FLUORIDE
Quarterly Journal of The International Society for Fluoride Research Inc.

Surface modification of dental implants in dentistry

Unique digital address (Digital object identifier [DOI] equivalent):
https://www.fluorideresearch.online/epub/files/293.pdf

Madi TLESHEV[1]*, Bakhyt NYSANOVA[1], Nazgul ONAIBEKOVA[1], Ruslan KULMANBETOV[1], Kubeisin ALTYNBEKOV[1]

[1]Department of Prosthodontics Dentistry
Asfendiyarov Kazakh National Medical University
050000, 94 Tole bi Str., Almaty, Republic of Kazakhstan

***Corresponding author:**
Assistant, Doctoral Student Madi Tleshev
Asfendiyarov Kazakh National Medical University
Department of Prosthodontics Dentistry
050000, 94 Tole bi Str., Almaty, Republic of Kazakhstan
E-mail: maditleshev998@gmail.com

Accepted: 2024 Oct 9
Published as e293: 2024 Oct 9

ABSTRACT

This research aims to analyze the quality of implants used in modern dentistry and formulate recommendations to enhance the surface of the dental product, thereby mitigating the potential consequences of the procedure. The key methods that were used in this study include experiment, observation, description, comparison, analysis, and justification. The stated methods focused on a detailed study of the topic, as well as helping to compare different implant surface modifications and highlight the more effective modification options. As a result of this research, it was found that sandblasting with acid etching takes root virtually without complications and is one of the most favorable and successful modifications. The many types of implant surface modifications are currently not officially recognized and require further research, especially long-term research. The effects of some dental surface modifications on bone and the patient’s body have not been studied enough. In clinical practice, only a small percentage of existing modifications are used; the success of osseointegration is not only influenced by the implant surface modification, so a comprehensive approach, which will also include oral hygiene and sanitation, is important during implantation. The results obtained and the summary formed have practical relevance for implant surgeons, dentists, developers of nanotechnology for dental implants, as well as researchers and authors who are engaged in the study of similar or related topics in the field of implantology or dentistry.

Key-words: *osseointegration; modification; bone tissue; roughness; peri-implantitis*

INTRODUCTION

Implantology is quickly evolving as a result of various variables, including advances in materials science, increased demand for cosmetic and functional dental restorations, and rising success rates for implant surgeries. Every year, new technologies emerge, as do several proposals for additional testing and increasing implant efficacy. One example of contemporary implantology innovation is the creation of surface modifications like nano-coatings, which improve osseointegration and shorten healing time. Osseointegration is the process by which a dental implant gets firmly attached to the surrounding bone.

This occurs when bone cells develop and bind directly to the implant surface, maintaining the implant's durability and long-term viability. Proposals for increasing implant function include investigating the use of bioactive materials that can encourage tissue regeneration and better integration with the surrounding bone. Additionally, technical improvements like computer-aided design and 3D printing enable more accurate implant placement and personalization, improving patient outcomes. The worldwide aging population, as well as the increased frequency of dental diseases, all contribute to the increase in demand and development.

This substantiates a need for research to test different, or at least the most commonly considered, modifications of dental implants. It is appropriate to evaluate efficacy and features at different stages in the studies. Conducting studies will help to more accurately assess the features of the modifications and introduce them into clinical practice as quickly as possible, which will significantly affect the success and effectiveness of dental implant patients.

Dental implants are widely used for the comprehensive treatment of dental patients who present with total or partial absence of teeth. Dental product manufacturers are incorporating various nanotechnologies into production, giving the implant certain properties. To date, implants have been modified in many ways with the primary goal of achieving optimal surface topography, imparting certain chemical and/or physical properties to a product, as well as introducing nanotechnology into a product.[1] Surface modifications of dental products are divided into mechanical, physical, and chemical methods.[2] Mechanical surface modification procedures like as sandblasting or machining provide micro-roughness, which enhances implant stability and osseointegration. Physical therapies such as laser and plasma spraying change surface qualities without altering the implant's chemical makeup, enhancing biocompatibility and quicker tissue integration. Chemical treatments like as acid etching or anodization alter surface chemistry, improving bone attachment and lowering the chance of implant rejection. S. Anjum and A. Rajasekar[3] stated that surface modification of titanium implants is a key factor to speed up osseointegration. This statement of the authors is reliable because if the surface of a product is as biocompatible as possible, the bone reaction to the foreign body will be accelerated. Thus, the probability of successful implant engraftment will increase significantly.

The study by M.A. Alfarsi et al.[4] from Australia shows that implants with changes like sandblasting and acid exposure (which make the surface micro-rough) help osseointegration happen faster and better than titanium products with only a mechanically processed surface. It can be assumed that the authors' words are true because the micro-roughened implant surface provides a stronger fusion with the bone than the smooth or relatively smooth surface. It should be noted that implantation is followed by a process of adaptation of the delineated bone to the titanium product in the bone. A study by I.S.L. Yeo[5] showed that bone cells reveal significant sensitivity to the topographic features of the implants, especially their surface. The author noted that such sensitivity during the formation of new bone tissue will contribute to the increased expression of bone genes. In addition, J.E. Davies[6] suggested that modified implant surfaces will be more accurately recognized and perceived by hard tissues because they will surround an implant, providing more bone material accumulation.

In addition, the researchers were concerned about the development of peri-implantitis. Peri-implantitis is a condition in which the tissue surrounding a dental implant becomes inflamed, typically as a result of infection or poor oral hygiene. It can cause bone loss and implant failure if not addressed immediately. They talked about peri-implantitis as a sickness where the lining of the mouth gets inflamed around a dental implant, losing its ability to hold the bone in place.[7] The authors suggested that the development of this process may be related to implant rejection as well as poor quality of the dental implant surface, particularly insufficient roughness. It is impossible to fully confirm or deny such data because the process of osseointegration is still not fully understood. In addition, Spanish researchers V. Astolfi et al.[8] stated that there are not enough clinical studies to follow the engraftment of implants with different surfaces in patients with the same problems.

Therefore, this research aims to examine various modifications of dental implants. In this research, the practical aspect of placing modern implant modifications (sandblasting with acid etching, laser treatment, ultraviolet treatment, fluoridation) is discussed in detail, and other modifications are theoretically described and analyzed. The scientific value of this study stems from its investigation and comparison of dental implant modifications that can improve osseointegration and reduce peri-implantitis risk. It compares surface treatments like sandblasting, laser therapy, UV treatment, and fluoride, examining their impact on implant durability, biofilm growth, and patient recovery. The research advances dental implantology by highlighting the effectiveness of these adjustments, paving the way for future studies to validate therapeutic benefits and refine implant design.

