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Ph.D. Thesis

Influence of abutment material and implant diameter on implant deformation, abutment removal torque loss, and static loading strength in conical connection implant-abutment assemblies after simulated long-term oral use

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INTRODUCTION

Dental implant therapy has been proven as a long-term reliable treatment in partially and fully edentulous cases [1-3]. However, careful consideration should be taken for many factors, such as the biological condition of the patient, aesthetic outcomes, and mechanical performance of the implant-abutment assembly [4-6].

In recent years, zirconia abutments have been widely adopted in dental implant practices, including the one-piece type and the type with a metal insert base. Owing to favorable mechanical properties and subsequent high success and survival rate, titanium abutments have been considered the gold standard option for implant treatments [7-10]. For zirconia abutments, there is no doubt concerning the superiority of the aesthetic performance over conventional titanium abutments due to their natural-looking color [11-15] and the mechanical properties over other ceramics such as alumina [16-18]. Therefore, it is usually recommended that zirconia abutments be used in cases with a high demand for aesthetics, such as anterior cases or cases with a thin gingival biotype [19]. Moreover, zirconia abutments are also reported to present less plaque accumulation and, subsequently, a better soft-tissue outcome than titanium abutments [20,21]. However, many issues are yet to be addressed concerning the mechanical degradation in implant-abutment assemblies over long-term oral use with zirconia abutments [5].

Narrow diameter implant-abutment systems are considered more susceptible to mechanical complications than regular diameter ones when coupled with zirconia abutments due to the weaker structure and higher tendency of stress focusing [5,22]. The internal implant-abutment connection has presented a significantly more favorable stress distribution in the connection area and, therefore, better resistance to mechanical complications than conventional external connections [23-26]. Unfortunately, how zirconia abutments work in these systems has not been well answered.

The masticatory load applied on implant-abutment assemblies is usually eccentric. Such an unbalanced distribution of stress repeated frequently over the years could cause implant components (implant body, abutment, abutment screw) to plastically deform or even fracture [27-29]. This process could be worsened by marginal bone loss around the implant [30]. Such deformation could lead to permanent misfit between the implant and abutment, which is reported to serve as a risk factor for peri-implantitis and fracture of the implant or abutment [31,32]. Because of the high stiffness of zirconia [17,33], abutments made of this material may transmit more stress to the implant body than titanium ones.

Literature has suggested that one-piece zirconia abutments could induce more implant wear [34-36]. This wear in the implant-abutment interface may also compromise the tight contact and lead to loosening of the abutment screw [37,38]. Furthermore, misfits formed in the joint could worsen bacterial microleakage and proliferation [39-41].

Abutment screw loosening has been reported as among the most common mechanical complications of implant treatments after long-term oral use [2,8,42]. Since zirconia has different mechanical and surface properties from titanium [17,43], there is still doubt whether one-piece zirconia abutments could present a different torque performance.

Static loading strength decrease in implant-abutment assemblies using internally conically connected one-piece titanium abutments has been reported to be minimal after cyclic mechanical loading [44]. However, when using zirconia abutments, the strength may degrade more due to the high brittleness and low-temperature degradation of zirconia, which could threaten the long-term prognosis of such clinical cases [17,23,45,46].

Scientific data has not addressed how zirconia abutments affect the aspects mentioned above of mechanical degradation in conically connected systems. Therefore, the purpose of this *in vitro* study was to comprehensively investigate the influence of three types of abutment materials (one-piece titanium, one-piece zirconia, and zirconia with a titanium alloy base) on implant deformation, abutment removal torque loss, and static loading strength in implant-abutment assemblies of regular and narrow diameters after a simulated long-term oral use.

Experiment 1: Implant deformation and conical contact surface morphological change

Purpose

To investigate the influence of abutment material on implant body deformation and conical contact surface morphological change in implant-abutment assemblies of regular and narrow diameters after a simulated long-term oral use.

Materials and methods

30 conical connection titanium alloy (Roxolid®; Straumann, Switzerland) implants (Bone Level Tapered implant 10 mm; Straumann, Switzerland) of regular and narrow diameters (regular, R: 4.1mm; narrow, N: 3.3mm, n=15 each) were randomly divided into six groups and paired with officially-made abutments of three materials (T: one-piece titanium, Z: one-piece zirconia, C: zirconia with titanium alloy base, n=5 each) and corresponding connection diameters while with identical connection design. Thus six groups of different abutment material and diameter combinations were established. The material-diameter combinations and group codes are shown in Table 1 and Fig 1.

The superstructure portion of all abutments was designed and fabricated into identical geometry and size using a CAD/CAM system (CARES Visual; Straumann, Switzerland). A simplified cylindrical geometry was adopted to design this portion of the abutments. For zirconia abutments with a titanium alloy base, the luting surface of the two components (zirconia and metal) were airborne abraded (Hiblaster Ovaljet; Shofu, Japan) with alumina particles of 50-70 μm under 0.4 MPa pressure for 5 seconds, followed by ultrasonic cleaning for 10 minutes. A metal primer (Metal Link; Shofu, Japan) and a ceramic primer (AZ Primer; Shofu, Japan) was then applied to corresponding luting surfaces before the two components were bonded with dual-cure resin cement (Resicem; Shofu, Japan). Finally, an additional light-curing process using a lab-use curing device (Solidilite V; Shofu, Japan) was applied to enhance the bonding performance.

All 30 implant bodies were scanned with a μCT (R_mCT2; RIGAKU, Japan) (90 kV, 200 μA) before connecting with abutments. A preliminary study was conducted to confirm the precision of the μCT to be approximately 4 μm. The CT images were converted into open-format standard triangle language (STL) format with a 3D processing software (Materialise Mimics 21.0; Materialise NV, Belgium).

The abutments were connected to corresponding implants at the tightening torque recommended by the manufacturer (35 Ncm) and retightened at the same torque after ten minutes to rule out the settling effect [47]. Reversal torque measurement for experiment 2 was performed before and after artificial aging.

As the initial step of the artificial aging process, all 30 specimens were subjected to a thermal cycling process (TTS-1; THOMAS KAGAKU, Japan). Then, a mechanical cyclic loading process was performed for all samples using the "mastication simulation" function of a universal testing device (ElectroPuls E3000; INSTRON, USA). Specific parameters adopted in the artificial aging process are shown in Table 2. The artificial aging protocol was adapted from a well-adopted regimen simulating long-term oral use in anterior and posterior scenarios respectively (narrow diameter: anterior, regular diameter: posterior) [48,49]. A 30° inclined loading setup (Fig 2) was adopted in reference to ISO 14801: 2016 standard [50]. The specimens were mechanically fixed (1400 Ncm) on a specimen holder with a 3 mm coronal exposure of the implant bodies to simulate peri-implant bone loss. The specimens were covered with a dome-shaped stainless steel loading cap during the mechanical loading. A layer of polytetrafluoroethylene (PTFE) film was placed between the inner surface of the loading cap and the specimen to rule out the friction force.

After the artificial aging, all 30 implant bodies were separated from abutments and again scanned with μCT. The images were converted into STL format. The 3D images extracted from implant bodies before and after artificial aging was imported into another two 3D processing software (Geomagic Control 2015, Geomagic Wrap 2015; 3D Systems, USA) and 3-dimensionally aligned using the software's "best-fit alignment" function. Owing to the grip-like mechanism of the specimen holder (Fig 3), the apical portion of the tested implants was undeformed after artificial aging. Therefore, a specific apical portion of the implants was selected for the alignment. After the alignment, the volume of the protruding parts of the post-aging images within the coronal 3 mm range was calculated as deformation amount (Fig 4). Since these protruding parts were not the subject of compressive stress during mechanical loading, the influence of implant body wear could be considered minimal.

An observation of the conical implant surface (Fig 5), which was constantly in contact with the abutment throughout the aging process, was performed for all specimens after aging using a scanning electron microscope (JSM6510LV; JEOL, Japan) (20 kV, 1200 ×).

Statistical analysis of implant deformation results was performed separately for regular and narrow diameter specimen groups using dedicated software (XLSTAT; Addinsoft, France). All data were confirmed as normally distributed using a Shapiro-Wilk test. A one-way ANOVA test was performed with a Tukey (HSD) post-hoc test. A confidence interval of 95 % (significance level: 0.05) was set for all tests.

Results

All specimens survived the artificial aging process without signs of compromised implant abutment integrity (cracks, fractures, screw loosening). The means, standard deviations, and statistical analysis results of implant body deformation amount are shown in Table 3 and Fig 6.

No significant difference in implant body deformation amount was confirmed among regular diameter groups ($p = 0.095$). The ZN group showed significantly less deformation than TN and CN groups in narrow diameter groups ($p < 0.0001$). The amount of implant body deformation was not statistically affected by abutment material in regular diameter. However, in narrow diameter, such influence was significant.

In SEM observation, ZR and ZN groups showed widespread distinct surface damage, with machine lines unidentifiable. However, only minor damage was confirmed in the other groups, with machine lines recognizable (Fig 7).

Summary

One-piece zirconia abutments showed better resistance to implant body deformation in narrow diameter after a simulated long-term oral use than those with metal connections. However, such a difference was not found in regular diameter. One-piece zirconia abutments also showed a more distinct morphological change in implant conical surfaces than those with metal connections in regular and narrow diameters. Zirconia abutments with a titanium alloy base showed similar results to one-piece titanium abutments.

