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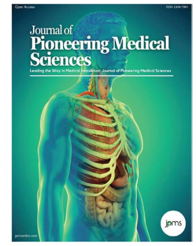

Comparative *In vitro* Study on the Osseointegration Potential of Titanium, Zirconia, and PEEK Dental Implants Using Simulated Bone Models

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Abstract **Objectives:** Success rates of dental implants heavily depend on the process of osseointegration. The standard practice in dentistry uses titanium implants because these materials demonstrate exceptional compatibility and structural integrity with bone tissue. Medical experts have adopted Zirconia and polyether ether ketone (PEEK) as implant choices because these offer better aesthetics together with superior biomechanical performance. In this laboratory research scientists examined the potential for root integration between titanium and zirconia and PEEK implant materials through synthetic bone model testing. **Methods:** Thirty titanium implants accompanied by thirty zirconia implants and thirty PEEK implants received placement inside simulated bone blocks. Surface wettability combined with roughness and insertion and removal torque measurements were the assessed parameters. The evaluation of bone-to-implant contact (BIC) through histomorphometric analysis took place after the blocks spent eight weeks in the incubator. A one-way ANOVA technique performed the statistical analysis with a threshold value of $p<0.05$. **Results:** The titanium implants achieved the greatest insertion torque level at 45.2±5.1 Ncm together with 30.5±3.2 Ncm removal torque levels and 65.8±4.5% bone-to-implant contact. The insertion torque amount for zirconia implants reached 38.4±4.3 Ncm but their BIC percentage achieved 58.2±3.9% while PEEK implants maintained the lowest quantitative performance with BIC 40.6±5.1%. **Conclusion:** During every evaluation step titanium outperformed other materials for bone integration processes. Zirconia represents an appropriate metal-free solution for applications where load-bearing is not necessary. The integration of PEEK materials remains restricted while their surface needs adjustment for better attachment. Additional in vivo tests and sustained studies need to take place to confirm these findings.

Key Words Osseointegration, Dental implants, Titanium, Zirconia, PEEK, Bone-implant interface, Biomechanics

INTRODUCTION

The field of prosthetic dentistry underwent a revolutionary change through dental implants which offer extensive durability for tooth replacement solutions. The success rates of dental implants heavily depend on their proper integration with the adjacent bone tissue known as osseointegration [1]. The medical community accepts titanium (Ti) as their preferred standard implant material because it demonstrates exceptional biocompatibility and mechanical durability as well as high success rates in clinical practice [2,3]. Medical professionals now examine zirconia and polyether ether ketone (PEEK) as substitution materials because they address metal hypersensitivity concerns and peri-implantitis risks as well as meet aesthetic requirements [4,5].

The dental industry has started using Zirconia implants thanks to their self-coloration and resistance properties together with their positive biological reaction [6]. Research demonstrates that zirconia implants achieve similar bone integration results to titanium although they show reduced pathogen adhesion while benefiting soft tissue interface [7].

Zirconia implants show weak points regarding their brittleness as well as diminished fracture toughness level which introduces ongoing clinical performance risks [8].

The biomaterial PEEK shows promise as a medical application because it duplicates natural bone elasticity and enables superior diagnostic visualization on X-rays [9]. PEEK has a drawback of reduced surface bioactivity that leads to inferior osseointegration performance when compared to titanium and zirconia [10]. Plasma treatment, bioactive coatings and nanostructuring represent surface modification methods that investigators have studied to improve PEEK implant osseointegration [11,12].

Staff members at academic institutions have performed separate evaluations of titanium, zirconia, and PEEK implant osseointegration however there remains limited data on direct comparison using simulated bone models. The main focus of this research involves studying the bone integration capabilities of three implant materials through bone-to-implant contact examination together with insertion torque and removal torque measurements in specially designed synthetic bone models. This study will add to the knowledge of choosing implant materials in dentistry while evaluating the realistic use of alternative implant materials for clinical practice. The research lacks a standardized *in vitro* model for comparing titanium against zirconia as well as PEEK despite individual tests conducted on each material separately. Synthetic bone models replace biological variations through controlled comparison of material properties during osseointegration. The investigation aims to fill this research deficit through testing of implant material insertion torque together with removal torque and BIC values under equivalent experimental parameters. The objective of this study was not only to assess and compare osseointegration potential but also to identify the suitability of each material for specific clinical applications, such as load-bearing versus esthetic zones, and metal-allergic patients.

METHODS

The purpose of this *in vitro* research was to evaluate the osseointegration potential between titanium and zirconia and polyether ether ketone (PEEK) dental implants through simulated bone models assessment. Dental implants consisting of titanium (Ti) (n = 30), zirconia (ZrO_2) (n = 30) along with PEEK (n = 30) were part of the evaluation. A standard dimension of 4.0 mm in diameter with 10 mm length served as the uniform requirement for each implant. The manufactured bone segments had structures that simulated human cortical and cancellous bone tissues in which this testing took place.