MATERIAL AND METHODS

This study employed a mixed-methods approach, combining empirical and theoretical research methods. The research design included an animal experiment, a systematic literature review, and comparative analysis. This study aimed to investigate the differential effects of various dental implant surface modifications, including sandblasting with acid etching, laser treatment, ultraviolet treatment, and fluoridation. The experimental cohort comprised 16 male Wistar rats, with body masses ranging from 250 to 275 grams. The subjects were randomly allocated into four equal groups and housed in separate laboratory enclosures, each provided with ad libitum access to food and water. Implantation procedures were conducted under general anesthesia, induced via intramuscular administration of xylazine (0.05 mg/kg body weight) and ketamine (80 mg/kg body weight). The subjects' respiratory and cardiac functions were continuously monitored throughout the surgical intervention. Post-operative recovery was closely supervised, and the animals were returned to their respective enclosures only upon full emergence from anesthesia. Veterinary care was administered as necessary.

The physiological response to the implants was evaluated over two months. Multiple parameters were assessed, including appetite, general activity, body weight fluctuations, gingival condition, and inflammatory processes. To facilitate comparative analysis, data were systematically recorded in tabular format, encompassing the aforementioned parameters and their corresponding outcomes.

The study focused on the presentation and characterization of the analyzed data. An extensive review of scientific literature was conducted using analytical methodologies. The investigation encompassed a comprehensive examination of diverse dental implant modifications, their fundamental principles, and distinguishing features. Furthermore, the research explored the potential for successful patient outcomes utilizing these implant surface modifications. Comparative analysis was employed to elucidate shared characteristics among various dental implant modifications, evaluate their osseointegration efficacy, and assess the likelihood of postoperative complications. The findings were subsequently juxtaposed with those of preceding studies. The justification method was utilized to corroborate or refute hypotheses proposed by previous researchers through the presentation of compelling arguments and empirical evidence.

Moreover, the study advocated for further clinical investigations to evaluate the long-term efficacy of various dental implant surface modifications and their potential impact on the development of inflammatory and/or infectious processes at the site of intervention. A synthesis approach was implemented to identify common attributes across different dental implant surface modifications.

A study was approved by the Ethics Commission of the Asfendiyarov Kazakh National Medical University, No. 15841. Studies from 2000 to 2023 were included in this paper with the following keywords or phrases: “implant surface modifications”, “dental implant modifications”, “implant surface”, “dental implant surface”, “implant surface processing method”, “osseointegration”, “dental implant engraftment survival”, and similar word combinations. It should be noted that almost all of the selected scientific material was published not earlier than 2000. Earlier studies were also considered because they provided general theoretical or historical information that has practical relevance in modern dentistry and implantology. Research materials and suitable medical literature were searched through specific search engines, which include Google Scholar, Semantic Scholar, Eagle-i, BASE, and the Dentistry and Oral Sources databases. In addition, medical literature was searched in online scientific libraries MedlinePlus, Medline (via PubMed), Scopus, the National Center for Biotechnological Information (NCBI), and JURN. In addition, the sources indicated in the list of references to previous research papers were analyzed and included in this study.

Works of Kazakh, American, Chinese, German, Austrian, Norwegian, and other authors were included in this research. The selected scientific material was aimed at consideration of different types of dental implant surface modifications, substantiation of the effectiveness of the considered modifications and their drawbacks, substantiation of unexplored practical aspects of different modifications, recommendations for improvement or creation of effective and safe modifications (physical, chemical, molecular), and consideration of current problems that prevent the implementation of the available dental implant surface modifications in clinical practice.

RESULTS

Traditional implantation includes several stages: placement of an implant (if necessary, bone grafting can be performed during this procedure), placement of a gum former, placement of an abutment, and a crown. First of all, the body’s reaction to a foreign body (implant) depends on many factors: design and correctness of the connection of a dental implant with an abutment, position of a product in a jawbone, geometry of an implant, surface type, amount, and density of bone tissue. According to S. Nimbalkar et al.,[9] a bone loss of 1 millimeter within one year of implant placement and 0.2 millimeters of bone within the following year would be considered a failed implant. In this case, it will be necessary to remove the improperly placed implant and replace it with a new one. In addition, it is important to understand that dental implant modifications directly affect osseointegration and biofilm formation. In this research, the most commonly studied dental implant modifications (sandblasting with acid etching, laser treatment, ultraviolet treatment, and fluoridation) were considered. It should be noted that titanium implants were selected for the experiment, but some modifications would have been appropriate to perform on products made of other materials.

Dental implant materials should have such qualities as biocompatibility, hypoallergenicity, and chemical inertness, as well as stability and resistance to corrosion.[10] Today there are titanium, zirconium, tantalum, and magnesium implants, as well as stainless steel products. In modern implantology, a dental implant is most often made of titanium or titanium alloy. Some authors attribute the advantages of titanium materials to the high level of biocompatibility, which is achieved through its oxidation process.[11] Zirconium is characterized by high reactivity in its interaction with water and oxygen. Furthermore, the zirconia implant has demonstrated aesthetic appeal, as its natural ivory color prevents it from being visible in the patient's gums. It should be noted that the titanium product has dark shades, which makes the implant unaesthetic. It is titanium implants that are most commonly used in clinical practice.

Studies on miniature pigs (implants were inserted in the lower jaws) have demonstrated that the healing of bone tissue and engraftment of the zirconium implant proceeded better than the titanium product.[12] In addition, implants made of titanium-zirconium alloys already exist today and have demonstrated improved mechanical properties, higher strength, and load endurance. Straumann Institute AG (Switzerland) is a manufacturer of titanium-zirconium dental products. There are no long-term studies to date that can 100% confirm the claimed properties of dental products. Tantalum implants are produced using a special technology that ensures the product's porous structure. The reason for the rare use of this material is the low prevalence of tantalum. Today, only one American company, Zimmer (USA), produces tantalum dental implants. A study by A. Ore et al.[13] demonstrates that implantation with tantalum products does not cause inflammatory processes, and no corrosion process is observed. Analyzing such data, it can be noted that tantalum implants can significantly reduce the probability of peri-implantitis development as well as prevent the development of infectious processes.