Experiment 2: Abutment removal torque loss

Purpose

To investigate the influence of abutment material on abutment removal torque loss in implant-abutment assemblies of regular and narrow diameters after a simulated long-term oral use.

Materials and methods

All abutment screws were fabricated from the same alloy (Ti6Al7Nb, TAN). Identical specimens as in experiment 1 were used. Before the artificial aging process, abutment removal torque was measured three times for each specimen with a digital torque meter (TME2; Tohnichi, Japan) following the workflow shown in Fig 8. A retightening was conducted for each measurement to rule out the settling effect [47]. The average value was adopted as abutment removal torque before aging (T_1). After the measurement, all abutments were again connected to corresponding implants and retightened.

After aging, all 30 implant bodies were disconnected from abutments, and post-aging abutment removal torque was measured (T_2). The same operator conducted all the torque measurements.

Initial and post-aging torque loss values were calculated with the following equations.

$$\textbf{\textit{Initial torque loss (Ncm)}} = 35\ Ncm - T_1$$

$$\textbf{\textit{Post-aging torque loss (\%)}} = (T_1 - T_2)/T_1 \times 100\%$$

They were statistically analyzed separately for regular and narrow diameter specimen groups. Since T_1 varies for each specimen, post-aging torque values were presented in percentages. Statistical analysis was performed using dedicated software (XLSTAT; Addinsoft, France). All data were confirmed as normally distributed using a Shapiro-Wilk test. One-way ANOVA tests were performed with Tukey (HSD) post-hoc tests. A confidence interval of 95 % (significance level: 0.05) was set for all tests.

Results

All groups showed significant torque loss initially and after the artificial aging process. The means, standard deviations, and statistical analysis results of initial and post-aging torque loss are shown in Table 4 and Fig 9-10.

For initial torque loss, ZR ($p < 0.0001$) and ZN ($p < 0.0001$) groups showed significantly greater values. For post-aging torque loss, ZR ($p < 0.0001$) and ZN ($p < 0.0001$) groups showed significantly greater values. Both initial and post-aging abutment removal torque loss were significantly affected by abutment material.

Summary

Regardless of implant diameter, one-piece zirconia abutments tend to induce larger abutment removal torque loss than those with metal connections initially and after a simulated long-term oral use. Zirconia abutments with a titanium alloy base showed similar results to one-piece titanium abutments.

Experiment 3: Static loading strength degradation

Purpose

To investigate the influence of abutment material on static loading strength in implant-abutment assemblies of regular and narrow diameters after a simulated long-term oral use.

Materials and methods

Specimens that survived aging were again connected (abutment and implant) at 35 Ncm and subjected to a static loading test until failure. Failure was defined as a specimen fracture or a clear stress peak identified in the stress-strain curve with loading head displacement over 1 mm. Identical loading setup (ElectroPuls E3000, INSTRON, USA) (head speed: 0.5 mm/min) as in the cyclic loading process was adopted (Fig 2). A layer of PTFE film was applied in the same manner as the cyclic loading process to rule out the friction force. 30 brand-new specimens (regular: 15, narrow: 15) with the same materials and configurations as in the aging test were subjected to a static loading test of the same method. Maximum load values were recorded and analyzed. Thus a comparison between specimens before and after aging could be performed to confirm the degradation of static loading strength after aging.

Statistical analysis of static loading strength results was performed separately for regular and narrow diameter specimen groups using dedicated software (XLSTAT; Addinsoft, France). All data were confirmed as normally distributed using a Shapiro-Wilk test. A two-way ANOVA test (abutment material, aging status) was performed with a Tukey (HSD) post-hoc test. A confidence interval of 95 % (significance level: 0.05) was set for all tests.

Results

Static loading strength results are shown in Table 5 and Fig 11. Two-way ANOVA and Tukey (HSD) post hoc results are shown in Tables 6-9.

Significant static loading strength degradation after aging was not confirmed for all tested abutment materials and diameters ($p > 0.05$). Despite the aging status, one-piece zirconia groups showed significantly lower strength than the other two materials ($p < 0.0001$) in both diameters.

Summary

Regardless of implant diameter, one-piece zirconia abutments showed lower static loading strength than those with metal connections before and after a simulated long-term oral use. The degradation of static loading strength in implant-abutment assemblies of the tested materials and diameters after a simulated long-term oral use was limited. Zirconia abutments with a titanium alloy base showed similar strengths to one-piece titanium abutments before and after a simulated long-term oral use.

DISCUSSION

Worries about potential implant deformation, implant conical surface damage, abutment removal torque loss, and strength degradation induced by zirconia-made abutments have troubled clinicians. Although zirconia-made abutments have been gaining clinical popularity in recent years, the concern of a more significant long-term mechanical degradation remains not addressed. An evident principle of the adoption of such abutments has yet been established. Therefore, the current *in vitro* study comprehensively investigated the influence of abutment material on three types of mechanical degradations of implant-abutment assemblies of regular and narrow diameters after simulated long-term oral use.

The artificial aging protocol adopted in the current study was adapted from a well-adopted regimen to simulate an equivalent of a 10-year oral use in the posterior region [49]. For the anterior scenario, the loading force was decreased to half the value for the posterior setting considering the physiological bite force in human dentitions [48]. Thus aging protocols simulating a worst-case long-term oral use for two scenarios were established.

Implant deformation and implant conical surface morphological change

Data concerning implant deformation in internally conically connected and narrow diameter implant systems have been scarce. Therefore, the current study investigated the influence of abutment material on implant body deformation and implant conical surface morphological change in implant-abutment assemblies of regular and narrow diameters after simulated long-term oral use.

The deformation amount results did not show a statistical difference among regular diameter groups. Considering the worst-case scenario aging setup adopted [50], it is implicated that long-term deformation in regular diameter implants may be limited under average physiological mastication load. However, specimens using one-piece zirconia abutments showed significantly less implant deformation in narrow diameter. This difference could have resulted from three factors. Firstly, it has been well-documented that one-piece zirconia abutments tend to cause more wear in titanium implants due to the high hardness of zirconia [34-36,51]. *In vivo* studies and case reports have found significant titanium particles in peri-implant soft tissue from zirconia-induced wear [52,53]. Although not evaluated quantitatively, the SEM images obtained in the current study agreed with such a conclusion with the distinct widespread damage on implant conical contact surfaces in ZR and ZN groups, in contrast to the minor morphological change in the other groups. Therefore, more load energy during aging may be consumed by the more significant wear formation in one-piece zirconia specimens, leading to less stress transmission to the implant body. Secondly, as confirmed in experiment 2, one-piece zirconia abutments tend to induce more abutment screw torque loss after a simulated long-term oral use. Although not significant enough to cause a detachment of the implant and abutment, such a loosening could facilitate the micro-movement between the two components during mechanical cyclic loading [38]. This may cause a greater proportion of stress to be transmitted to the abutment screw than when the screw is tightly fastened. In this way, the screw may serve as a buffer for the implant body, preventing more significant deformation in the latter. Thirdly, with the weaker structure and greater tendency of stress concentration from the narrow diameter [5,22], the difference in deformation was able to show significance in narrow diameter specimens. The results indicate that adopting one-piece zirconia abutments in narrow diameter systems may cause less implant deformation after long-term oral use than those with a metal connection.

Previous studies on implant deformation mainly conducted evaluations from perspectives that could only provide limited information about this change. Hoyer et al. and Gratton et al. [54,55] evaluated externally connected implant-abutment joint opening on the outer surface of the assembly with liquid metal strain gauges. Queiroz et al. [56] conducted the same measurement with an optical linear measuring microscope. S. A. Gehrke et al. and Mattheos et al. [57,58] analyzed implant-abutment misfit in mechanically cut cross-section images of the assemblies. In contrast, the current study provided a direct and original perspective: volumetric deformation amount. With a complete 3-dimensional image of the deformed parts, a comprehensive quantitative evaluation of implant deformation was performed.

The current study also differed from the previous studies in results. The reports mentioned above showed that one-piece zirconia abutments could induce more damage to the implant (joint opening or misfit). Considering that both deformation and wear could cause such damage (joint opening or misfit), it is necessary to investigate the two separately. Unfortunately, most of the previous studies did not distinguish these two factors. As described in the methods section, the current study could single out implant deformation by analyzing the protruding images only. In this sense, the seemingly different results from previous studies, especially those also investigated conically connected implants [34,35], may be explained as that wear played a significant role in such implant damage formation.

The current study confirmed that using one-piece zirconia abutments could lead to minor implant deformation in narrow diameter and significant implant conical surface damage. Zirconia abutments with a titanium alloy base showed mechanical properties similar to one-piece titanium abutments. This finding should encourage clinicians to select one-piece zirconia abutments only in areas with high aesthetic demand but low occlusal load, especially anterior regions.

Abutment removal torque loss

The best tightening method of one-piece zirconia abutment screws has been controversial. Data concerning the torque performance of one-piece zirconia abutments used with conically connected implants have been limited. Therefore, the current study investigated the influence of abutment material on abutment removal torque in implant-abutment assemblies of regular and narrow diameters after simulated long-term oral use. To distinguish the influence of abutment and aging process, removal torque measurement was done immediately after initial tightening and after aging. The results showed that one-piece zirconia abutments led to significantly more initial and post-aging torque loss in regular and narrow diameters.

