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Original Article

Assessment of osseointegration mechanisms in a novel zirconia implant: From experimental insights to clinical comparison

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KEYWORDS
Zirconia implant;
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Clinical trial

Abstract *Background/purpose:* Zirconia has been proposed as a substitutive material for the next generation of implants. This study aimed to evaluate the osseointegration of a newly developed zirconia implant and compare its clinical parameters with titanium implants.

Materials and methods: Beagle dog animal model were used for evaluation of two groups of zirconia implants, with one group subjected to a newly developed sandblasting surface treatment technique and the other using a commercially available zirconia implant. The implants were randomly placed in bilateral edentulous mandibular sites and evaluated at 4, 9, and 13 weeks. The bone-to-implant contact (BIC) ratio was calculated and the fluorescence labelling for evaluation of osseointegration.

Clinical trials compared the peri-implant parameters of the zirconia implants with titanium implants to assess peri-implant tissue condition.

Results: Animal study indicated that zirconia implant osseointegration was observed between 4 weeks and 9 weeks, accompanied by osteoid deposition. A statistically significant difference was found between the 4-week and 13-week BIC ratio ($P = 0.045$). Clinical trials revealed that zirconia implants maintained minimal plaque postoperatively for up to three months, while titanium implants accumulated more plaque. In terms of plaque index, zirconia outperformed titanium implants.

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Conclusion: This study provides comprehensive insights into zirconia implants. During early osseointegration, bone cells exhibited affinity for the implant surface, emphasizing the role of surface treatment. Clinical trials suggest that zirconia implants may offer a slight advantage in maintaining peri-implant periodontal conditions compared to titanium implants.

Introduction

Zirconium oxide, discovered in 1789, initially found applications in industrial settings. Its earliest use in the biomedical field was as a substitute for hip joints in hip replacement surgeries.[1] In dentistry, it was used for the of all-ceramic crowns.[2] Over the years, its utilization has steadily increased for aesthetic demands.[3—5] Because of its natural tooth-like appearance, mechanical property, and good biocompatibility, it has the potential to become the substitutive material for the next generation of implants.[6—8]

Biocompatibility is the key feature for materials used as artificial implants.[9] They must possess adequate corrosion resistance, remain unaffected by the human body's internal environment, avoid tissue rejection, and exhibit no cytotoxicity.[10] Recent research has demonstrated the excellent biocompatibility of zirconium oxide.[11] Consequently, numerous mammalian animal studies comparing zirconium oxide with titanium alloys have emerged in recent years. Kohal et al.[12] implanted two types of implants in the monkeys animal models and fitted them with metal crowns after two months, subjecting the implants to mechanical stress for five months after implantation. There was no significant difference in the comparison of bone-to-implant contact (BIC), which indicated similar bone integration outcomes. Additionally, there was no impact on the thickness of the peri-implant soft tissues. Koch et al.[13] found the similar outcome in dog animal model, both zirconium oxide and titanium implants exhibited similar BIC ratio, which were higher than those of polyetheretherketone (PEEK) implants. Later more, Depprich found no significant difference in BIC ratio after 1, 4, and 12 weeks between the zirconia and titanium implants in experimental models of pigs.[14,15]

Focusing on the human trials of zirconium oxide dental implants, many study revealed that the zirconia and titanium implants have similar biocompatibility and stability. Especially in the critical aspect of bone-implant integration, the zirconia implants demonstrate comparable performance to the titanium implants.[3,4,16,17]

According to the literature review, while the mechanisms of osseointegration for titanium implants are well established, the early stage osseointegration process of zirconia implants remains inadequately understood. The hardness of zirconia makes it too challenging to create thin-sliced specimens. Meanwhile, fluorescence staining is the crucial step for investigating the progression and understanding the sequence of osseointegration in zirconia implants.[18,19]

This study aimed to conduct a serial investigation into the osseointegration of a newly developed zirconia implant. In the animal model, non-decalcified ground sections combined with bone fluorescence labeling analysis were employed to investigate the chronological bone healing process surrounding zirconia implants. Furthermore, a small-scale clinical trial was conducted to assess potential differences in peri-implant tissue conditions between zirconia and titanium implants. These investigations aimed to substantiate the clinical viability of zirconia implants and to elucidate their appropriate clinical indications. Ultimately, the findings will contribute to the development of standardized clinical protocols for the application of this novel implant material.

Material and methods

Selection of zirconia implants

In this study, two types of zirconia implants were used for comparative analysis. Both implants featured a one-piece design with a diameter of 3.6 mm and a sandblasted surface treatment. The experimental group comprised newly developed zirconia implants manufactured by (COHO biomedical technology, Taoyuan City, Taiwan). These implants were characterized by a one-piece configuration with a root-shaped, threaded portion measuring 8 mm in length. The control group consisted of commercially available zirconia implants, specifically the Z-Look 3 (Z-Systems®, Oensingen, Switzerland), which also exhibited a one-piece design with a threaded portion measuring 10 mm in length.