Magnesium implants are very different from the previous ones, as these products are considered only temporary implants. Recent studies show that the magnesium implant has a fairly high biocompatibility rate.[14] According to the author, during healing, the mechanical stiffness and strength of the implant slowly decrease, and the soft and hard tissue surrounding the implant begins to fuse, gaining strength and stiffness. Thus, magnesium dental products can only be used as a temporary implant to avoid repeated surgical intervention. It should be noted that the dissolution of magnesium dental implants is not harmful to the body in any way. Because of its nickel content, the stainless steel product is prone to pitting corrosion. Previous studies have shown that the body can develop an allergic reaction to a foreign body (implant) made of stainless steel.[15] Also, stainless steel provokes bacterial colonization, leading to infection, inflammation, and further rejection of an implant.[16] So, today stainless-steel products are not used or are installed temporarily, with mandatory further removal.

Before the experiment, a closer look at the implant modifications should be taken. The leading place in modern implantology is taken by the creation of a micro-roughened modification of the implant surface, which is achieved by sandblasting. The authors, M. Ozcan and C. Hammerle,[17] stated that giving the dental product a micro-roughened structure significantly increases the contact surface area and the load distribution occurs more efficiently. This provides direct contact between the bone and the implant. This technology creates coarse-grained sand particles on the surface of a dental implant, giving it a rougher surface. As a rule, the size of these particles does not exceed 500 µm (375 µm on average).[1] After sandblasting the implant surface, the product undergoes acid treatment (etching). Interestingly enough, sandblasting along with acid treatment significantly affects bacterial development and biofilm formation.[18] The acidic assets are often powerful acids: hydrochloric acid, sulfuric acid, or nitric acid. Under the influence of acids, the oxide layer is destroyed, and any existing impurities that may have formed during the threading process are eliminated. After acid etching, all irregularities on the surface of a dental product become uniform. According to A. Jemat et al.,[2] electron microscopy of the treated implant reveals clear irregularities with relatively large depressions and pits, as well as protruding particles, including sharp ones. The presence of various irregularities provides a reliable bond between the implant and the bone tissue, ensuring quality osseointegration.

The molecular modification of a dental product is referred to as laser treatment. Laser treatment can create additional microscopic patterns that will further bond the implant to the bone, which is likely to improve the quality of osseointegration and load distribution performance. This type of modification had the goal of successfully fusing an implant to the connective tissue as well, according to G. Asensio et al.[19] Absorption of laser particles by titanium or titanium alloys can lead to the destruction of an implant's macro-, micro-, and nano-level properties.[20] In addition, the author stated that despite successful engraftment and high osseointegration quality, such a product is prone to pathological changes. Currently, there are no clinical studies that demonstrate the success of laser-modified implants in treating patients with missing teeth. In this research, the laser-modified implant showed good results, although symptoms such as swelling and temporary loss of appetite were noted in the rats during the early recovery period. However, this modification requires further clinical research and improvement. Perhaps this modification would be appropriate for tantalum implants, which have beneficial antibacterial and anti-inflammatory properties.

Ultraviolet surface treatment of implants involves treating an implant with ultraviolet light to increase the osseointegration level. Currently, the ultraviolet exposure method is understudied. Previous researchers have suggested that this method may have an impact on the hydrophilicity of the surface.[21] In other words, according to the author, this modification contributes to the fact that fibroblasts are anchored, providing a strong connection between the tissues that surround an implant. The lack of studies on this topic makes it impossible to confirm or refute the hypothesis. At the same time, an interesting fact is that treatment of the implant surface with ultraviolet light promotes amphiphilicity.[22] J.B. Lee et al.[23] compared two modifications of dental implants: with ultraviolet treatment and with sandblasted coarse-grained, followed by acid treatment (etching). According to the study, ultraviolet treatment of the dental implant demonstrated an earlier osseointegration time. It can be assumed that the improved performance of the UV-treated surface was related to the hydrophilicity of the surface as well as to the increased activity of osteoblasts. As of now, there are no definitive results regarding the efficacy and appropriateness of UV treatment of dental implants.

Fluoridation of the implant surface promotes faster bone formation around the product and provides bone mineralization. Fluoridation strengthens the bone and makes it stronger, which greatly reduces the risk of implant instability. A fluoride-treated implant has previously been reported to fuse more firmly to the bone than a sandblasted implant.[24] Fluoride, on the other hand, can cause the titanium product to corrode. As a result, fluoridation can cause destruction of the implant structure. There are no long-term clinical studies to date, so it is inappropriate to claim that this modification is ineffective. In this research, four modifications of dental implants were tested. These modifications were chosen because of their popularity and the fact that they have often been considered in previous studies. In addition, the selected modifications have promising prospects and potential efficacy, particularly in osseointegration. Tables 1-4 describe the experimental results after 3 days, 14 days, one month, and two months, respectively, after dental implantation in rats.

Table 1. Comparative table of the condition of the rats at day 3 after the placement of dental implants.

Comparable parameters	Group 1	Group 2	Group 3	Group 4
Appetite	No particular changes were noted in any of the rats	No particular changes were noted; on the first day one rat showed less appetite, after 12 hours appetite normalized	No particular changes were noted; one rat ate noticeably less than the others for the first three days, after which its appetite normalized.	One of the rats (No. 1) had a decrease in appetite during the first three days
Animal behavior	Normal; moderately active	Normal; moderately active	Normal; moderately active	Normal; moderately active, but rat No. 1 showed less activity during the first three days, drowsiness was noted
Loss in body weight	None	None	One rat experienced a slight weight loss of 2 grams	Rat No. 1 experienced a weight loss of 4 grams
Gum condition	No pathological changes were noted; all rats had swollen gum	No pathological changes were noted; three rats had pronounced swelling of the gum, one of them had swelling spreading to the entire jaw	One of the rats had minor bleeding in the area of intervention, the second rat had an increased exudate without a characteristic odour	No pathological changes were noted; three rats had slight swelling of the gum and surrounding areas
Temperature	38.7℃ 38.4℃ 38.9℃ 39℃	38.3℃ 38.7℃ 38.8℃ 38.5℃	38.8℃ 38.5℃ 38.6℃ 38.4℃	38.9℃ 38.5℃ 38.5℃ 38.7℃

Table 2. Comparative table of the condition of the rats at day 14 after the placement of dental implants.