In the current study, one-piece zirconia groups (ZR and ZN) showed significantly more initial torque loss than the other two types with metal connections. Kim et al. [47] investigated the settling effect in abutment screws after initial tightening and suggested a retightening technique to minimize the initial torque loss. Since a retightening 10 minutes after initial tightening was done for all specimens in the current study, the initial torque loss result could be analyzed without the settling effect as a significant factor. Hess [59] described the correlation of interface friction, screw configuration, and tightening torque with screw preload in a bolted joint with the following equation.

$$F_p = T_t \cdot \frac{1}{\frac{p}{2\pi} + \frac{\mu_t r_t}{\cos\beta} + \frac{\mu_n r_n}{\cos\alpha}}$$

Here (Fig 12), F_p is the screw preload, T_t is the tightening torque, p is the screw thread pitch, μ_t is the thread-implant interface friction coefficient, r_t is the thread surface radius, α is the seating surface angle of the screw head, β is the thread half angle, r_n is the screw head radius, and μ_n is the screw head-abutment interface friction coefficient. In the current study, all the variables except for μ_n stay the same for different abutment materials. It has been reported that dry lubricant coating in such interfaces could decrease the friction and better maintain initial screw preload [60-62]. Sikora et al. [43] reported that the friction coefficient is significantly higher in a zirconia-titanium interface than in a titanium-titanium interface. The angle and area of the screw head seating surface also affect the preload [59,63]. In the current study, the one-piece zirconia abutment screws had a flat angle and reduced area of the screw head seating surface than the screws for the other two types of abutments (Fig 13). Considering that such modifications made by the manufacturer are intended to prevent torque loss in one-piece zirconia abutment screws, the greater initial torque loss confirmed with these abutments might be attributed mainly to high friction in the screw-abutment interface.

Reports showed significant initial torque loss in one-piece titanium abutments [64-66]. As for one-piece zirconia abutments, Nakano et al. [67] investigated titanium and zirconia abutments in internally connected implants and found initial torque loss results in agreement with the current study. On the other hand, Butignon et al. [68] investigated abutment torque in external hexagon implants. They found no difference in initial torque loss for different abutment materials (titanium, gold, zirconia). The different results could be from several factors such as connection type, abutment screw type, and different tightening torque for zirconia and metal abutments. It is worth noting that, according to Hess [59], together with interface friction, tightening torque is also associated with the preload. Therefore, to evaluate the influence of abutment material, similar comparative studies must unify the tightening torque between experimental groups.

Previous studies have demonstrated that with external and internal connection designs, using one-piece zirconia abutments could lead to significantly more post-aging torque loss [37,67,68]. The results in the current study suggest that similar torque loss could also occur in a conically connected system. According to the joint failure mechanism described by Bickford [38], external forces could progressively erode the preload due to screw vibration, wear of the mating surfaces, and settling. With wear creating space for screw vibration and wider screw vibration leading to more wear, a vicious cycle could be established, allowing preload loss to build up through the aging process. It has been well-reported that zirconia could lead to more implant contact surface wear [34-36]. In the current study, such damage was also confirmed in SEM images. Additionally, the high elastic modulus of zirconia [17,33] may cause more stress concentration in abutment screws during mechanical loading, thereby increasing the risk of screw loosening [69]. Therefore, the preload loss process may be accelerated when one-piece zirconia abutments are used. In this way, the more post-aging torque loss found in one-piece zirconia groups could be explained.

The current study compared the initial and post-aging torque performance of conically connected abutments of three materials that have been closely scrutinized in recent years. In addition, to the author's knowledge, this is the first study to have investigated the influence of abutment material on torque maintenance in a narrow diameter implant system. The results suggest that, compared with abutments with a metal connection, one-piece zirconia abutments are disadvantageous in maintaining screw torque.

Static loading strength

Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) ceramic has been proven to present significantly better mechanical properties than other ceramic materials [17,33]. However, the strength could degrade after long-term oral use due to low-temperature degradation of the material [70,71]. This degradation is defined as a gradual transformation from a tetragonal phase to a monoclinic phase in aqueous environments [72]. Fractures of zirconia-made prosthetic femoral heads have been reported and attributed to this type of degradation [73]. The same degradation has been reported to occur slowly in the oral cavity [74,75]. Inaccuracy in lifetime prediction extrapolated from accelerated aging test (high temperature and pressure) results has been discussed in the literature [75]. As of the current study, the thermal cycling between 5 ℃ and 55 ℃ in the artificial aging process was intended to trigger the low-temperature degradation and simulate the potentially more significant strength decrease with zirconia abutments than titanium ones. At the same time, degradation of the adhesive interface of zirconia and titanium alloy base was also simulated [76,77].

Dittmer et al. [44] reported that the static loading strength decrease after artificial aging in implant-abutment assemblies using internally conically connected one-piece titanium abutments was minimal. The current study confirmed that the standardized artificial aging process did not induce a significant strength degradation in both diameters, even in one-piece zirconia groups. In agreement with Borchers et al. [74], one explanation could be that the increase of monoclinic phase content in the zirconia material was not significant enough to cause a decrease in bulk strength. Additionally, the implant-abutment connection design could have contributed to the unexpected results. Dittmer et al. [44] found the internal conical connection significantly stronger than internal and external designs. Finite element analyses have also demonstrated that the internal conical connection design has less stress concentration, meaning better strength [78,79].

Furthermore, considering that officially-made abutments from the same manufacturer of the implants present a better fit at the implant-abutment connection [58], the adoption of these abutments may have contributed to this result.

The result that one-piece zirconia abutments showed significantly lower strength than the other two types is in line with previous studies [80-84]. The weaker mechanical properties of zirconia could explain it. The zirconia abutment material tested in this study (Y-TZP) has a fracture toughness of approximately 5 to 10 MPa $m^{1/2}$ [17,85,86], which is significantly lower than the tested titanium abutment material (Ti6Al7Nb, TAN, 68 to 75 MPa $m^{1/2}$) [87]. However, it is worth noting that both the maximum load values of regular and narrow diameter implant-abutment assemblies were well above the maximum bite forces [48] of their dedicated tooth positions (regular: posterior, narrow: anterior).

This study's findings favor the adoption of one-piece zirconia abutments in the anterior region only. In such a region of weaker occlusal load and higher demand of aesthetics, the advantages of this material could be better exploited. At the same time, the disadvantages (torque loss, implant wear, and low strength) may be avoided. In the posterior region, zirconia abutments with a titanium alloy base may be more favorable due to the similar mechanical performance to one-piece titanium abutments. When adopting one-piece zirconia abutments, higher tightening torque, careful patient follow-up, and measures to avoid excessive occlusal load (patient selection, prosthetic design) may be necessary.

The current study results must be interpreted considering the specific material and design of the tested specimens and the aging condition. Extrapolation of these results should be made with caution. Although may lack adaptability to actual clinical situations, future studies using highly customized or self-made specimens, instead of commercialized products, with better control of variables may further clarify the mechanism of mechanical degradations. Clinical studies concerning this topic should verify the findings of the current study.

CONCLUSIONS

Within the limitations of this *in vitro* study, the following conclusions could be drawn:

1. Regardless of implant diameter, one-piece zirconia abutments showed larger abutment torque loss and lower static loading strength both before and after a simulated long-term oral use than those with metal connections.
2. For narrow diameter implants, one-piece zirconia abutments induced smaller implant body deformation than those with metal connections, while such difference was not found for regular diameter implants.
3. Simulated long-term oral use in this study induced limited static loading strength degradation regardless of abutment material and implant diameter.
4. Zirconia abutments with a titanium alloy base showed mechanical performances similar to one-piece titanium abutments in regular and narrow implant diameters.

DISCLOSURES

The author has no conflict of interest to disclose.

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Table 1. Specimen specifics

Group	Abutment type	Abutment product name	Connection design	Abutment screw material
TR	One-piece titanium	CARES Ti; Straumann, Switzerland	Internal conical	Ti6Al7Nb, TAN
ZR	One-piece zirconia	CARES ZrO_2; Straumann, Switzerland		
CR	Zirconia with a titanium alloy base	CARES ZrO_2 + Variobase; Straumann, Switzerland		
TN	One-piece titanium	CARES Ti; Straumann, Switzerland		
ZN	One-piece zirconia	CARES ZrO_2; Straumann, Switzerland		
CN	Zirconia with a titanium alloy base	CARES ZrO_2 + Variobase; Straumann, Switzerland		

Group	Implant system diameter	Implant product name
TR	Regular, 4.1 mm	Bone Level Tapered Implant 10 mm Roxolid; Straumann, Switzerland
ZR		
CR		
TN	Narrow, 3.3 mm	
ZN		
CN		

Table 2. Artificial aging protocol specifics

	Implant system diameter	Parameters	Device	Manufacturer
Thermal cycling	Regular, 4.1 mm	5 ℃-55 ℃, 2 minute/cycle × 12,000 cycles	TTS-1	THOMAS KAGAKU; Japan
	Narrow, 3.3 mm			
Mechanical cyclic loading	Regular, 4.1 mm	10 N-150 N, 1.67 Hz × 800,000 cycles	ElectroPuls E3000	INSTRON; USA
	Narrow, 3.3 mm	10 N-75 N, 1.67 Hz × 800,000 cycles		

Table 3. Implant body deformation results summary

	TR	ZR	CR	TN	ZN	CN
Mean	0.5582	0.5116	0.6693	1.0478	0.4610	0.9880
Standard deviation	0.1532	0.0992	0.0896	0.1454	0.0765	0.1546

