treatment provides a closer contact with the implant compared to other options [8, 9]. The influence of the method of loading implants on the quality of osseointegration is still under debate.

There are separate publications on the need to develop implant channels for the administration of drugs with antibacterial and osseointegrating properties [10]. This technology was first used by us in implants for osseointegration. It should be noted that the production of such channels, especially with small implant sizes, is not possible without additional technologies.

The aim of the study was to evaluate the osseointegration potential of innovative stainless steel implants manufactured using additive technologies in the context of tibial bone prosthetics in rabbits.

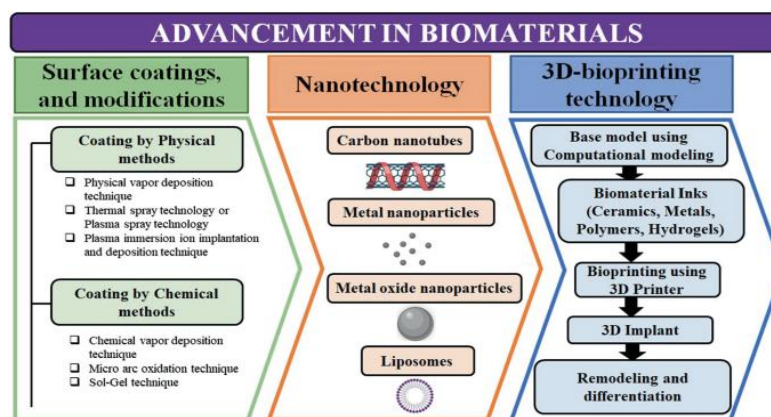


Figure 2.

RESEARCH METHOD

We developed a tubular bone tail (RF patent No. 152558) manufactured using additive technology from EOS PH1 stainless steel powder (GLW Technology, Canada) using the EOSINT280 installation (EOS GmbH, Germany). The chemical composition of the material: iron Fe (normal); chromium Cr (18%); nickel Ni (4%); copper Cu (4%); manganese Mn (1%); silicon Si (0.75%); molybdenum Mo (0.5%); niobium Nb (0.16%); carbon C (0.07%)

Mechanical properties were determined in accordance with ISO 6892:1998 (E). For the test studies, the parts were manufactured with a layer with a diameter of 5 mm, a length of 25 mm and a thickness of 20 μm . The ultimate tensile strength in the vertical direction after manufacturing and heat treatment was 1450 ± 100 MPa. The heat treatment was carried out at a temperature of 482 ° C with a holding time of 4 hours. Rockwell hardness (HRC) measurements were carried out in accordance with DIN EN ISO 6508-1. The hardness of the samples was 41 HRC. The thermal conductivity of the samples after manufacturing and heat treatment was: 15.7 ± 0.8 W / (m ° C) in the horizontal plane, 15.8 ± 0.8 W / (m ° C) in the vertical plane. Specific heat capacity - 470 ± 20 J / (kg ° C). Inside the implant there is a channel with side holes for the introduction of drugs (Fig. 2, a).

Implantation of the tubular bone tail in the experimental stages: a - general view of the implant; b - plastic support; c - X-ray of the operated limb after the operation; d - X-ray of the tibia of rabbits 12 weeks after the operation

Experimental studies were conducted on 6 Soviet chinchilla rabbits weighing 3.12 ± 0.35 kg, 6–8 months of age. All animals underwent a leg amputation at the border of the upper third under general anesthesia. The soft tissues were sutured in layers with internal sutures. Then, the bone marrow canal was drilled to 4.5 mm, a 5 mm diameter implant was screwed into the tibial tail, and a support was attached. Then, the segment was fixed using an Ilizarov apparatus consisting of two supports. For this, cross-wires were passed through the proximal metaepiphysis of the tibia, and the distal wires had a stopping platform. The Ilizarov apparatus was dismantled after 6 weeks.

Clinical observation of animals was carried out throughout the entire period of the experiment. At the same time, the general condition was taken into account, the function of the limbs and the condition of the soft tissues in the area of the spokes were determined. Control radiography was performed on a portable X-ray machine TOSHIBA Rotanode E7239 (Toshiba, Japan) before surgery and on days 1, 21, 42 and 84 after surgery.

Permission to conduct experimental studies was obtained from the Ethics Committee of the Russian Scientific Center for Restorative Traumatology and Orthopedics named after Academician G.A. Ilizarov". Animals were kept and surgical interventions were performed in accordance with the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (adopted in Strasbourg on 18.03.1986 and ratified in Strasbourg on 15.06.2006). All rabbits were euthanized 12 weeks after surgery using an overdose of barbiturates.