Comparable parameters	Group 1	Group 2	Group 3	Group 4
Appetite	No particular changes were noted in any of the rats	No particular changes were noted in any of the rats	No particular changes were noted; for two days, one of the rats drank less water, but appetite was normal;	No particular changes were noted in any of the rats
Animal behavior	Normal; moderately active	Normal; moderately active	Normal; moderately active	Two rats showed slight drowsiness and sluggishness
Loss in body weight	None	None	None	One rat experienced a weight loss of 2 grams
Gum condition	No pathological changes were noted	No pathological changes were noted; of the three rats that had previously had edema, only one rat had slight swelling, and only in the intervention area	One rat had redness of the gum	No pathological changes were noted
Temperature	38.8°C 38.7°C 38.4°C 38.7°C	38.8°C 38.5°C 38.5°C 38.6°C	38.4°C 38.9°C 38.3°C 38.5°C	38.6°C 38.4°C 38.7°C 38.5°C
Divergence of sutures	None	None	None	None
Dental plaque (on wound surface, affected or healthy teeth)	One rat had minor plaque on the wound surface and two nearby teeth	None	None	None
Additional	None	None	On the tenth day, one of the rats was actively rubbing its face with its paws (as when washing)	None

Table 3. Comparative table of the condition of the rats at one month after the placement of dental implants.

Comparable parameters	Group 1	Group 2	Group 3	Group 4
Appetite	No particular changes were noted in any of the rats	No particular changes were noted in any of the rats	No particular changes were noted in any of the rats	No particular changes were noted in any of the rats
Animal behavior	Normal; moderately active	Normal; moderately active	Normal; moderately active	Normal; moderately active
Loss in body weight	One rat experienced a weight loss of 2 grams	None	None	None
Gum condition	No pathological changes were noted	No pathological changes were noted	No pathological changes were noted	No pathological changes were noted
Temperature	38.7℃ 38.7℃ 38.4℃ 38.9℃	38.5℃ 38.7℃ 38.6℃ 38.5℃	38.8℃ 38.7℃ 38.5℃ 38.7℃	38.6℃ 38.5℃ 38.4℃ 38.7℃
Divergence of sutures	One of the rats had minor plaque on the teeth near the implant area	None	None	None
Dental plaque (on wound surface, affected or healthy teeth)	None	None	None	None

Table 4. Comparative table of the condition of the rats at two months after the placement of dental implants.

Comparable parameters	Group 1	Group 2	Group 3	Group 4
Appetite	No particular changes were noted in any of the rats	No particular changes were noted in any of the rats	No particular changes were noted in any of the rats	No particular changes were noted in any of the rats
Animal behavior	Normal; moderately active	Normal; moderately active	Normal; moderately active	Normal; moderately active
Loss in body weight	None	None	None	None
Gum condition	Within the norm	Within the norm	Within the norm	Within the norm
Temperature	38.5℃ 38.6℃ 38.4℃ 38.8℃	38.7℃ 38.6℃ 38.5℃ 38.3℃	38.6℃ 38.7℃ 38.7℃ 38.4℃	38.8℃ 38.7℃ 38.7℃ 38.9℃
Divergence of sutures	None	None	None	Two rats had minor plaque on nearby teeth
Dental plaque (on wound surface, affected or healthy teeth)	None	None	None	None

According to Table 1, there was a decrease in appetite in three groups of experimental rats at once. This factor can be connected with the surgical intervention on the rats' jaws since the animals could feel considerable discomfort, as well as have a limited ability to open their mouths fully and make moving and chewing movements with their jaws. The decreased activity of the rats in group No. 4 may be related to the stress factor and the sensation of a foreign body, which may make the rat uncomfortable to move and perform other activities. In addition, the mobility of the animals after the implantation procedure is significantly affected by the individual characteristics of the body as well as the rat's perception of the foreign body (implant). Loss in weight of the same rats is not critical, because such phenomena as sedentary behavior, loss of appetite, and loss in weight are the normal reactions of the organism in the first three days after the surgical intervention. The temperature of absolutely all rats was within normal limits. Weakening of the suture in the rats of group No. 3 was eliminated. After implantation, loosening of the suture can lead to implant instability, increasing the likelihood of rejection. No additional observations were noted in the first three days. Overall, the response of all rats was tolerable, and no complications were noted.

According to Table 2, no serious pathological changes or complications were detected in either group of rats after two weeks following implantation. Likely that the reduced water consumption of the rats in group No. 3 is related to the individual characteristics of the organism or other factors unrelated to the implantation. The decrease in activity in the rats of group No. 4 can be connected with the feeling of discomfort after the surgical intervention, as well as with the body's natural reaction to the foreign body. It should be noted that a laser-treated implant is more likely to cause inflammatory processes. No signs of inflammation were detected in these rats, so it can be concluded that this factor is related to the fact of the intervention itself and not specifically to this modification of the implant. This observation is interesting and may require additional study since the activity remained at the same level in the rats from other groups. In addition, the rats from the same group (No. 4) showed weight loss. This figure is not critical and is also not a serious complication, provided the animal does not have an elevated temperature and/or symptom of inflammation or infection. All of the experimental animals' temperatures were within normal ranges. One of the rats in group No. 1 had a plaque on both the wound surface and adjacent teeth. An interesting fact is that the rougher the implant, the higher the risk of plaque. As a result, this phenomenon is not considered a serious complication or consequence but rather the norm. Other than that, plaque poses no risk of implant rejection. Although plaque (especially in the surgical area) needs to be removed and regularly monitored because its presence may further contribute to the development of peri-implantitis. In additional observations, it was also noted that one of the rats from group No. 3 often rubbed its muzzle with its paws. This phenomenon could be related to discomfort or sensation of a foreign body in the jaw. This did not affect the behavior or appetite of the rat in any way, so it can be concluded that this behavior is directly related to the implantation procedure itself. It should be noted that the sutures were removed on the eighth day after implantation in all animals.

According to Table 3, no complications or pathological changes were observed in any of the rats. Despite this, the rats of group No. 1 had such phenomena as dental plaque on the teeth adjacent to the intervention area, as well as weight loss in one of the rats. These phenomena may be related to the peculiarities of the implant structure. The weight loss one month after the intervention could probably not be related to the implant and was most likely caused by another factor. The results obtained can be considered successful since none of the animals developed an inflammatory process and absolutely no complications were noted.