(mm^3)

Table 4. Abutment removal torque loss results summary

		TR	ZR	CR	TN	ZN	CN
Initial torque loss (Ncm)	Mean	3.22	5.85	3.22	1.34	5.39	1.13
	Standard deviation	0.99	0.40	0.63	0.33	0.30	0.24
Post-aging torque loss (%)	Mean	15.59	36.20	15.34	11.11	41.76	13.55
	Standard deviation	4.72	3.76	4.99	3.42	2.19	3.20

Table 5. Static loading strength results summary

Aging status		TR	ZR	CR	TN	ZN	CN
Brand-new (non-aged)	Mean	849.34	557.68	848.29	440.48	311.17	421.63
	Standard deviation	42.51	11.57	29.34	14.13	22.18	6.36
Aged	Mean	774.99	530.51	802.83	425.39	313.76	434.27
	Standard deviation	28.03	53.81	48.02	14.56	20.78	12.19

(N)

Table 6. Two-way ANOVA results of regular diameter specimen static loading strength

Source	DF	Sum of squares	Mean squares	F	p value
Aging	1.000	15278.452	15278.452	10.537	**0.004**
Abutment Material	2.000	490392.965	245196.483	169.105	**< 0.001**
Aging × Abutment Material	2.000	2947.215	1473.608	1.016	0.378

Table 7. p values from Tukey (HSD) post-hoc test of regular diameter specimen static loading strength

		Brand-new (non-aged)			**Aged**		
		TR	ZR	CR	TR	ZR	CR
Brand-new (non-aged)	TR		**< 0.0001**	0.999	0.075	**< 0.0001**	0.473
	ZR			**< 0.0001**	**< 0.0001**	0.885	**< 0.0001**
	CR				0.108	**< 0.0001**	0.624
Aged	TR					**< 0.0001**	0.852
	ZR						**< 0.0001**
	CR						

Table 8. Two-way ANOVA results of narrow diameter specimen static loading strength

Source	DF	Sum of squares	Mean squares	F	p value
Aging	1.000	0.021	0.021	< 0.0001	0.993
Abutment Material	2.000	92914.438	46457.219	182.858	**< 0.001**
Aging × Abutment Material	2.000	985.609	492.805	1.940	0.166

Table 9. p values from Tukey (HSD) post-hoc test of narrow diameter specimen static loading strength

		Brand-new (non-aged)			Aged		
		TN	ZN	CN	TN	ZN	CN
Brand-new (non-aged)	TN		**< 0.0001**	0.443	0.670	**< 0.0001**	0.989
	ZN			**< 0.0001**	**< 0.0001**	1.000	**< 0.0001**
	CN				0.999	**< 0.0001**	0.806
Aged	TN					**< 0.0001**	0.947
	ZN						**< 0.0001**
	CN						

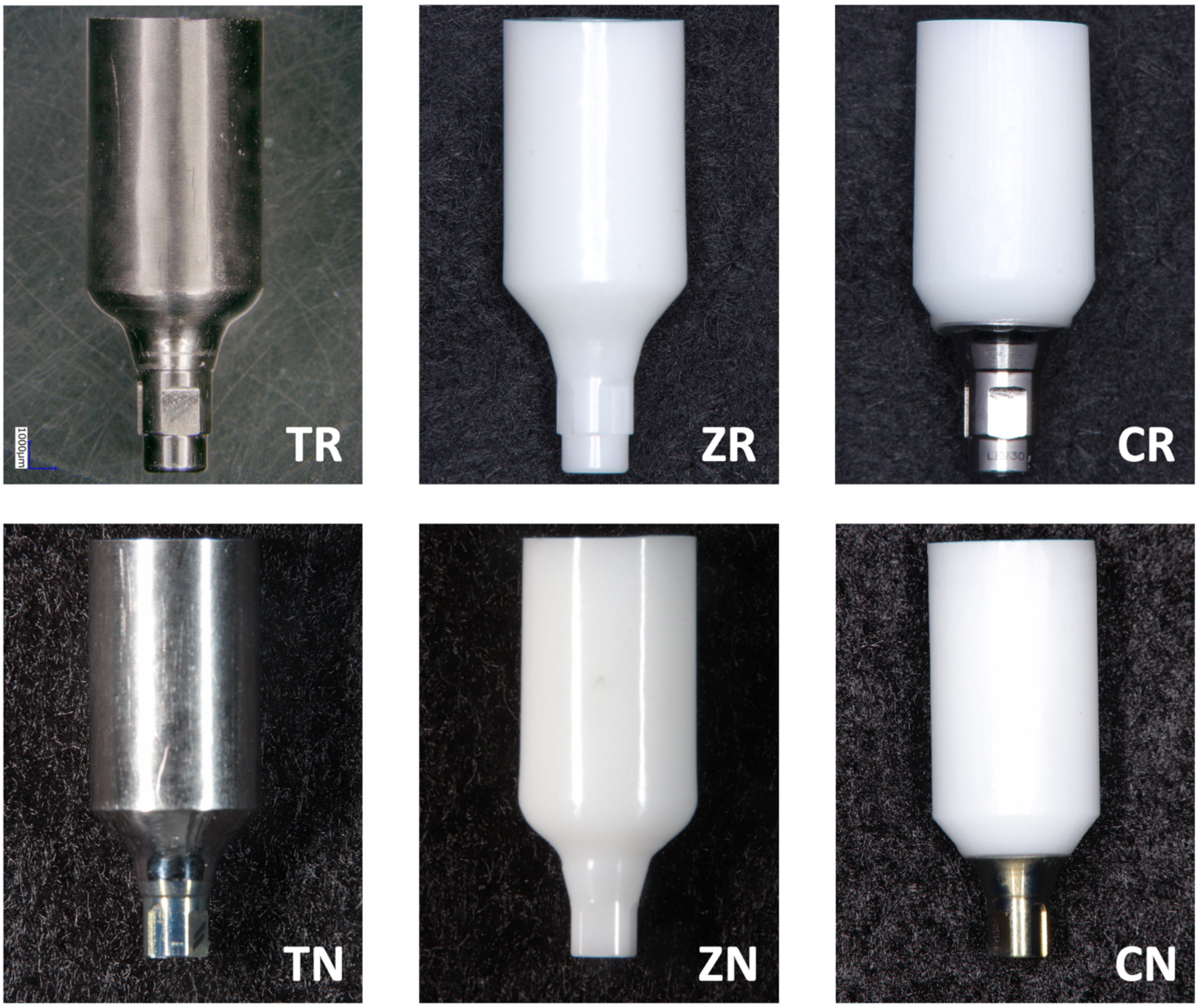

Fig 1. Tested abutments

TR: regular diameter one-piece titanium, ZR: regular diameter one-piece zirconia, CR: regular diameter zirconia with a titanium alloy base, TN: narrow diameter one-piece titanium, ZN: narrow diameter one-piece zirconia, CN: narrow diameter zirconia with a titanium alloy base

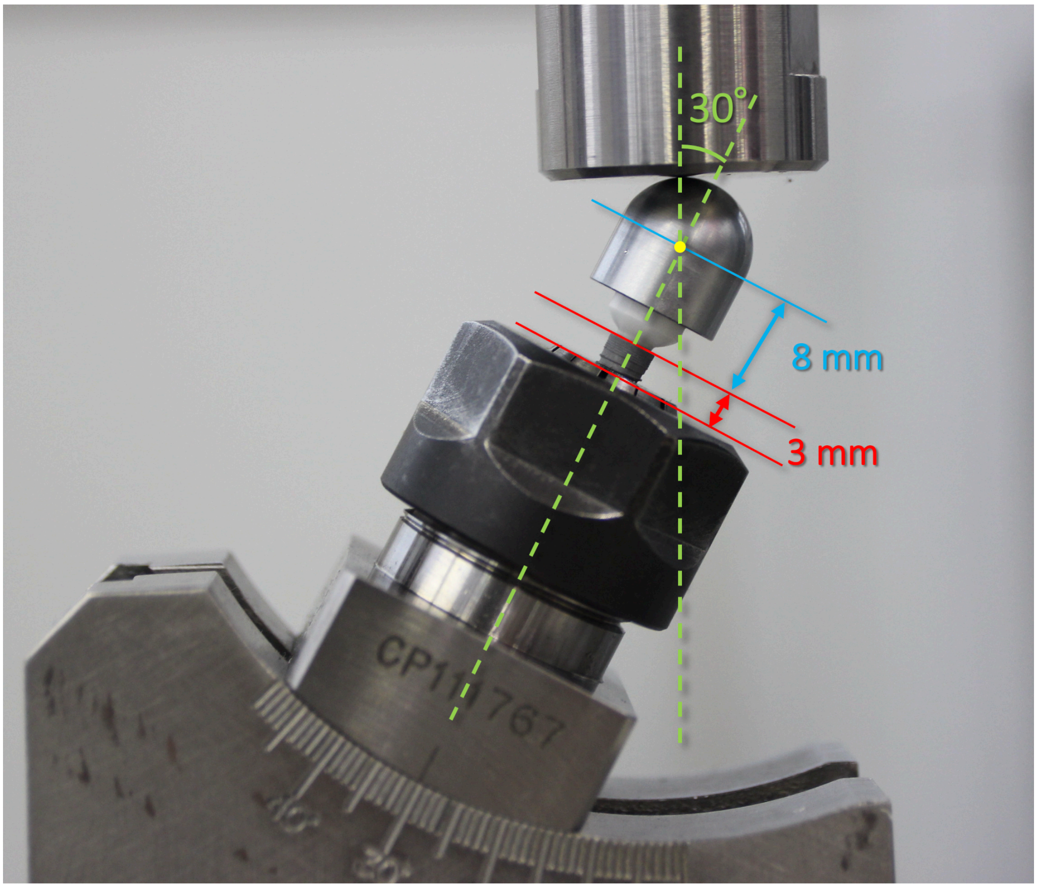

Fig 2. Mechanical loading setup. A 30° inclination and 3 mm coronal exposure of the implant body was adopted.