Animal model

Three one-year-old male Beagle dogs, each weighing 10—15 kg, were individually housed at the Experimental Animal Center of the National Taiwan University College of Medicine. They were provided with standard animal feed, hydration, and received weekly oral hygiene care as well. This animal experiments were conducted in compliance with the protocol that was reviewed and approved by the Institutional Animal Care and Use Committee (IACUC) at College of Medicine, National Taiwan University (IACUC Approval No: 20110238). And all surgical procedures were conducted in the animal surgery room of the Experimental Animal Center and were following the regulations of the Institutional Animal Care and Use Committee of National Taiwan University. This article was written in accordance with the ARRIVE guidelines.

The experiment was conducted over three timepoints: 4 weeks, 9 weeks, and 13 weeks. In the experimental group, 18 implants were placed, while the control group received 7 implants. Tooth extractions were performed under anesthesia eight weeks prior to the initial implantation, targeting the first premolar (P1), second premolar (P2), third premolar (P3), and first molar (M1) on both sides of the mandible. After the extraction sites had healed, implantation surgery was carried out in the edentulous area. Post-surgery, the animals were carefully monitored for vital signs and wound condition, and received postoperative prophylactic medications, including pain relief and antibiotics. They were provided with soft food soaked in water for feeding. Throughout the intervals between surgeries, we conducted weekly observations of their food intake, activity levels, and weight changes. Different fluorescent bone labeling dyes were injected, and undecalcified specimens were obtained after animal euthanasia to observe bone growth and fluorescence labeling at various points. Bone-to-implant contact (BIC) ratio was calculated based on histological sections.

Preparation of undecalcified specimens

Undecalcified specimens contain both implants and surrounding soft tissues. The specimens were sequentially dehydrated in alcohol baths for 2 h each and then placed in 100 % alcohol for further processing. The specimens were removed from 100 % alcohol and placed in dedicated embedding rings. Epoxy resin was mixed with a resin base and hardener and used for embedding the specimens. After fully hardening resin, the specimens were sectioned into thin slices using a microtome (Leica SP1600, Deer Park, IL, USA). The specimens were then ground to a thickness of 100 μm and stained. Thin sections were fixed onto glass slides using specialized glue and polished using abrasive papers (120, 180, and 600 grits) with water. Manual polishing with 1200-grit paper was performed to reduce surface scratches. This process prepared undecalcified specimens for further analysis, including staining with Stevenel's blue and Alizarin red S for experimental results.

Calculation of bone-to-implant contact

In planar images, the total length of the outer contour of the threaded portion of the implant was used as the denominator. In contrast, the total length of bone growth directly attached to the implant was used as the numerator without any interposing connective tissue. These two measurements' ratios were defined as the bone-to-implant contact (BIC) ratios. BIC ratio is a commonly used parameter for assessing osseointegration in implantation animal experiments. This study calculated BIC ratio for each specimen using stained undecalcified sections. Since zirconia implants are translucent, images of the implant and surrounding tissues were captured using an optical microscope equipped with a digital camera. Image analysis software, ImageJ® (National Institutes of Health, Bethesda, MD, USA), was used to calculate BIC ratio. The BIC ratio obtained for both treatment groups was averaged to obtain the final data.

Bone fluorescent labelling

The fluorochromes binding to calcium ions, were used after dental implantation surgery to label the areas of new bone formation and calcification on the undecalcified ground sections, using an inverted fluorescence microscope (Axiovert 200M Zeiss/Photometrics CoolSnap HQ, White Plains, NY, USA). The images were captured and processed with imaging software (Axio Vision Rel 4.8, Carl Zeiss, White Plains, NY, USA). Different fluorescent filters were used to capture specific colours of fluorescence. By overlaying images obtained with different fluorescent dyes at different time points, details of bone formation, including timing and location, were observed. During bone maturation process, different fluorescent dyes applied at different time points exhibit distinct deposition locations and colours, making them valuable for studying the dynamic process of osseointegration[17] of artificial implants. Additionally, these bone labelling fluorochromes have lower biotoxicity compared to other radiolabelling substances[18] and are commonly used in studies involving bone tissues and dental implants in large animal models.[19–21] In this experiment, the fluorescent dyes used were Xylenol orange (60 mg/kg, 10 ml PBS) at 13 weeks after implantation surgery, Alizarin complexone (30 mg/kg, 10 ml 1.4 % NaHCO3) at 9 weeks after implantation surgery, and Tetracycline (10 mg/kg, 10 ml PBS) administered 4 weeks before sacrifice.