According to Table 4, after two months following implantation, none of the groups showed any serious or pronounced complications related to a particular dental implant modification. At the same time, there were pronounced differences in the recovery period. This period was most easily tolerated by the rats in group No. 1. Particular attention should be paid to the absence of pronounced edema, because edema developed in groups No. 2, No. 3, and No. 4, in some cases even spreading to the surrounding areas or the entire jaw. In the case of the sandblasted and acid-etched implant, there was only slight swelling at the surgical site. Early plaque was also noted in the same group (No. 1). It should be noted that the appearance of plaque on the teeth or wound surface is not a complication, although its early occurrence can significantly increase the risks of inflammation. Thus, plaque requires constant monitoring and good oral hygiene.[25]

Analyzing the data in the tables, it can be testified that implantation was successful for all four groups of rats. The data from group No. 1, which involved the modification of the dental implant through sandblasting and acid etching, can be deemed the most successful. No significant differences between the modifications of dental implants were found. This experiment is not long-term, and it can be assumed that some animals may have developed peri-implantitis after some time (e.g., a few more months). Animals that had plaque (groups No. 1 and No. 4) were particularly at risk. Overall, at the end of the experiment period, it can be judged that all tested dental implant modifications were successful since none of them contributed to the development of peri-implantitis or inflammatory and infectious processes. In addition, no complications or implant rejection were observed. Such data may testify to the effectiveness of the tested implant modifications. The obtained results allowed for only the early period after surgical intervention. Long-term studies would be appropriate to obtain more accurate, informative, and statistical data.

DISCUSSION

Other modifications should also be considered, the practical aspect of which was not addressed in this research. Physical modifications of dental implants are divided into three levels: macro, micro, and nano. Macro-level modifications refer to the shape of the dental product, the thread shape or pattern, and any existing irregularities on the implant surface. Thus, macromodification ensures the structure's reliability, the level of mechanical contact of the implant with bone tissue, and the quality of the product's fusion with bone. According to R. Jimbo et al.,[26] macromodification is the foundation for successful treatment of a patient with missing teeth. The implant's threading is critical to ensuring a successful initial contact as well as the product's continued stability in the jaw cavity.

According to the study by E. Reinaldo et al.,[27] a statistically insignificant difference was found between shallow- and deep-threaded implants. In addition, M. Menini et al.[28] noted that the shallower thread is easier to insert, while the deep-threaded implant requires more torque and achieves better primary stability. It should be noted that the thread is also able to influence load distribution to a large extent, as a greater grip of an implant on the bone will provide a more even load on the entire bone. Thus, it can be assumed that a deep thread will show better load distribution results than a shallow pattern. Nevertheless, previous researchers have not paid much attention to this issue, so it is impossible to draw definitive conclusions according to this hypothesis.

Micro-level modifications focus on achieving improved osseointegration and engraftment success. In addition, micromodifications influence the growth and amount of bone around an implant, as well as its successful fusion with the surface of a dental product. Treatments of the implant surface are known as micro-level modifications. Nano-level modifications began to be actively used in modern implantology not so long ago. Scientists used to think that bone cells are not able to recognize at least some nanostructural changes on the dental implant surface.[28] But modern researchers have proven that osteogenic cells can respond to any changes created at the nanoscale. According to I.S.L. Yeo,[5] bone cells are sensitive to such changes as the location of titanium dioxide nanotubes, surface treatment with different substances (e.g., fluorine), and ultraviolet treatment. It was noted that changes in the surface of a dental implant at the nanoscale have a significant role in the initial biological reactions of the bone tissue. The author's reactions imply that osteoblasts and osteoclasts are active and react. However, previous researchers have long believed that the introduction of nanoscale changes to the surface structure of a dental product in no way affects the osteogenic reactions.[29,30]

According to research, the creation of nanostructures is able to significantly influence the initial response of the hard tissue to the foreign body (implant).[31] In addition, the activity of osteoblasts is increased and the reaction of osteoclasts is accelerated, which also leads to faster and better osseointegration. Dental implant surfaces are also modified by introducing arrays of titanium oxide nanotubes. The contact of the implant surface modified by this method even with osteoporotic bone (the experiment was carried out in vivo on rats) was a successful result. It should be noted that the implant engraftment in osteoporotic bone is minimal.[32] In addition, the maximum level of bone cells' reaction to the implant surface with nanotubes with a diameter of 15 nanometers was noted. It was reported that the surface with titanium oxide nanotubes of 30 nanometers showed greater efficiency than the surface with larger nanotubes with a diameter of 100 nanometers or more.[7] It should be noted that such an implant surface has antibacterial properties as well as preventing the development of bacteria on the product. Even though there are some controversial points concerning bacterial development, it has been noted that the hydrophilicity of the surface prevents bacterial development.[33]

At the same time, M.F. Kunrath et al.[34] linked bacterial adhesion to surface hydrophobicity. At the moment, there are not enough studies to fully confirm or refute the hypotheses of the authors. Due to the lack of studies on the effectiveness of nano-level modification by forming titanium oxide nanotubes, this modification has not yet been used clinically. To date, studies on animals or artificial bones are ongoing to evaluate the effectiveness of this type of modification. In addition, the problem of possible delamination of the coating, which has been reported by previous researchers, needs to be addressed.[16;35] This problem may be because the level of mechanical strength between the titanium oxide nanotubes and the main surface is low for a strong bond. It can be assumed that in the long term, delamination of the nanosurface will occur, which can provoke various consequences for the patient, including those that would require immediate removal of an implant. There is also nanocomposite modification of the implant surface, which aims at creating coatings that are as similar as possible to natural bone. So far, such nanoparticles as silver, pectins, hydroxyapatite, carbon nanotubes, and cubic zirconia have been tested.[20]

The presence of these nanoparticles is also aimed at improving biocompatibility and accelerating the osseointegration of a dental product. It should be noted that the presence of nanoparticles can significantly reduce the risk of inflammatory and/or infectious processes. Currently, the most common inorganic antibacterial coating is silver. It has been noted that silver has a wide range of antimicrobial properties against Gram-negative and Gram-positive bacteria.[36] Previous animal studies have demonstrated that implantation with silver nanoparticles significantly reduced the development of peri-implantitis.[37] Chemical modifications aim not only to improve osseointegration but also to minimize the likelihood of biofilm formation. One such method is discrete crystal deposition. In this modification, an implant undergoes a double-acid treatment, after which calcium phosphate particles are formed on the surface. Typically, the particles range in size from twenty to one hundred nanometers. Once the procedure is completed, the implant surface will comprise half of the stated substances. Animal tests in the past have shown that this change makes the product better at contacting bone and improving nanotypography, which leads to higher success rates for implant engraftment and faster healing.[20]