Fixation of the tibia with the implant inserted into it was carried out in a paraformaldehyde fixative (2% paraform, 2% glutaraldehyde in phosphate buffer, pH = 7.4) at 4 ° C. After 7 days, the bone was sawn in the longitudinal direction so that the fused implant with an open cut surface remained in one piece. The implanted bone pieces were dehydrated in increasing concentrations of ethanol (from 70 to 100%), immersed in camphene and air-dried. The resulting preparations were mounted on an electrically conductive base and sputtered with platinum and palladium ions in an IB-6 vacuum ion sprayer (Eiko, Japan). The preparations were examined under a JSM-840 scanning electron microscope (Jeol, Japan), images were obtained in the secondary electron mode. The calcium and phosphorus concentrations in the tissue substrate adhered to the surface of the implant metal structures were determined using an INKA Energy 200 X-ray electron probe microanalyzer (Oxford Instruments Analytica, UK) mounted on a JSM-840 scanning electron microscope. The results of the study were obtained in the form of elemental maps (Start Map) and quantitative elemental analysis data in weight percent.

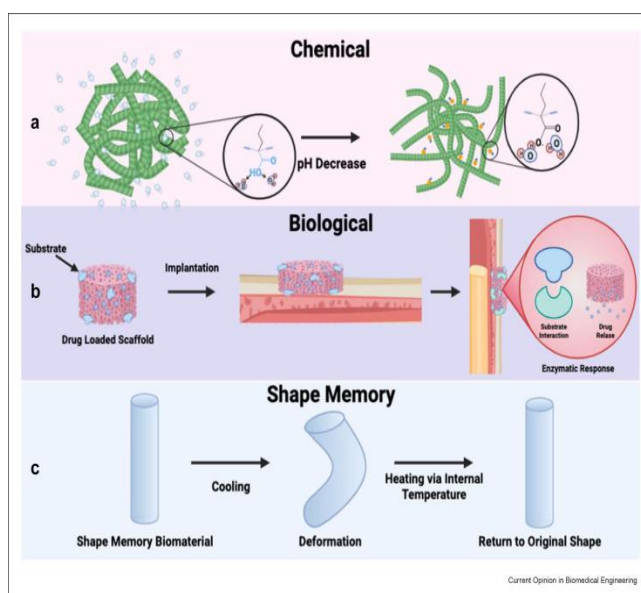


Figure 3.

Non-implanted tibia sections were decalcified in Richmann-Gelfand-Hill solution, dehydrated in increasing concentrations of alcohol, and embedded in paraffin. Longitudinal histological sections were stained with hematoxylin and eosin. Histotopographic sections 7–8 μm thick were prepared on a sledge microtome (Reichard, Germany) and stained with hematoxylin and eosin.

Microscopic light-optical examination of tibia histological preparations was performed using an AxioScope A1 stereomicroscope and an AxioCam IC 5 digital camera (Carl Zeiss Micro Imaging GmbH, Germany) with Zen blue software.

RESULTS AND DISCUSSION

The clinical condition of the rabbits during the experiment was satisfactory. In the first three days, edema was detected in the caudal region in all animals. In three rabbits,

purulent inflammation of the soft tissues around the implant was observed for 10-14 days. Purulent inflammation was stopped by antibiotic therapy for 7-10 days (Cefazolin 0.05 g / kg). The supporting function of the limb, as a rule, was restored on the 4-5th postoperative day and was present throughout the experiment. This technology made it possible to restore the function of the amputated limb for the first time in the early postoperative period.

Radiographs of three rabbits revealed the formation of canals and bone resorption around the implant by week 6 of the experiment, and severe osteoporosis of the cortical plate by week 12. In one case, a fracture of the tibia occurred at the level of its upper third.

In the other three rabbits, after 12 weeks, signs of osseointegration were detected at the interface between the implant and bone tissue. This was reflected in the preservation of the density and thickness of the cortical plate. There were no signs of bone resorption around the implant. In the projection of the bone marrow canal in the areas between the implant and the cortical plate, shadows of increasing radiopacity were noticeable, indicating endosteal osteogenesis (Fig. 2, d).

Studies using histological methods in these rabbits showed that by this time - 12 weeks after implantation of the metal structure into the medullary canal of the tibia - there were no signs of osteoporosis of the compact layer (Fig. 3, c). The bone tissue of the compact plate was firmly attached to the implant in the distal part of the tibia and had a normal structure along its entire length (see Fig. 3, a, c). In other areas, there was a gap between the implant and the compact plate, repeating the conical shape of the implanted structure, in which the formation of trabecular bone of the mesocellular structure connecting the inner surface of the compact plate and the surface of the implant embedded in the bone was noted (Fig. 3, f). The intertrabecular spaces were filled mainly with red bone marrow.

Formation of the "bone-implant" block after 12 weeks of the experiment: a - section of the tibia of a rabbit with an implant; b - implant surface with an adherent tissue substrate; scanning electron microscope (SEM), $\times 22$; c - compact plate; staining with hematoxylin and eosin; $\times 63$; d - electron image of the contact between the compact plate and the implant; SEM, $\times 22$; distribution map of Ca (red) and P (green) in the bone-implant block; e - trabecular bone in the space between the bone and the implant; staining with hematoxylin and eosin; $\times 400$; e - bone trabeculae, hematopoietic bone marrow in the space between the compact plate and the screw structure; SEM, $\times 150$; g, h - adhesion of bone matrix to the implant surface: g - SEM, $\times 350$; h - X-ray electron probe microanalysis map of the distribution of Ca (red) and P (green) on the implant surface (Fe implant material - blue); $\times 350$