Clinical trial procedure and implant imaging assessment

The clinical trial was approved by National Taiwan University Hospital IRB (Case No: 20151102 RINA). All participants were fully informed of the study protocol and provided written informed consent following the initial consultation. Subsequently, they were randomly assigned into two groups. The COHO Zirconia implants were used as the experimental group, while the titanium implants served as the control group.

A total of twenty systemically healthy patients with partial edentulism were enrolled in this randomized controlled study. Participants were randomly assigned to receive either non-submerged zirconia implants ($n = 10$) or submerged titanium implants ($n = 10$). Preoperative assessments included periapical radiographs and cone-beam computed tomography (CBCT) scans to evaluate alveolar bone conditions. Implant stability was assessed using a Periotest device at three time points: immediately post-implantation, at one month, and at three months post-operatively. Standardized periapical radiographs were also obtained at each follow-up to evaluate early marginal bone resorption.

Assessment of implant stability

Implant stability was evaluated using a handheld, non-invasive electronic device, the Periotest® M (Medizintechnik Gulden e. K., Modautal, Germany) that provides a quantitative measure known as the Periotest value (PTV), which ranges from −8 to +50. Lower PTVs indicate greater implant stability. According to previous clinical studies,

PTVs between −5 and +5 are generally associated with successful osseointegration, whereas values exceeding +10 are indicative of insufficient implant integration.

Peri-implant plaque level

The assessment of antibacterial efficacy and the accumulation of clinical plaque utilized the Mombelli index as described by Todescan et al.,[20] which comprises four levels:

Level 0: No visible plaque accumulation.
Level 1: Plaque is visible but can be removed with a periodontal probe.
Level 2: Plaque is visible to the naked eye.
Level 3: Abundant plaque accumulation.

Observations and assessments of plaque levels were recorded at three time points: immediately after surgery, one month, and three months.

Implant gingival inflammation index

Observations and assessments of gingival inflammation were also recorded at three time points: immediately after surgery, one month, and three months.

The Gingival Index (GI) assesses gum inflammation and is categorized into four levels:

Level 0: Normal gum, no inflammation, bleeding, or colour changes.
Level 1: Mild inflammation, no bleeding, but increased redness and surface gloss.
Level 2: Moderate inflammation, redness, swelling, and bleeding upon probing or pressure.
Level 3: Severe inflammation with significant redness, swelling, spontaneous bleeding, and ulcers.

Results

Bone-to-implant contact ratio analysis

There were no significant differences in the BIC ratio between the two types of zirconia implants in the 4-week (52.0 % ± 1.7 %; 51.5 % ± 2.1 %), in the 9-week (64.0 % ± 11.2 %; 62.5 % ± 8.1 %), and in the 13-week (61.73 % ± 6.0 %; 64.1 % ± 5.2 %) time points. However, within the experimental group, there was a statistically significant difference in the BIC ratio between the 4-week and 13-week time points ($P = 0.045$), with no significant differences among all the other groups (Fig. 1).

Undecalcified section imaging assessment

In specimens with a thickness of approximately 100 μm, soft tissues stained with Stevenel's blue appeared blue. Mature calcified bone tissue stained with Alizarin red S