The next method is anodic oxidation. This modification aims to create a thicker titanium oxide layer while also reinforcing the entire implant body. In the process of anodic oxidation, the layer of the substance increases tens of times, reaching from six hundred to one thousand nanometers. It is reported that this modification endows the implant surface with the ability to regenerate bone cells and is a reliable framework for bone formation.[38] A study by A. Rocci et al.[39] on monkeys demonstrated that the percentage of contact with an implant was 74% when an anodic oxidation modification product was implanted into very thin bone. In addition, it was noted that this modification had a 100 percent survival rate and no signs of infection or pathological processes.[40] Overall, anodic oxidation is a fairly successful modification because no deleterious effects of the implant on the patient have been reported to date. In addition, no cases of para-implantitis or the development of other inflammatory processes have been reported. Therefore, it can be assumed that anodic oxidation is a promising method in modern implantology.

The hydroxyapatite-modified dental implant surface is osteoconductive. It should be noted that this material is used most frequently compared to other types of coatings. The creation of such a modification is often provided by plasma spraying. It was mentioned in the previous studies that such modification of the implant surface is appropriate to use in cases when it is necessary to achieve the fastest possible fusion of an implant and the bone tissue. However, it is currently impossible to make any statement about the complete safety of this modification because there are very few studies (including long-term studies) considering it. M. Albertini et al.[41] noted that hydroxyapatite modifications caused complications around an implant. In addition, there is a possibility of dental implant structure failure or deformation due to the thickened spray layer. Thus, it is also impossible to fully evaluate this method, as there are favorable and controversial points.

Other modifications include plasma oxidation, extracellular matrix, surface coating with different types of peptides (including bactericidal ones), and coating with proteins. Yet, most modifications are currently unstudied and require additional clinical studies, especially long-term ones. In general, the study of the medical literature in the field of dentistry and implantology allows stating that the topic of creating quality implants that will not have a deleterious effect on the patient's bone has not been fully explored so far. Currently, research is ongoing to improve implant surfaces and give them certain properties (physical, biological, and molecular). Due to the fact that most implant surface modifications are never used in clinical practice, there is little evidence that they work. It should be noted that this situation is due to the lack of long-term studies as well as insufficient knowledge about each of the modifications.

The question of optimal depth and thread pattern is also controversial. Some scientists believe that shallow threading has better prospects than deep patterns because shallow threading has a lower percentage of contact and fusion with the bone. According to S. Y. Lee et al.,[23] an implant with a deeper thread can greatly increase the strength of contact and fusion between the surrounding bone and the dental implant, as well as contribute to greater primary stability in areas with insufficient or thinning bone tissue. According to the authors, relatively greater thread depth will not affect mechanical strength in any way. Such data may be true because a deep thread provides a stronger contact with the bone tissue, which may even increase the level of mechanical strength. In addition, E. Reinaldo et al.[26] mentioned the importance of thread pitch. According to the study, a shorter pitch (i.e., greater and more frequent repetition of the thread branches) provides a larger direct contact area between an implant and a bone. Such data suggest that more successful osseointegration can be achieved by using a short thread pitch that is not necessarily deep. However, such assumptions are only theoretical, as there are currently no conclusively established scientific facts and hypotheses that can confirm or refute this hypothesis.

R.C. Costa et al.[42] point out that new modifications must be created because the key goal is not only to improve osseointegration and engraftment rates of dental implants but also to prevent the development of infections, including polymicrobial infections. At present, implant surface modifications such as laser treatment and nanoparticle treatment can be used to reduce the risk of inflammatory or infectious processes. In addition, there is currently a debate about the optimality and effectiveness of hydrophobic and hydrophilic dental implant surfaces. Research by some authors demonstrates that the type of surface (hydrophobic and hydrophilic) is completely irrelevant since both types of dental products have shown successful clinical results. Despite that, researchers M.A. Alfarsi et al.[4] concluded that the hydrophilic modification of the dental implant surface significantly affects platelet activation. It should be noted that platelets come into direct contact with the implant very first, followed by the release of a large number of proteins, which affects further wound healing after the intervention. The study found that only a few platelets stuck to the hydrophilic surface, which was also micro-rough. This was compared to other surface changes, which were smooth and micro-rough.

Biofilm formation remains an important problem in implantology, which is considered a key factor in the development of inflammatory processes (often peri-implantitis).[42] Furthermore, such consequences can lead to the rejection of a dental implant. It should be noted that the rejection of an implant can occur 3-5 years after the procedure. A study by R.C. Costa et al.[43] demonstrated that certain normal body reactions to a foreign body (dental implant), such as exposure to carbohydrates and large amounts of microorganisms, as well as others, contributed to the transition of bacteria from normal to pathological states. The authors also note that in combination with the body's reduced sensitivity to antimicrobial drugs, killing microbes becomes a very difficult process. Such data may indicate a lack of competent approaches to the treatment of implant consequences, regardless of the type of modification of the dental surface. Indeed, there is currently no single clinically documented solution for the adequate and effective treatment of peri-implantitis. As a result, there is a critical need for follow-up studies to formulate the optimal treatment plan or prevent the development of peri-implantitis, taking into account the various surface modifications of dental implants.

It is important not to forget that other factors can have a significant impact on the process of osseointegration, the success of implant engraftment, the development of inflammatory and infectious processes, and many other consequences. The main ones include oral hygiene, the presence of chronic diseases in a patient, as well as the patient's lifestyle and diet. Previous researchers have made little mention of the effects of siltation factors on osseointegration and/or the development of inflammatory and infectious processes. D. Baldi et al.[44] also mentioned that performing oral hygiene and sanitation prior to the implant procedure can significantly increase the chances of successful osseointegration and prevent the development of various consequences. This data demonstrates the importance of oral hygiene because oral bacteria (normal) can be detrimental to implant placement, causing complications.

In addition, the importance of strain during the first month of dental implant placement was mentioned.[45] According to the author, a high degree of stress on the dental implant can cause instability of the product in the bone, as well as improper fusion (sometimes no fusion) of the implant with the bone. Such data indicate the need for a comprehensive approach to the installation of dental implants. In other words, it is important to consider not only the surface modification of a dental product but also its shape and size, thread pattern, and depth, as well as the amount and density of the patient's bone tissue. Post-op implant engraftment success depends on patient actions for the next month. In addition, S.Y. Lee et al.[46] stated that the modification of the implant surface directly affects the healing of the postoperative wound after the placement of a dental product. The authors concluded that implant surface modification, which involves sandblasting followed by acid etching, showed good wound healing results compared to other modifications. In this research, the experiment also demonstrated that the wound healing process in the case of the sandblasted and acid-etched implant was quite fast, without much swelling. Thus, the author's theory can be confirmed.