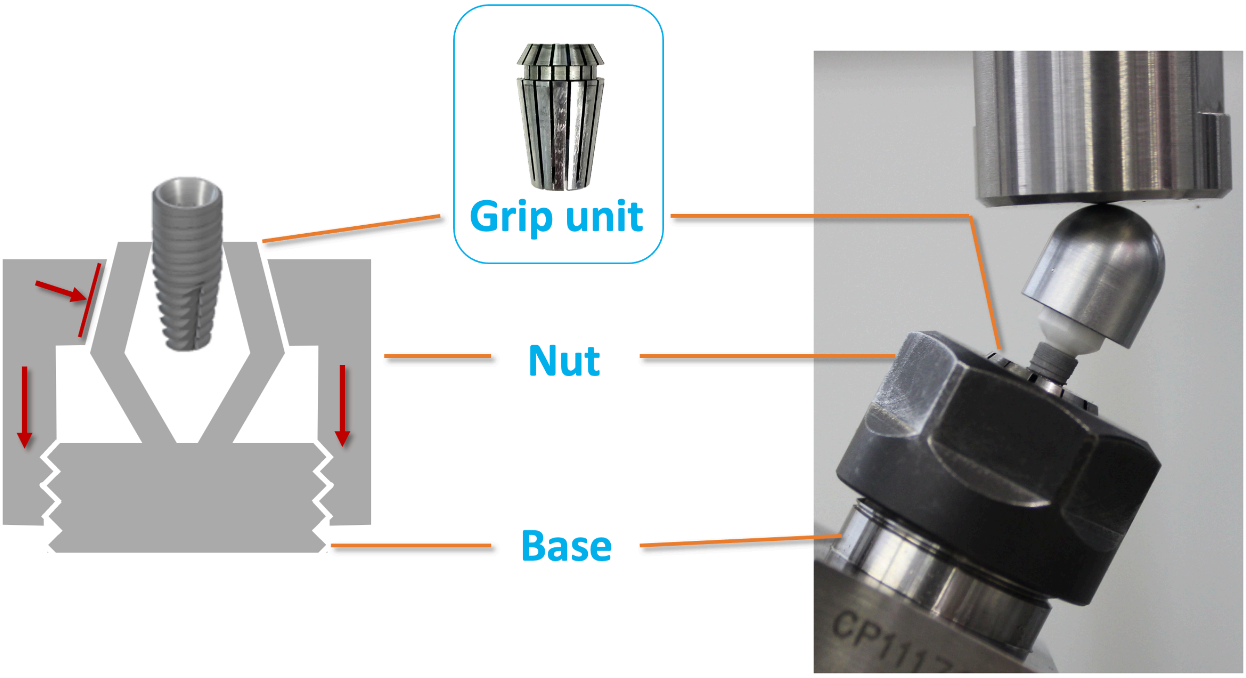

Fig 3. Mechanism of the specimen holder. With only the coronal part of the implant body grip-held by the specimen holder, the apical part was undeformed after aging.

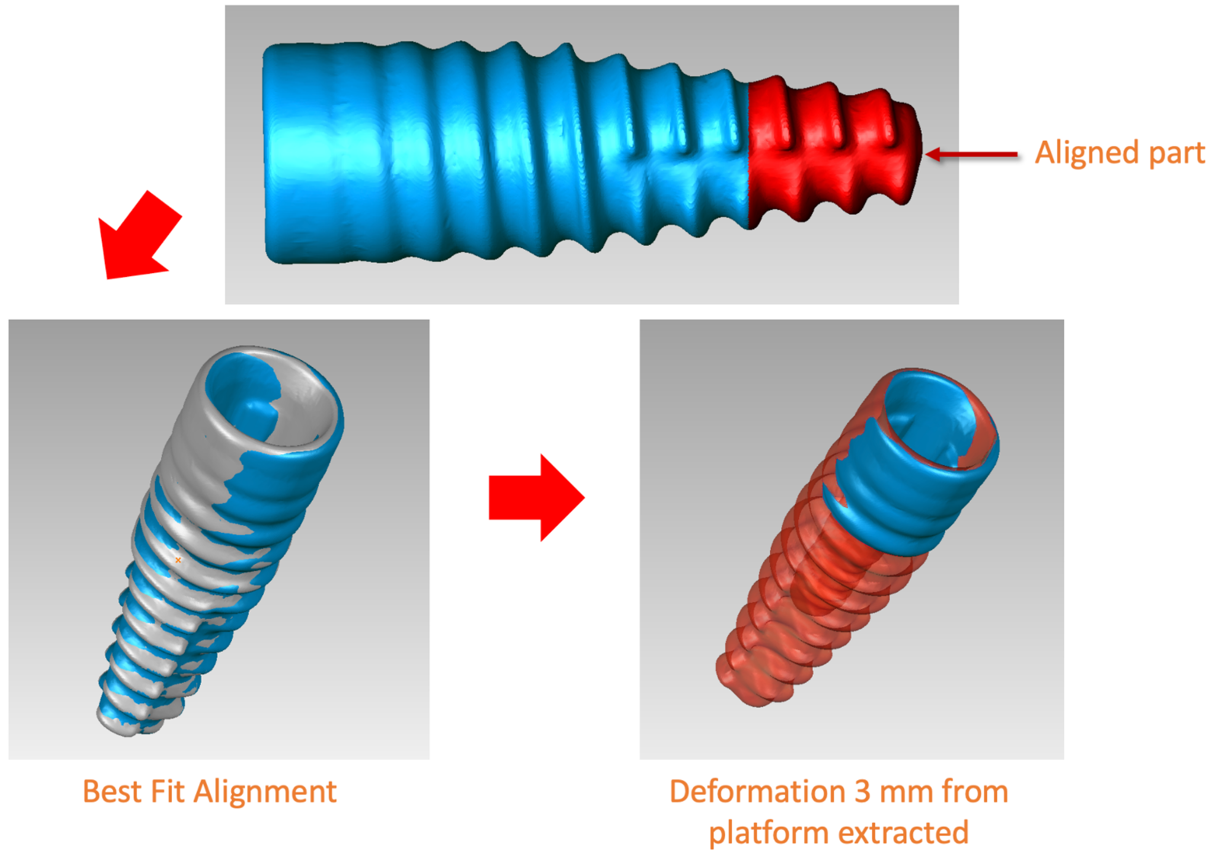

Fig 4. Deformation amount calculation method. 3D images of the implant body before and after aging was aligned with software (upper and lower left figures). Deformation 3D image 3 mm from implant platform was extracted (lower right figure).
Upper figure: red – part aligned with software, lower left figure: gray – 3D image of implant body before aging, blue – 3D image of implant body after aging, lower right figure: blue – 3D image of implant body deformation within 3 mm from implant platform.