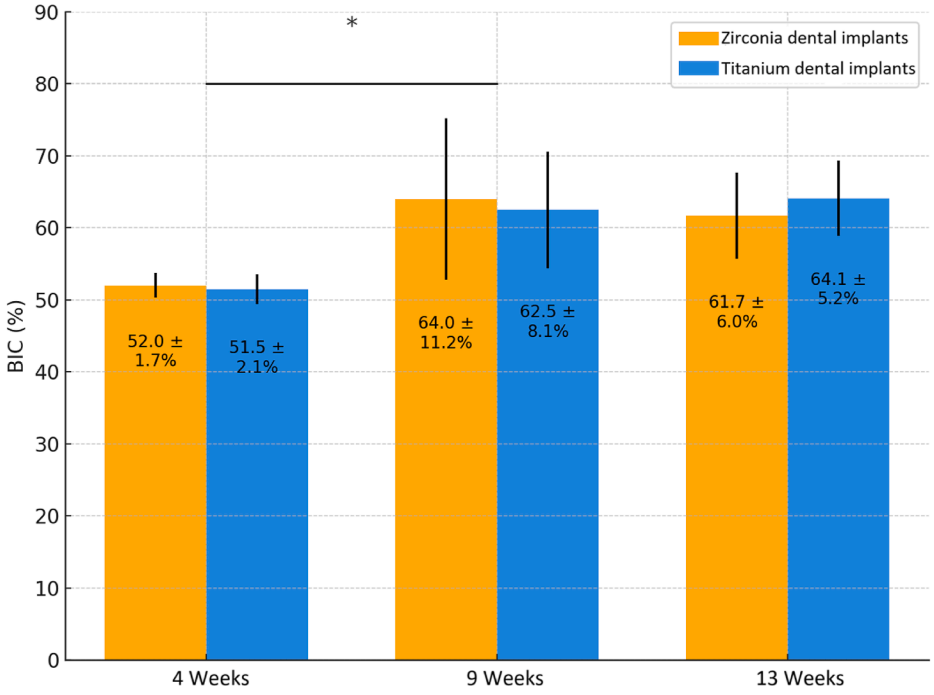

Figure 1 The bone-to-implant contact (BIC) ratio for each implant was obtained by averaging the bone-implant contact ratios from undecalcified samples. In the 4-week group, the experimental group had a BIC ratio of 52.0 ± 1.7 %, while the control group had a BIC ratio of 51.5 ± 2.1 %. In the 9-week group, the experimental group had a BIC ratio of 64.0 ± 11.2 %, and the control group had a BIC ratio of 62.5 ± 8.1 %. In the 13-week group, the experimental group had a BIC ratio of 61.7 ± 6.0 %, and the control group had a BIC ratio of 64.1 ± 5.2 %. There was no significant difference between the two types of implants in these three timepoint. Furthermore, in the comparisons between different time points within the same group, there was a statistical difference between the 4-week and 13-week periods in the experimental group ($P = 0.045$). In contrast, no differences were observed in control group. Abbreviations: BIC = bone-to-implant contact.

appeared red. (Fig. 2). shows that in the 4-week group specimens, some areas inside the threads still appeared blue, indicating non-calcified mature bone tissue but rather osteoid secreted by osteoblasts. Since osteoid had not yet calcified, it stained with Stevenel's blue instead of Alizarin red S. This area represented the mechanism of bone healing on the implant surface and would gradually grow into the gaps in the thread grooves. In this phase, there was still some inflammatory response. Subsequently, bone cells would gradually fill in and even tightly integrate with the threads, achieving osseointegration in this area. In the 9-week and 13-week groups, bone tissue could be seen directly adhering to the threads, indicating a considerable level of osseointegration, and many threads contained calcified bone tissue (see Figs. 3—6).

Bone labelling and fluorescent microscopy

In this experiment, we used three different fluorescent dyes sequentially: Xylenol orange (13 weeks before sacrifice), Alizarin complexone (9 weeks before sacrifice), and Tetracycline (administered 4 weeks before sacrifice). We performed fluorescence microscopy on undecalcified ground sections before staining. In Fig. 2, both the 9-week experimental group and the control group showed red fluorescence at 25× magnification, indicating bone formation at week 0, and green fluorescence denoting bone formation at 5 weeks post-implantation. This suggests that the primary phase of bone calcification occurred between 5 and 9 weeks after implantation, indicating the osseointegration process within the threads.

In the control group at 9 weeks, red fluorescence in the distal region of the implant resembled the process seen in undecalcified stained slides, indicating concentric bone fluorescence resulting from osteoblast activity. Some threads displayed red fluorescence at both 9 and 13 weeks, implying similar bone integration timing for both implant types.

At 13 weeks, the orange fluorescence was challenging to distinguish from red fluorescence, indicating bone cells had grown along the implant surface. Green fluorescence marked bone formation between 9- and 13-weeks post-implantation. Comparing the 9-week and 13-week images showed similar results for both implant types, suggesting analogous bone integration processes.