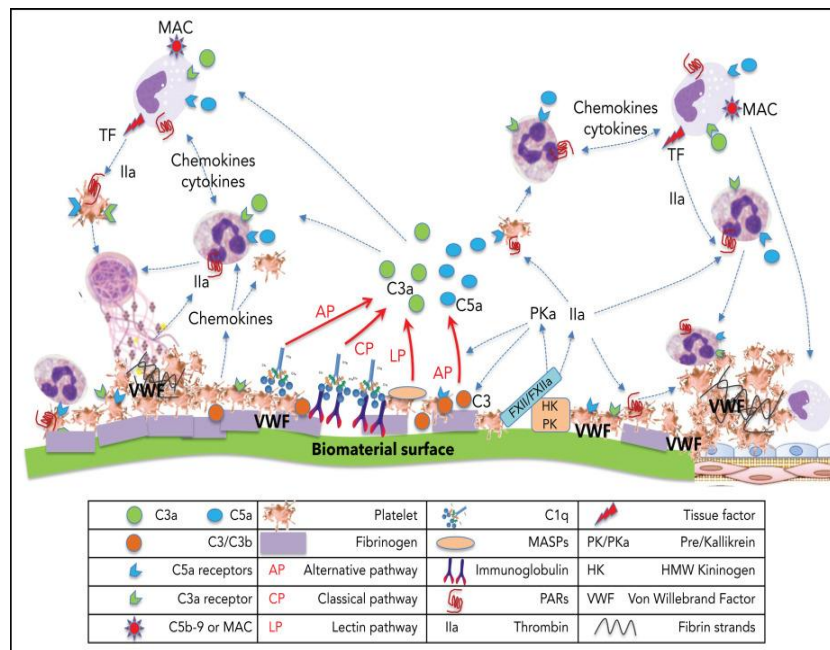


Figure 4.

When examining the tissue substrate attached to the surface of the implanted product using X-ray electron probe microanalysis, the presence of Ca and P was detected in it (Fig. 3, d , e , g , h), which indicated the formation of newly formed bone tissue in the studied sample.

When conducting quantitative studies, it was found that the Ca content in the newly formed bone tissue on the implant surface was 7-9%, with a Ca/P ratio of 0.3 to 1, which is reticulofibrous bone tissue in terms of the degree of mineralization.

This fact was also confirmed by the results of scanning electron microscopy. Both in the toothed grooves and in the ribs of the screw intraosseous structure, bone trabeculae were found, closely connected to the implant surface by the fibrous component (see Fig. 3, d). The tissue substrate contained osteogenic cells and hematopoietic bone marrow cells, which also confirmed the presence of newly formed bone tissue on the surface of the metal structure.

Similar results were typical for all areas of the implanted structure (Figure 4).

Adhesion of newly formed reticulofibrous bone tissue on the surface of an implanted intraosseous metal construct: a - c - areas of the implant surface in the lower, upper and middle thirds; SEM, $\times 22$; d - maps of Ca distribution on the implant surface in the lower, upper and middle thirds, respectively; X-ray electron probe microanalysis, $\times 22$

Discussion

Previous experimental studies have shown that one of the main components in the implantation of screw structures is to ensure the formation of a full-fledged "implant-bone" complex with sufficient strength to withstand mechanical loads [1]. Our study has shown that the use of additional technologies allows you to set the necessary parameters of the implant (surface structure, individuality in shape and size, etc.) to form a strong implant-bone block. In addition, the basic concept of the traditional technology of intraosseous prosthetics is a two-stage operation: in the first stage, the implant is installed

in the intramedullary canal, then after 3-6 months (when a strong bone-implant block is formed), the adapter prosthetic structures for fixation are attached to the implant through a skin incision. The entire duration of treatment (including the rehabilitation period) takes 6-18 months [2, 11]. When using the combined prosthetic technology developed by us with implant fixation using the Ilizarov apparatus, stability at the bone-implant interface and early loading of the limb are ensured before the onset of full osseointegration. This allows you to restore the function of the limb in a short time.

CONCLUSION

Fundamental Finding: This study concludes that screw implants made from a stainless steel-based alloy using additive manufacturing technologies demonstrate effective osseointegration, with newly formed bone tissue exhibiting sufficient mineral content to support functional mechanical loading after 12 weeks. **Implication:** These findings highlight the promising potential of additive manufacturing in the development of biocompatible, mechanically stable tubular bone implants, offering new opportunities for enhancing orthopedic implant design and performance. **Limitation:** The study's limitations include a small sample size, short observation period, and the use of an animal model, which may limit the generalizability of the results to human clinical applications. **Future Research:** Future research should focus on long-term clinical studies with larger sample sizes to validate these findings, explore the impact of different bioactive coatings on osseointegration, and optimize implant designs for improved performance in human orthopedic procedures. **Research Funding:** This work was supported by a grant from the Russian Science Foundation under the project "Establishment of Osseointegration Patterns of Medical Implants Based on the Production of Bioactive Coating Additives" (No. 16-15-00176).

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