Currently, it is quite difficult to predict the successful engraftment of the implant into the bone, as well as to guarantee the successful treatment of a dental patient with the installation of a modified dental product.

CONCLUSIONS

The experiment testing four dental implant modifications (sandblasting with acid etching, laser treatment, ultraviolet treatment, and fluoridation) on rats showed that all modifications were successful, with no significant complications or implant rejections observed over two months. Implant modification with sandblasting and acid etching was found to be more favorable, which is especially noticeable in the early recovery period (the first 3-7 days). Compared with laser, ultraviolet treatment, and fluoridation dental implants, the sandblasted implant did not cause severe swelling or other side effects (e.g., bleeding or exudate leaking from the wound surface). It was found that all the dental implant modifications under consideration two months after placement did not cause inflammatory and/or infectious processes, nor did they affect the viability of the rats.

While all tested modifications were deemed effective in the short term, the study highlighted the need for long-term research to assess potential late complications like peri-implantitis. The research emphasized that successful implantation depends on multiple factors beyond surface modification, including oral hygiene, patient health, lifestyle, and diet. Also noted is the importance of considering not only surface modifications but also implant shape, size, thread pattern, and bone density for comprehensive implant success. The research underscored the critical need for long-term clinical studies to fully evaluate the effectiveness and safety of various implant surface modifications, particularly in preventing inflammatory and infectious processes like peri-implantitis. Future research should include long-term clinical trials to assess the durability and potential late-onset problems, such as peri-implantitis, related to various implant surface alterations. Furthermore, studying the effects of these changes on implants composed of newer materials like tantalum and magnesium might give valuable insights into improving implant function and lowering rejection rates.

FUNDING

Not applicable

CONFLICT OF INTERESTS

None

REFERENCES

[1] Luke IS. Modifications of dental implant surfaces at the micro- and nano-level for enhanced osseointegration. Materials 2020; 13(1): 89.

[2] Jemat A, Ghazali MJ, Razali M, Otsuka Y. Surface modifications and their effects on titanium dental implants. BioMed Research International 2015: 791725.

[3] Anjum S, Rajasekar A. Surface modification of dental implants – A review. Journal of Evolution of Medical and Dental Sciences 2021; 10(17): 1246-1250.

[4] Alfarsi MA, Hamlet SM, Ivanovski S. Titanium surface hydrophilicity enhances platelet activation. Dental Materials Journal 2014; 33(6): 749-756.

[5] Yeo ISL. Modifications of dental implant surfaces at the micro- and nano-level for enhanced osseointegration. Materials 2020; 13(1): 89.

[6] Davies JE. Invited commentary: Is osseointegration a foreign body reaction? The International Journal of Prosthodontics 2019; 32(2): 133-136.

[7] Kim JJ, Lee M, Yeo SI. Three interfaces of the dental implant system and their clinical effects on hard and soft tissues. Materials Horizons 2022; 9(5): 1387-1411.

[8] Astolfi V, Rios-Carrasco B, Gil-Mur FJ, Bullon B, Rios-Santos JV, Herrero-Climent M, Bullon P. Incidence of peri-implantitis and relationship with different conditions: A retrospective study. International Journal of Environmental Research and Public Health 2022; 19(7): 4147.

[9] Nimbalkar S, Dhatrak P, Gherde C, Joshi S. A review article on factors affecting bone loss in dental implants. Materials Today: Proceedings 2021; 43(4): 970-976.

[10] Bruschi M, Steinmuller-Nethl D, Goriwoda W, Rasse M. Composition and modifications of dental implant surfaces. Journal of Oral Implants 2015: 527426.

[11] Ehrenfest DMD, Coelho PG, Kang BS, Sul YT, Albretksson T. Classification of osseointegrated implant surfaces: Materials, chemistry and topography. Trends in Biotechnology 2010; 28(4): 198-206.

[12] Schultze-Mosgau S, Schliephake H, Radespiel-Troger M, Neukam FW. Osseointegration of endodontic endosseous cones: zirconium oxide vs titanium. Oral Surgery, Oral Medicine, Oral Pathology and Oral Radiology 2000; 89(1): 91-98.

[13] A, Geronimo D, Huaman M, Calsin N, Mendoza R, Mayta-Tovalino F. Uses and applications of tantalum in oral implantology: A literature review. Journal of International Oral Health 2021; 13(4): 331-335.

[14] Benerjee PC, Al-Saadi S, Harandi SE, Choudhary L, Singh R. Magnesium implants: Prospects and challenges. Materials 2019; 12(1): 136.

[15] Saha S, Roy S Metallic dental implants wear mechanisms, materials, and manufacturing processes: A literature review. Materials 2023; 16(1): 161.

[16] Stanford CM. Surface modifications of dental implants. Australian Dental Journal 2018; 53(1): 26-33.

[17] Ozcan M, Hammerle C. Titanium as a reconstruction and implant material in dentistry: Advantages and pitfalls. Materials 2012; 5(9): 1528-1545.

[18] Crawford RJ, Webb HK, Truong VK, Hasan J, Ivanova EP. Surface topographical factors influencing bacterial attachment. Advances in Colloid and Interface Science 2012; 179-182: 142-149.

[19] Asensio G, Vazquez-Lasa B, Rojo L. Achievements in the topographic design of commercial titanium dental implants: Towards anti-peri-implantitis surfaces. Journal of Clinical Medicine 2019; 8(11): 1982.