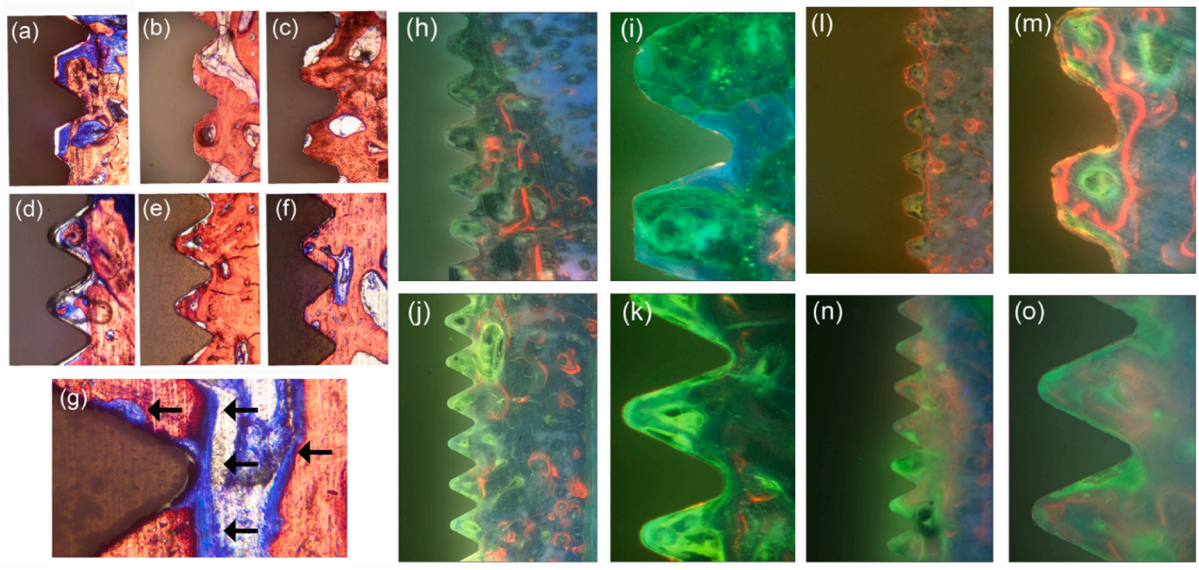

Fig. 2 (a), (b), and (c) depict images at 100× magnification of the experimental group at 4, 9, and 13 weeks, respectively, showing the implant threads. Fig. 1(d), (e), and (f) show images at 100× magnification of the control group at 4, 9, and 13 weeks, respectively, displaying the implant threads. Fig. 1(g) is a histological image magnified 250 times from Fig. 1(f). In the pictures, the brown portions represent the zirconia implants, and you can observe the process of bone formation around the implant. The blue area at the border with the red calcified tissue (indicated by black arrows) represents osteoid secreted by osteoblasts. Since the osteoid has not yet undergone calcification, it is stained with Stevenel's blue rather than Alizarin red S. Both zirconia implants exhibit similar growth patterns during the same period, with osteoid formation starting at four weeks. This region is actively involved in the bone healing mechanism on the implant surface, gradually pushing growth toward the gap between the threads and the bone. This process continues until bone cells densely cover the threads, achieving osseointegration in this region. (h) Moreover, (i) represent the 9-week experimental group at 25x and 100× magnifications, respectively. (j) and (k) depict the 9-week control group at 25x and 100× magnifications, respectively. In these images, red fluorescence indicates bone formation at 0 weeks after implantation, while green fluorescence illustrates the state of bone formation five weeks after implantation. Images of the 13-week experimental group at 25x (l) and 100× (m) magnifications, as well as the 13-week control group at 25x (n) and 100× (○) magnifications, were also shown. In these images, the red-stained new bone can be observed adhering and growing along the implant threads at this time point. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

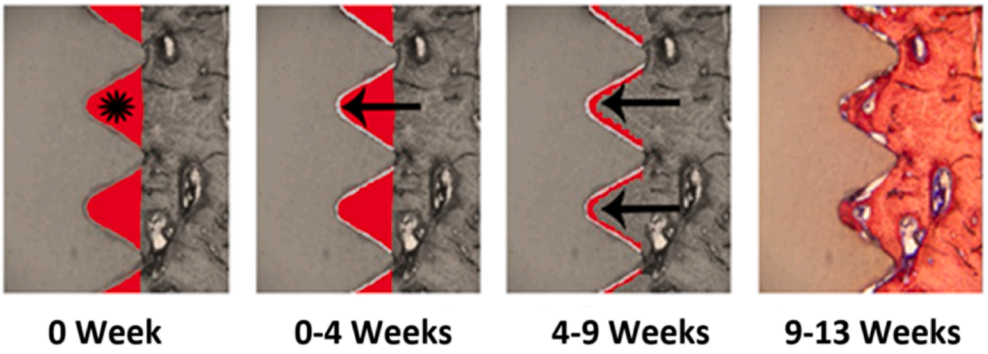

Figure 3 Marked as "✳" in the picture of 0 week, represents the immediate post-implantation phase. This area initially exhibits a bone defect gap that is filled with blood clot tissue from drilling and grinding. The arrows in 0—4 weeks indicate that the earliest bone cells adhere to the thread; new bone formation is observed along the implant threads' surface during the first four weeks. In the 4—9 weeks image, the black arrows illustrate bone tissue growing from the pre-existing bone into the implant cavity. Finally, at 9—13 weeks the bone further mineralization, forming a complete osteo-integration.

Clinical evaluation and imaging analysis

Each group included 10 implants. In the zirconia (experiment) group, 6 implants were placed in female patients and 4 in male patients, with a mean age of 50.3 ± 9.28 years. In the titanium (control) group, 5 implants were placed in female patients and 5 in male patients, with a mean age of 48.3 ± 9.75 years. Implant sites included 2 in the anterior region and 3 in the posterior region of the maxilla, as well as an equal distribution in the mandible, for both groups. No significant differences were observed between the two groups in pre-operative conditions.