Testing of implant surface roughness along with wettability occurred before dental implant placement. Surface roughness calculations (Ra) were performed with a profilometer whereas wettability tests happened on a contact angle goniometer. SEM analysis revealed the surface characteristics of each implant type through its examination process.

A motorized surgical unit inserted the implants into synthetic bone models following specifications for torque application. A torque device logged the highest torque values for every implant installation. A digital torque gauge conducted removal torque (RT) measurements during week 8 when the implants experienced 8 weeks in simulated physiological conditions to determine bone-implant interface stability.

The examination of bone-implant interfaces took place after the 8 week testing period through histological sectioning combined with staining procedures. The ImageJ software measured Bone-to-implant contact (BIC) data where results appeared as the percentage rate between implant surface and bone contact. The experimental conditions were controlled at 37°C with 60% relative humidity to achieve physical simulation of human physiological environment. The placement procedures for implants were performed by one operator who utilized a digital surgical unit to control variations between operators. A digital torque meter provided accurate ±0.1 Ncm measurement of torque insertion by performing each measurement three times.

ImageJ software facilitated evaluation of BIC by two researchers who analyzed histological slides without knowledge of experimental conditions. Measuring reliability was confirmed through intraclass correlation coefficient agreement (ICC = 0.92) between observers for the study.

Data analysis occurred through SPSS software version 25.0. The three implant groups received statistical comparison through one-way analysis of variance (ANOVA) regarding insertion torque, removal torque and BIC measurements. The statistical determination of significance occurred at $p<0.05$.

RESULTS

The three implant materials exhibited different insertion torque stability levels during placement but titanium implants achieved maximum stability results. The clinical test recorded titanium implants with 45.2±5.1 Ncm mean insertion torque as the highest and zirconia implants had 38.4±4.3 Ncm mean insertion torque whereas PEEK implants showed 24.8±3.5 Ncm mean insertion torque. The results between groups produced statistically important variations ($p<0.05$) according to Table 1.

The observation period revealed equivalent mechanical stability results through removal torque measurements. The mean removal torque measurements demonstrated that titanium implants reached 30.5±3.2 Ncm which outperformed zirconia implants at 24.7±2.8 Ncm and both surpassed the PEEK implants at 15.3±2.6 Ncm. The groups demonstrated differences which reached statistical significance ($p<0.05$) according to the removal torque findings shown in Table 2.

Bone-to-implant contact measurements allowed identification of the degree of implant bone fusion. The titanium implants surpassed both zirconia (58.2±3.9%) and PEEK (40.6±5.1%) implants by yielding the highest bone

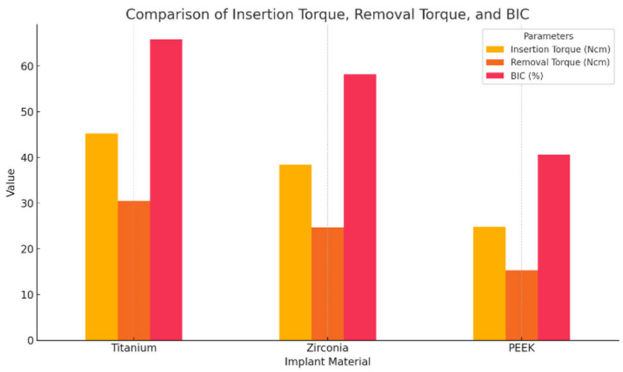

Figure 1: Comparison of insertion torque, removal torque, and bone-to-implant contact (BIC) for Titanium, Zirconia, and PEEK implants. Titanium consistently outperformed other materials in all parameters ($p<0.05$)

Table 1: Mean Insertion Torque (Ncm) for Different Implant Materials

Implant Material	Mean Insertion Torque (Ncm)	Standard Deviation (SD)
Titanium	45.2	5.1
Zirconia	38.4	4.3
PEEK	24.8	3.5

$p<0.05$, statistically significant difference between groups

Table 2: Mean Removal Torque (Ncm) for Different Implant Materials

Implant Material	Mean Removal Torque (Ncm)	Standard Deviation (SD)
Titanium	30.5	3.2
Zirconia	24.7	2.8
PEEK	15.3	2.6

$p<0.05$, statistically significant difference between groups

Table 3: Bone-to-Implant Contact (BIC) Percentage for Different Implant Materials

Implant Material	Mean BIC (%)	Standard Deviation (SD)
Titanium	65.8	4.5
Zirconia	58.2	3.9
PEEK	40.6	5.1

$p<0.05$, statistically significant difference between groups

implant contact percentage (65.8±4.5%). Expressions of bone-to-implant connective tissues showed a substantial variation between the tested groups ($p<0.05$) (Table 3, Figure 1). The results showed significant statistical variations between groups with $p<0.05$. The analysis based on partial eta-squared (η^2) showed substantial effects on insertion torque ($\eta^2 = 0.78$) and removal torque ($\eta^2 = 0.82$) and BIC ($\eta^2 = 0.85$) among the studied groups which verified significant differences in osseointegration results.