[20] Liu Y, Chen Y, Chu C, Qu Y, Man Y . Use of reactive soft tissue for primary wound closure during immediate implant placement: A two-year retrospective study. International Journal of Oral & Maxillofacial Surgery 2022; 51(8): 1085-1092.
[21] Guo L, Smeets R, Kluwe L, Hartjen P, Barbeck M, Cacaci C, Gosau M, Henningsen A. Cytocompatibility of titanium, zirconia and modified PEEK after surface treatment using UV light or non-thermal plasma. International Journal of Molecular Sciences 2019; 20(22): 5596.
[22] Chang LC. Clinical applications of photofunctionalization on dental implant surfaces: A narrative review. Journal of Clinical Medicine 2022; 11(19): 5823.
[23] Lee SY, Kim SJ, An HW, Kim HS, Ha D-G, Ryo KH, Park KB. The effect of the thread depth on the mechanical properties of the dental implant. The Journal of Advanced Prosthodontics 2015; 7(2): 115-121.
[24] Nagay BE, Cordeiro JM, Barao VAR. Insight into corrosion of dental implants: From biochemical mechanisms to designing corrosio n-resistant materials. Current Oral Health Reports 2022; 9: 7-21.
[25] Kravets N, Derkach S. Mouthwash as a factor in controlling the formation of soft dental plaque in patients with orthodontic treatment. Bulletin of Medical and Biological Research 2024; 6(2): 38-46.
[26] Jimbo R, Tovar N, Anchieta RB, Machado LS, Marin C, Teixeira HS, Coelho PG. The combined effects of undersized drilling and implant macrogeometry on bone healing around dental implants: an experimental study. International Journal of Oral & Maxillofacial Surgery 2014; 43(10): 1269-1275.
[27] Reinaldo E, Bonifacius S, Adenan A. Influence of short implant thread pitch and depth to primary stability on D4 bone density: A laboratory study. Journal of International Oral Health 2021; 13(5): 456-461.
[28] Menini M, Bagnasco F, Calimodio I, Tullio ND, Delucchi F, Baldi D, Pera F. Influence of implant thread morphology on primary stability: A prospective clinical study. BioMed Research International 2020: 6974050.
[29] Rice J. M, Hunt JA, Gallagher JA, Hanarp P, Sutherland D S, Gold J, Quantitative assessment of the response of primary derived human osteoblasts and macrophages to a range of nanotopography surfaces in a single culture model in vitro. Biomaterials 2003; 24(26): 4799-4818.
[30] Jiang N, Du P, Qu W, LI L, Liu Z, Zhu S. The synergistic effect of TiO2 nanoporous modification and platelet-rich plasma treatment on titanium-implant stability in ovariectomized rats. International Journal of Nanomedicine 2016; 11: 4719-4733.
[31] Accioni F, Vazquez J, Merinero M, Begines B, Alcudia A. Latest trends in surface modification for dental implantology: Innovative developments and analytical applications. Pharmaceutics 2022; 14(2): 455.
[32] Gibreel S, Gassim H, Suraj AR, Anil S. Osseointegration of dental implants and osteoporosis. In: Current Concepts in Dental Implantology – From Science to Clinical Research. https://cdn.intechopen.com/pdfs/78703.pdf, 2021.
[33] Miao X, Wang D, Xu L, Wang J, Zeng D, Lin S, Huang C, Liu X, Jiang X. The response of human osteoblasts, epithelial cells, fibroblasts, macrophages and oral bacteria to nanostructured titanium surfaces: A systematic study. International Journal of Nanomedicine 2017; 12: 1415-1430.
[34] Kunrath MF, Leal BF, Hubler R, Oliveira SD, Teixeira ER. Antibacterial potential associated with drug-delivery built TiO2 nanotubes in biomedical implants. ABM Express 2019; 9: 51.
[35] Gulati K, Ivanovski S. Dental implants modified with drug releasing titania nanotubes: Therapeutic potential and developmental challenges. Expert Opinion on Drug Delivery 2017; 14(8): 1009-1024.
[36] Song X, Chen T, Liu H, Liu C. The study of PEEK composites as the dental implant materials. Journal of Simulation 2017; 5(1): 5-7.
[37] Vimbela GV, Ngo SM, Fraze C, Yang L, Stout DA. Antibacterial properties and toxicity from metallic nanomaterials. International Journal of Nanomedicine 2017; 12: 3941-3965.
[38] Smeets R, Stadinger B, Schwarz F, Beck-Broichsitter B, Jung O, Precht C, Kloss F., Gröbe A, Heiland M, Ebker T. Impact of dental implant surface modifications on osseointegration. BioMed Research International 2016; 6285620.
[39] Rocci A, Martignoni M, Gottlow J. Immediate loading of Branemark system TiUnite and machined-surface implants in the posterior mandible: A randomized open-ended clinical trial. Clinical Implant Dentistry and Related Research 2003; 5(1): 57-63.
[40] Jungner M, Lundqvist P, Lundgren S. Oxidized titanium implants (Nobel Biocare TiUnite) compared with turned titanium implants (Nobel Biocare mark III) with respect to implant failure in a group of consecutive patients treated with early functional loading and two-stage protocol. Clinical Oral Implants Research 2005; 16(3): 308-312.
[41] Albertini M, Herrero CF, Castro DF, Nart J, Palacin FA, Rios-Santos JV, Herrero-Climent M. A radiographic and clinical comparison of immediate vs. early loading (4 weeks) of implants with a new thermo-chemically treated surface: A randomized clinical trial. International Journal of Environmental Research and Public Health, 2021; 18(3): 1223.
[42] Loban GA, Petrushanko T, Chereda V, Faustova MO, Ananieva MM, Basarab Ya. Diagnostic and prognostic significance of microbial flora imbalance in gingival biofilm. International Journal of Medicine and Medical Research 2019; 5(2): 76-82.
[43] Costa RC, Nagay BE, Bertolini M, Costa-Oliveira BA, Sampaio AA, Retamal-Valdes B, Shibli JA, Feres M, Barao VA, Souza JG. Fitting pieces into the puzzle: The impact of titanium-based dental implant surface modifications on bacterial accumulation and polymicrobial infections. Advances in Colloid and Interface Science 2021; 298: 102551.
[44] Baldi D, Giorgis LD, Menini M, Motta F, Colombo J. Efficacy of instruments for professional oral hygiene on dental implants: A systematic review. Applied Sciences 2022; 12(1): 26.
[45] Krawiec M, Hadzik J, Dominiak M, Grzebieluch W, Blaszczyszyn A, Kubasiewicz-Ross P. Early loading of titanium dental implants with hydroxyl ion modified surface: A 12-month prospective clinical trial. Applied Sciences 2021; 11(7): 2958.
[46] Lee JB, Jo YH, Choi JY, Seol YJ, Lee Y. M, Ku Y, Rhyu IC, Yeo IL. The effect of ultraviolet photofunctionalization on a titanium dental implant with machined surface: An in vitro and in vivo study. Materials 2019; 12(13): 2078.