Radiographic evaluations were performed immediately after surgery, at 1-month follow-up, and 3-month follow-up, which revealed that all implants, whether zirconia or titanium, were properly implanted in the alveolar bone without any radiographic evidence of marginal bone-loss. Furthermore, clinical examination showed healthy gingival tissue surrounding all the implants.

Implant stability test

On the day of implantation, all zirconia implants exhibited negative Periotest values, with particularly low readings on the buccal side. Over time, implant stability remained consistently within a defined range of negative Periotest values. In contrast, the titanium implant groups initially presented with positive Periotest values at the time of implantation, indicating an early phase of inflammation and remodeling between the implant and the surrounding alveolar bone. At the 1-month follow-up, an improvement in implant stability was observed, with negative Periotest values indicating the establishment of biological stability through osseointegration.

Peri-implant plaque level

In the assessment of anti-bacterial efficacy, zirconia implants, after surface modification, achieved plaque levels ranging from 0 to 1, indicating minimal visible plaque accumulation that could be easily removed with a periodontal probe or was not visible to the naked eye. In contrast, the titanium implants showed more plaque accumulation over time.

Implant gingival inflammation index

With respect to peri-implant inflammation, zirconia and titanium implants demonstrated distinct patterns. Postoperatively, titanium implants consistently exhibited mild inflammatory responses persisting for up to three months. In contrast, zirconia implants showed variable inflammatory reactions, although most remained within the range of no inflammation to only mild symptoms. In one case, bleeding was observed at the 3-month follow-up, which was not associated with bacterial plaque accumulation or compromised implant stability. Instead, it may be attributable to excessive occlusal forces or occlusal trauma according to the clinical examination.

Discussion

The animal experiment's results showed no significant differences between the experimental and control groups at each time point. In the 4-week group, the BIC ratio were 52.0 % ± 1.7 % for the experimental group and 51.5 % ± 2.1 % for the control group. These values were lower compared to the 9-week and 13-week groups. Notably, there was a significant increase in osseointegration between the experimental group at 4 weeks and 13 weeks, However, due to the smaller sample size in the control group, no significant differences were observed.

Histological images revealed incomplete bony integration and ongoing healing around the implants at 4 weeks, indicating incomplete osseointegration. However, both the experimental and control groups showed no significant BIC ratio differences at 9 and 13 weeks, suggesting osseointegration was achieved by the 9-week timepoint, representing the bone remodeling phase. Bone labelling fluorescent staining confirmed this, with increased calcification within implant threads observed at 9 weeks post-implantation.

Reviewing similar animal studies, such as Koch et al., 's 2010 research[12] using dog mandibles in a 16-week study