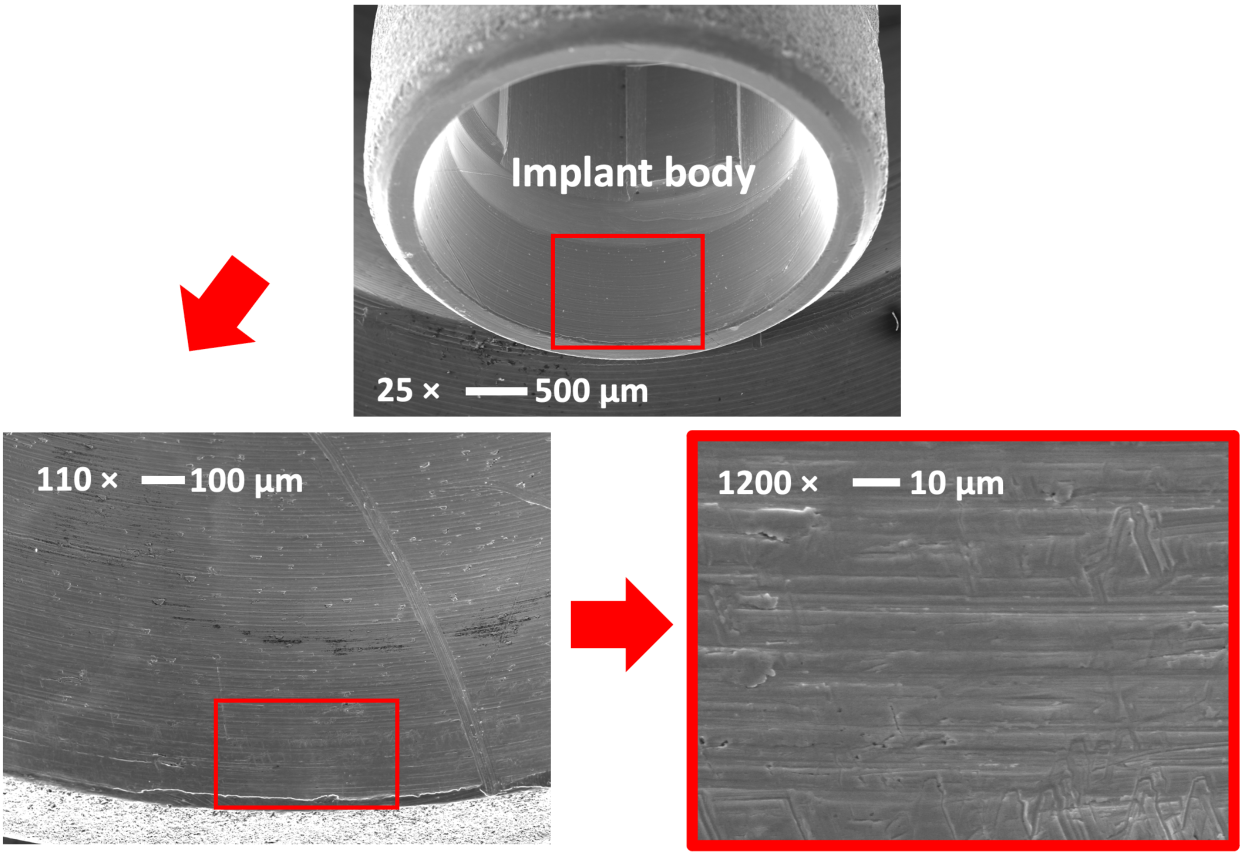

Fig 5. Region observed in the implant conical surface with a scanning electron microscope.

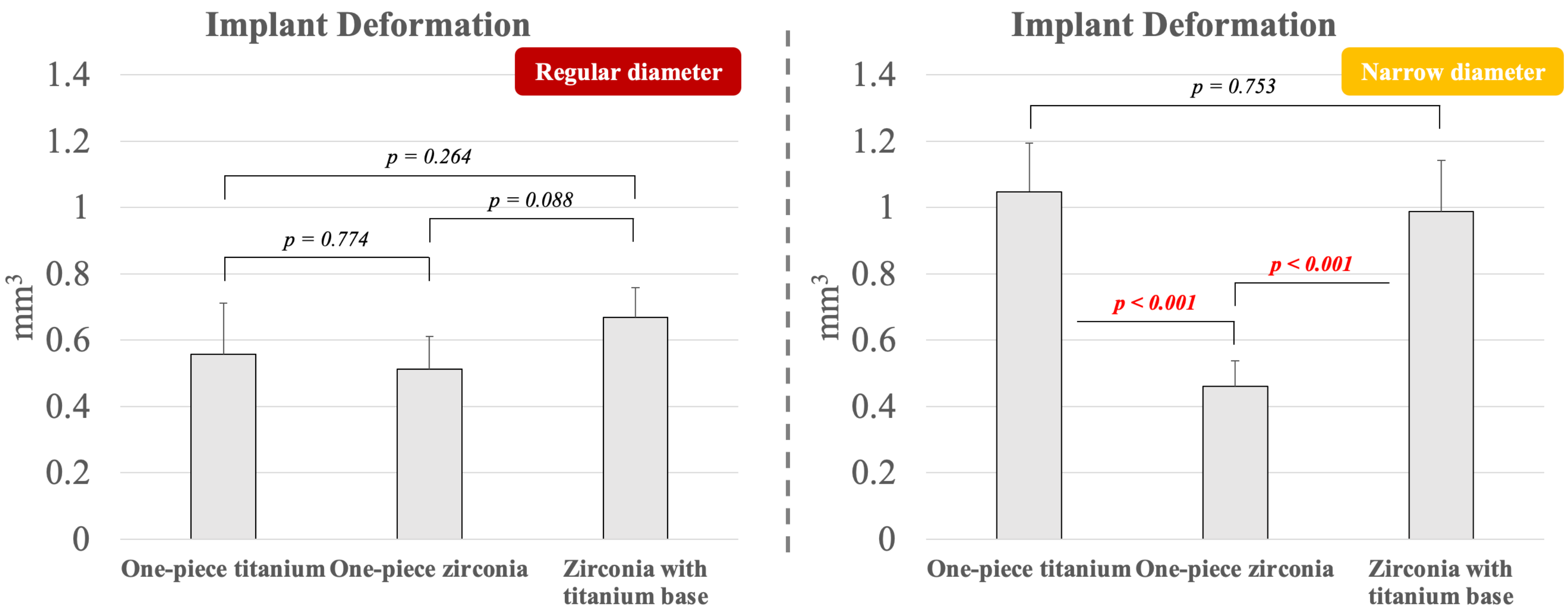

Fig 6. Comparison of implant body deformation amount for different abutment materials in regular and narrow diameters. Bold red characters indicate statistical difference (One-way ANOVA with Tukey HSD test, α = 0.05). No significant difference in implant body deformation amount was confirmed among regular diameter groups. The ZN group showed significantly less deformation in narrow diameter groups.

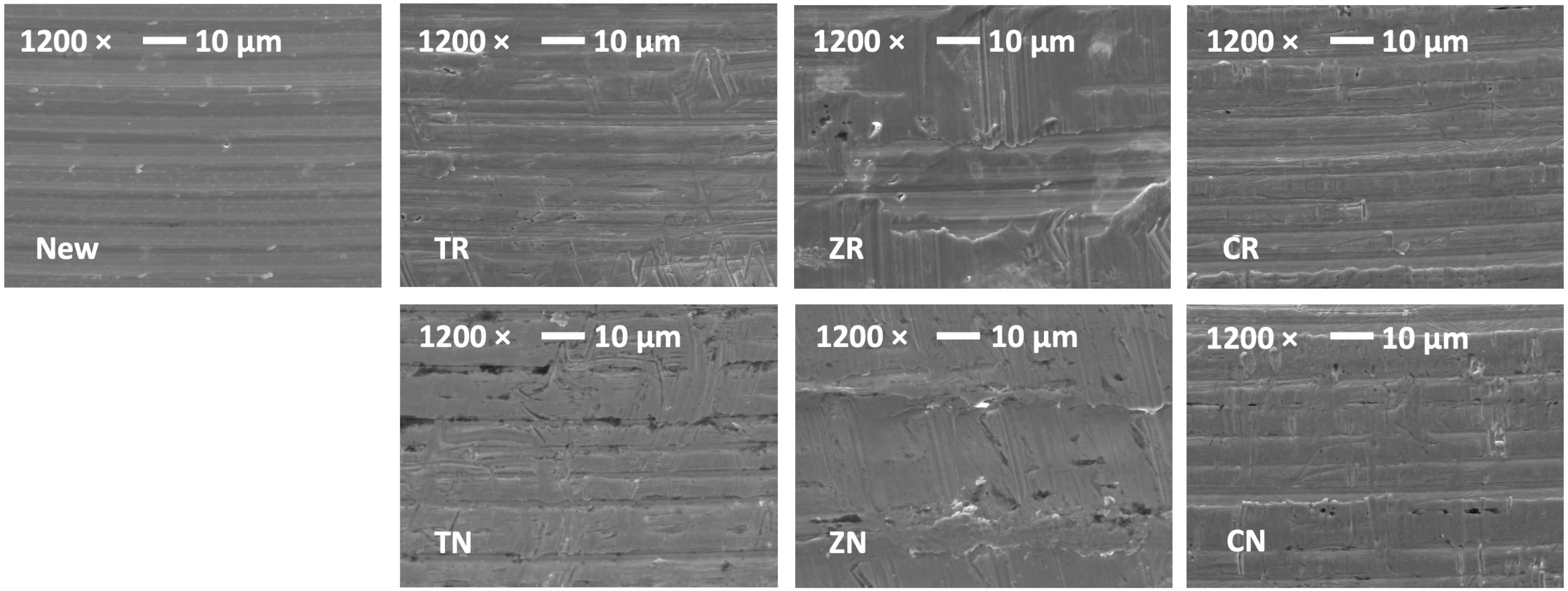

Fig 7. Typical SEM images for each experimental group. Clear transverse machine lines were observed in brand-new samples. Minor damage was observed for groups TR, CR, TN, and CN with machine lines recognizable. Groups ZR and ZN showed widespread distinct damage with machine lines disappearing.