These findings indicate that titanium implants exhibit the highest osseointegration potential, as evidenced by superior insertion torque, removal torque, and BIC values (Table 1-3). Zirconia implants showed promising results but were inferior to titanium, while PEEK implants demonstrated significantly lower values across all parameters.

DISCUSSION

Dental implant success depends heavily on the ability to integrate with bone tissue and this potential relates to implant materials and surface characteristics along with structural integrity. The titanium implants achieved higher insertion torque values as well as better removal torque results and bone-to-implant contact (BIC) than both zirconia and PEEK implant types. Experts agree that titanium stands out for dental implants since it shows great biocompatibility alongside strong mechanical properties and natural bone conduction ability [1,2].

The insertion torque and removal torque values for titanium implants remained the highest since they provided superior primary and secondary stability. The mechanical interlocking property of titanium achieves its high insertion torque value of 45.2±5.1 Ncm due to its bone-affinity surface topology [3]. Different studies have proven that titanium surface modification through roughening can boost cell adherence and proliferation thereby increasing bone integration into the implant structure [4,5]. The measurements of removal torque on titanium exceeded those recorded for zirconia and PEEK which demonstrates superior implant stability regarding timeline [6].

The osseointegration capability of zirconia implants resides between titanium and PEEK because their insertion force and removal torque measurements occupied intermediate levels between these materials. The zirconia solutions achieved an average BIC value of 58.2±3.9% thus showing potential as a titanium replacement for patients who need allergy-free or aesthetically pleasing dental products [7,8]. Scientific studies demonstrate Zirconia exhibits positive biological behavior by reducing bacterial adhesion while enhancing soft tissue integration which tends to lower peri-implantitis susceptibility [9]. However, its lower mechanical strength and risk of fracture limit its application in high-load-bearing areas [10].

PEEK implants produced the lowest values for insertion torque and removal torque and BIC measurements thus indicating poor osseointegration potential of the material. PEEK shows poor bone integration tendency with BIC levels at 40.6±5.1% because of its natural impediments to bone bonding without surface modifications [11]. PEEK demonstrates limited bone bonding properties mainly due to its hydrophobic characteristics and bioinert behavior which reduces its suitability for direct contact purposes [12]. The attempts to enhance PEEK's osseointegration by using plasma treatment combined with hydroxyapatite coatings and nanostructuring have yielded insufficient results compared to the performance of titanium and zirconia [13,14].

Statistical analysis showed there were essential differences ($p<0.05$) in the insertion torque along with removal torque along with BIC values between the three implant materials. The research demonstrates zirconia could act as an alternative to titanium but PEEK needs substantial modification before it can function successfully as a load-bearing dental implant [15]. Patient satisfaction with zirconia implant durability remains problematic because these substances exhibit brittleness and exhibit degradation at low temperatures thus affecting cyclic loading performance. Zirconia demonstrates good compatibility with soft tissues in the mouth yet its mechanical weakness requires doctors to select it carefully in regions with high mechanical stress.

Plasma immersion ion implantation combined with HA nanoparticle coating and sulfonation of PEEK implant surfaces has produced better bioactivity results during recent research developments. The current modifications made to PEEK material have not succeeded in reaching the level of osseointegrative capability that titanium and zirconium exhibit in actual clinical approaches. This study is limited by its *in vitro* nature, which does not fully replicate oral environmental variables such as saliva, microbial load, pH fluctuations, and mechanical loading forces. Additionally, the influence of corrosion, fatigue resistance, and material aging under physiological conditions was not assessed. Future investigations should include cyclic loading and thermal aging to better simulate clinical scenarios.

Future Directions:

- Conduct *in vivo* clinical trials with long-term follow-up.
- Evaluate implant performance under cyclic loading to mimic masticatory forces.
- Investigate the efficacy of novel nanocoatings on PEEK and zirconia to improve osseointegration.
- Assess site-specific implant outcomes based on bone density and anatomical location.

CONCLUSIONS

The *in vitro* examination established that titanium showed the best connection between bone tissue and material based on mechanical assessment with supporting histopathological findings. The combination of attractive aesthetics and metal allergy tolerance in zirconia coverage needs to consider its insufficient mechanical strength. The current use of PEEK implants faces limitations for medical purposes because they demonstrate weak bone integration properties which require surface modification techniques to become effective. Long-term clinical testing and evaluation procedures should be used to verify laboratory findings about material properties so that doctors can make better implant choices.

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