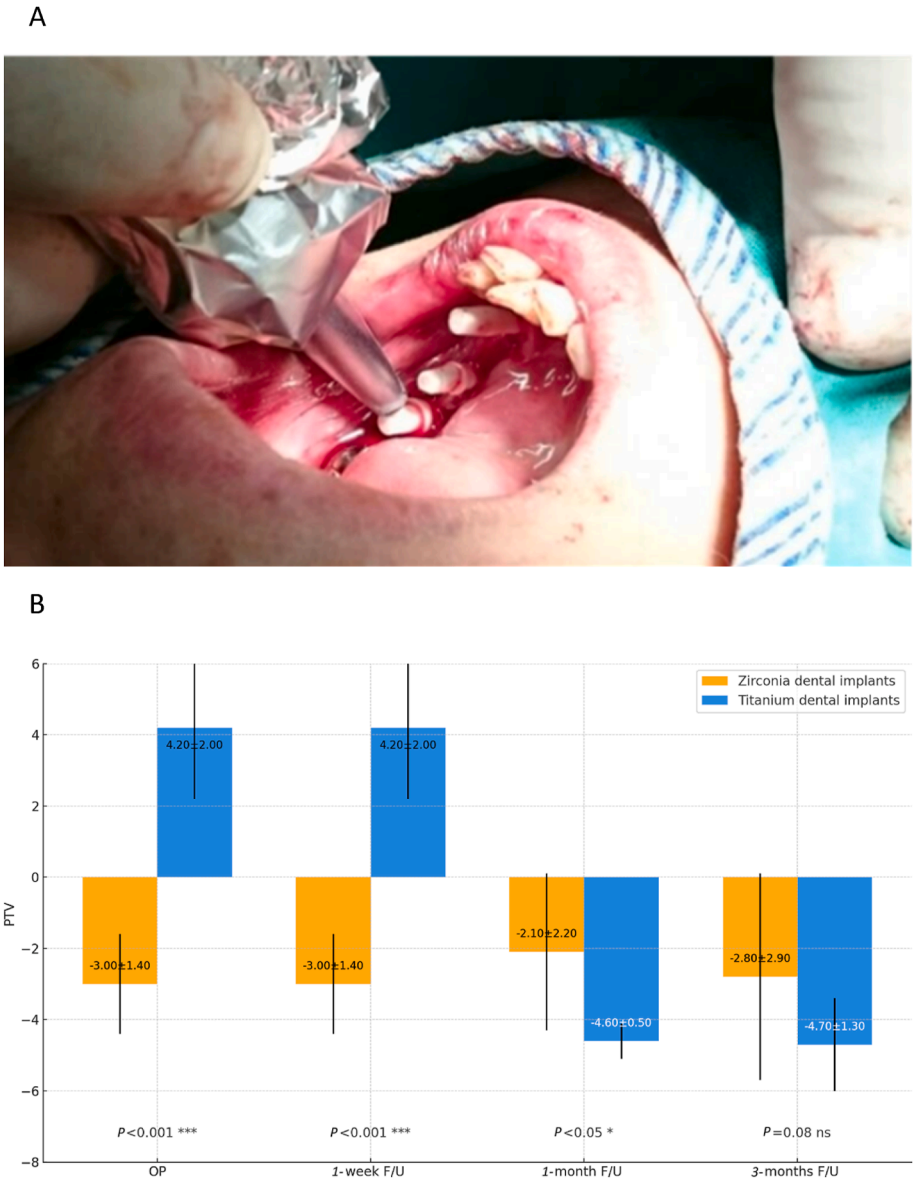

Figure 4 The periotest value (PTV) data collected in these two groups: zirconia and titanium implants at four time-point. A is clinic photo showed periotest was recorded from the buccal side of implants. All of ten zirconia implants showed negative values at all time-point. In the contrast, the titanium implants had positive periotest value in the first week. B showed that at the first week, zirconia implants exhibited better PTV than titanium implants, but they all exhibited similar patterns: The PTV became more negative in the 3- month follow-up, which represented that dental implants have better stability as healing process. And no significant difference between two groups. Abbreviations: PTV = periotest value.

with uncoated and titanium dioxide-coated zirconia implants, they reported BIC ratio results of 59.2 % and 58.3 %, showing no significant difference between the two groups. In the study by Dubruille et al., in 1999,[21] which compared titanium, alumina, and zirconia implants in dog mandibles over 10 months, they found BIC ratio of 68 % ± 13.9 % for alumina, 64.2 % ± 12.7 % for zirconia, and 54 % ± 12.9 % for titanium, with no significant differences among the groups. Akagawa's 1993 experiment[22] on zirconia implants in beagle mandibles, divided into loaded and unloaded groups, found after 12 weeks BIC ratio of 81.9 % ± 11.9 % for the unloaded group and 69.8 % ± 14.2 % for the loaded group, without statistically significant differences reported. Reviewing the existing BIC data from similar animal experiments, primarily involving zirconia implants in dog mandibles, results generally fell in the range of 60 %—70 %, aligning with the outcomes of this study.

However, this study has some limitations, such as the comparison of different zirconia implants with varying features or morphology, surface treatments, and thread designs. Standardizing these factors, focusing solely on surface treatments, could provide more precise results. Nonetheless, it's noteworthy that both locally manufactured zirconia implants and commercial ones display consistent patterns of osseointegration despite the different thread designs. This underlines that zirconia

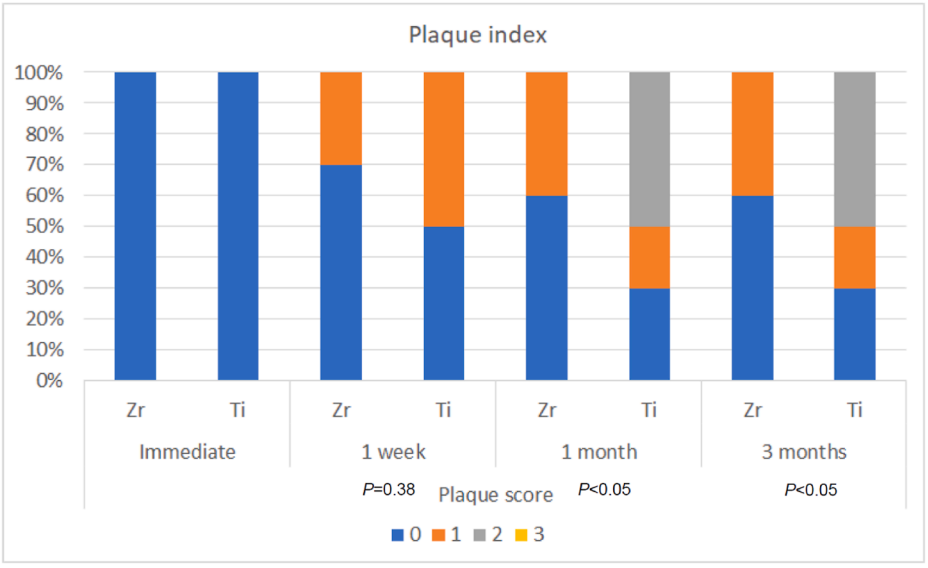

Figure 5 In the plaque index, it can be observed that after surface modification, zirconia implants reached plaque index levels of 0—1. This indicates that visible plaque accumulation was minimal on the zirconia implant surface, and any plaque present could be easily removed with a periodontal probe. In contrast, titanium implants showed increased plaque accumulation over time after surgery. Abbreviations: Zr = zirconia implant group; Ti = titanium implant group.