New: brand-new implant, TR: regular diameter one-piece titanium, ZR: regular diameter one-piece zirconia, CR: regular diameter zirconia with a titanium alloy base, TN: narrow diameter one-piece titanium, ZN: narrow diameter one-piece zirconia, CN: narrow diameter zirconia with a titanium alloy base

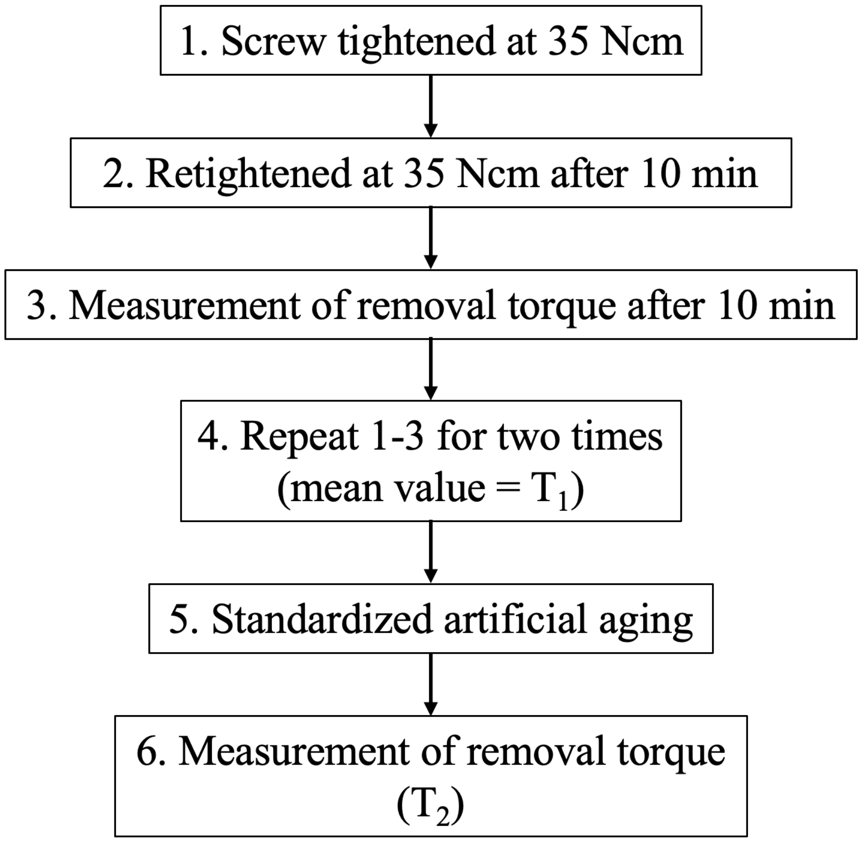

Fig 8. Abutment removal torque test workflow

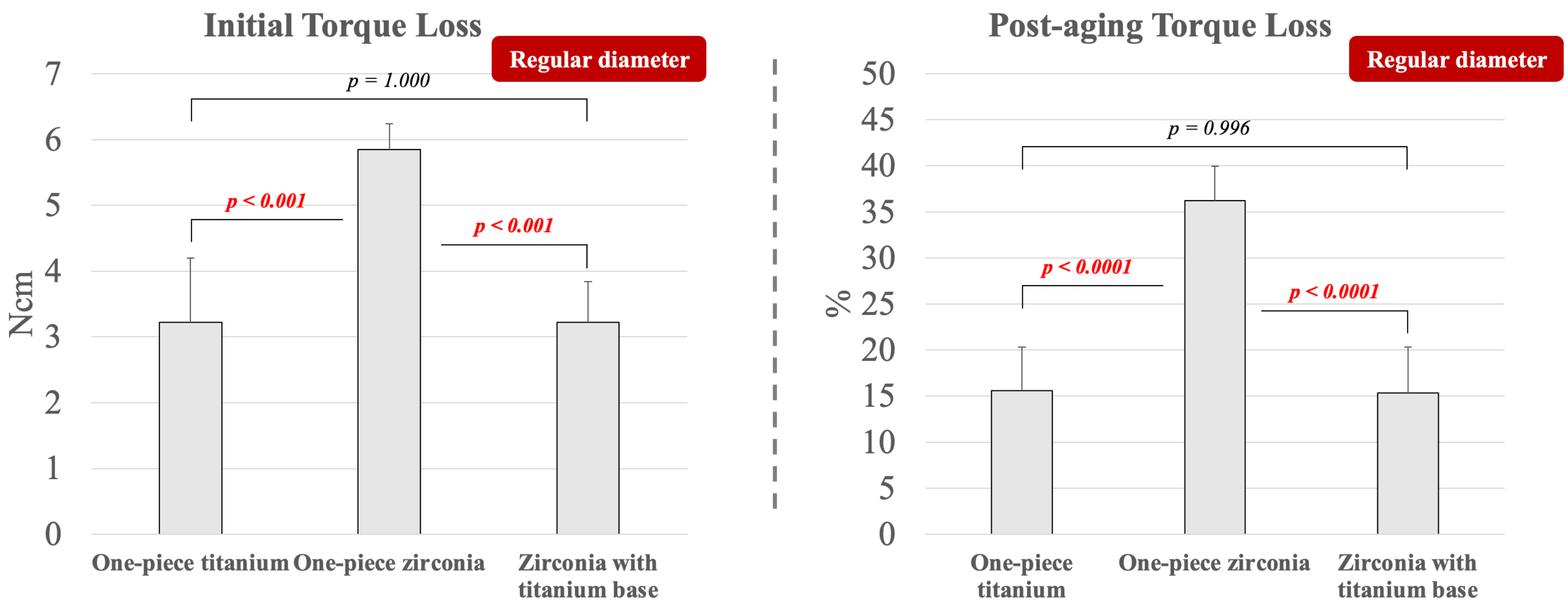

Fig 9. Comparison of abutment removal torque loss before and after aging for different abutment materials in regular diameter. Bold red characters indicate statistical difference (One-way ANOVA with Tukey HSD test, α = 0.05). Group ZR showed significantly more abutment removal torque loss before and after aging.

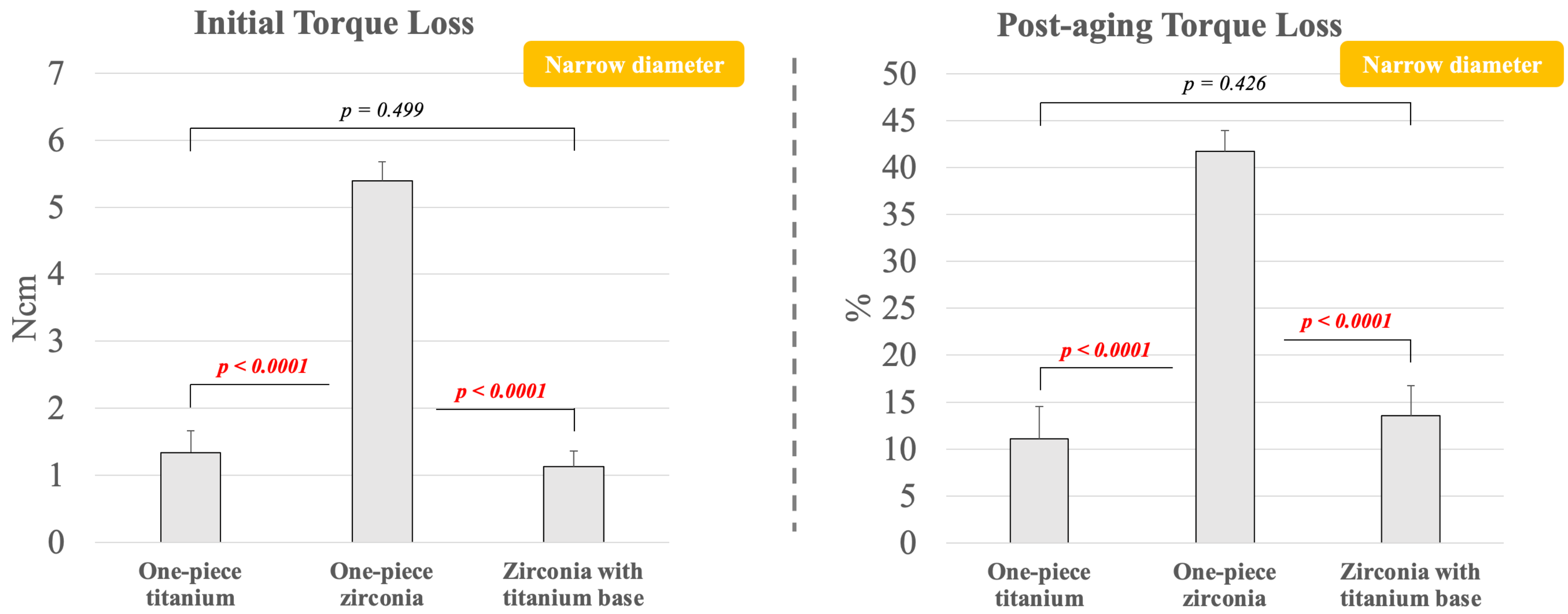

Fig 10. Comparison of abutment removal torque loss before and after aging for different abutment materials in narrow diameter. Bold red characters indicate statistical difference (One-way ANOVA with Tukey HSD test, α = 0.05). Group ZN showed significantly more abutment removal torque loss before and after aging.