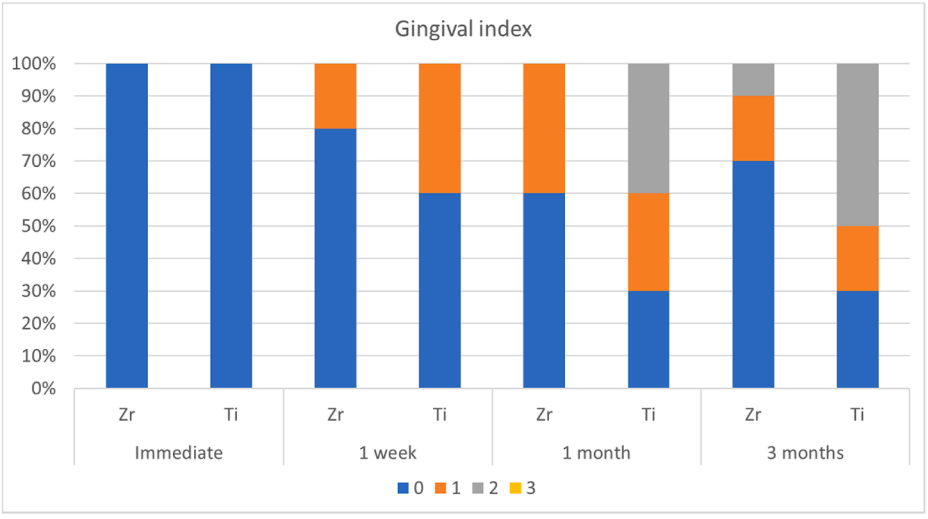

Figure 6 Comparing the gingival index, it can be observed that both titanium and zirconia implants exhibited some degree of gingival inflammation after surgery. However, the titanium implants still showed mild inflammation even up to three months post-surgery. On the other hand, the inflammatory response with zirconia implants varied but generally remained at either a non-inflammatory level or displayed only mild inflammatory symptoms. One instance of bleeding was associated with one zirconia implant at the three-month. However, considering the plaque index and implant stability, this inflammation might be attributed to excessive biting force or improper occlusion. Abbreviations: Zr = zirconia implant group; Ti = titanium implant group.

implant with new sandblasting treatments promote effective osseointegration, suitable for clinical use.

Comparative analysis in our preliminary clinical trial revealed no significant differences in post-operative clinical findings between zirconia and titanium implants. However, periotest value demonstrated better immediate primary stability for zirconia implants, whereas titanium implants exhibited more variable stability values. Theis finding suggest that zirconia implants may achieve more rapid osseointegration. During the 3-month follow-up, titanium implants also reached stable values (ranging from −2 to −6) gradually.

However, although zirconia implants initially demonstrated favorable stability (ranging from 0 to −4), but a slight decline was observed in 1-month follow-up. We think this is potentially attributable to its one-piece design, which may lead to early functional overloading. Despite this, both implant types maintained clinically acceptable stability throughout the follow-up period. According to Aparicio's study, high resonance frequency

analysis values combined with low periotest values are indicative of successful osseointegration,[23] which the same pattern could be observed in our study.

Meanwhile, the zirconia implants displayed an excellent antibacterial effect with minimal plaque accumulation over the 3-month follow-up period. In contrast, titanium implants demonstrated greater plaque accumulation following surgery. With respect to peri-implant inflammation, titanium implants exhibited mild inflammatory responses persisting for up to three months, whereas zirconia implants generally remained free of inflammation or presented only mild symptoms.

In conclusion, this animal experiment confirmed that locally manufactured zirconia implants achieved similar outcomes to the control group implants. Decalcified sections and bone fluorescence labeling also prove the same tendency in each timepoint. And in the preliminary clinical trial, zirconia and titanium implants demonstrated comparable clinical stability and success rates. However, zirconia implants showed an advantage in plaque and gingival inflammation indexes. However, a two-piece implant—abutment design is generally preferred for submerged placement, and it will help to minimize the risk of early occlusal overloading. Therefore, this serial research revealed that zirconia implants demonstrate favorable osseointegration mechanism, immediate stability, antibacterial properties, and limited inflammatory responses, making them a promising clinical option.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

Acknowledgments

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