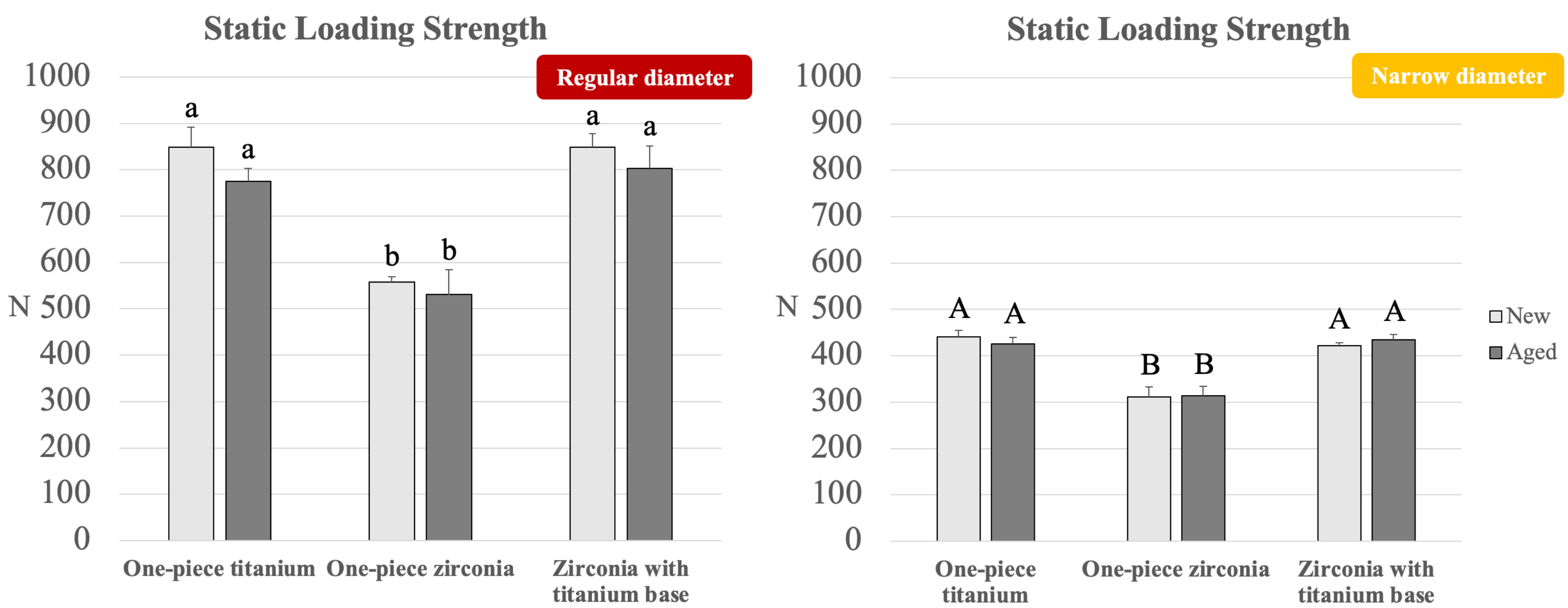

Fig 11. Comparison of static loading strength before and after aging for different abutment materials in regular and narrow diameters. Different top letter indicates statistical difference (Two-way ANOVA with Tukey HSD test, $\alpha = 0.05$). Significant static loading strength degradation after aging was not confirmed for all tested abutment materials and diameters. Despite the aging status, one-piece zirconia groups showed significantly lower strength than the other two materials in both diameters.

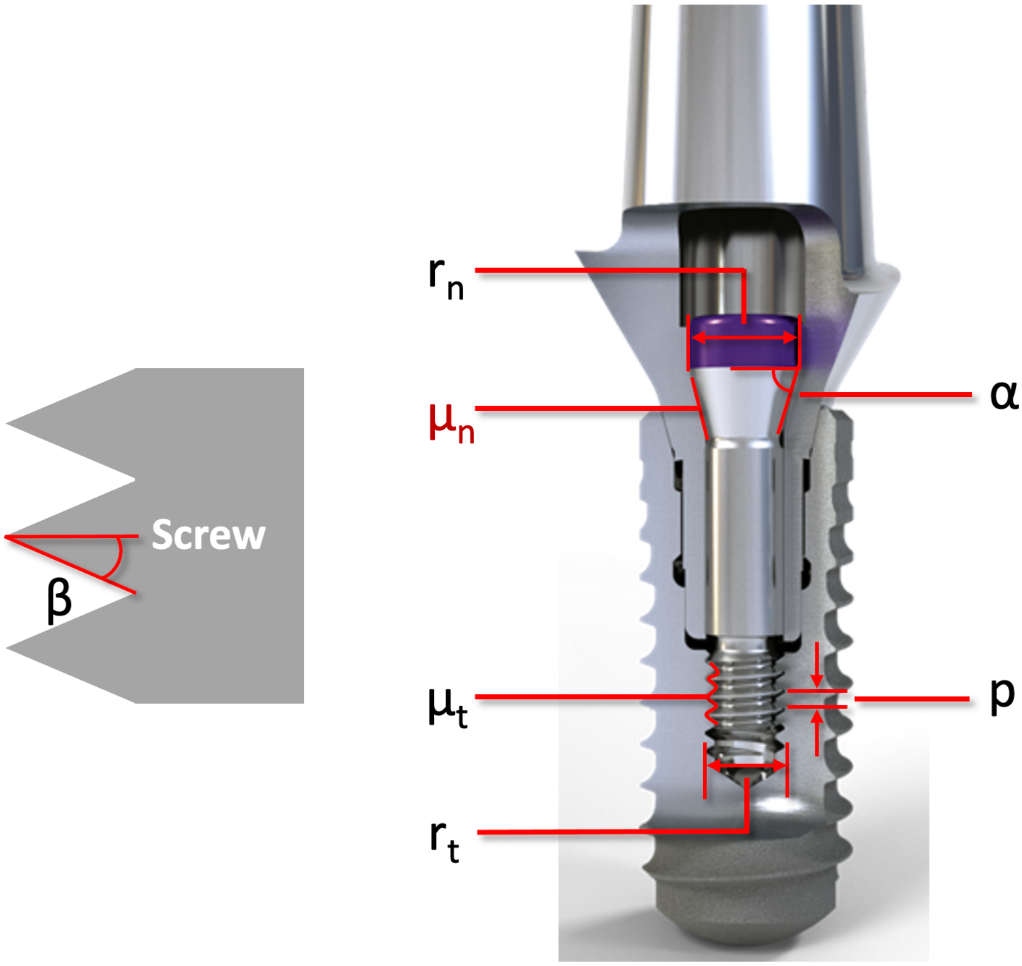

Fig 12. Character indications in the preload equation. Right figure adapted from: *https://www.straumann.com/en/dental-professionals/science/literature/original-on-original.html*

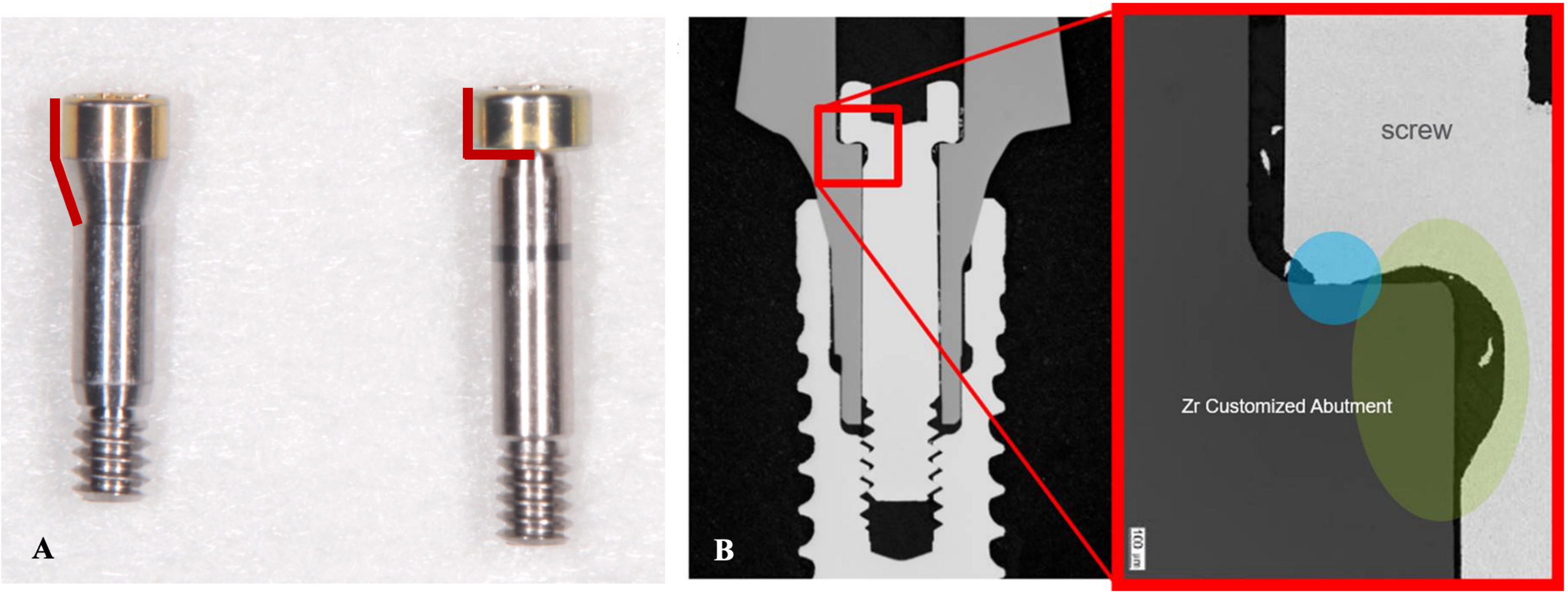

Fig 13. Modifications made to one-piece zirconia abutment screws by the manufacturer. One-piece zirconia abutment screw has a flat seating surface angle and reduced seating surface area compared to the one for the other two types of abutments.

A. left: One-piece titanium/zirconia with alloy base abutment screw, right: one-piece zirconia abutment screw
B. reduced screw head seating surface area of one-piece zirconia abutment screw. Figure adapted from pamphlet "Clinical review: Straumann CARES Abutment Zirconium Dioxide" (Straumann, Switzerland).