THE IMPACT OF DIFFERENT CONE-ANGLE IMPLANT-ABUTMENT RELATIONSHIPS ON THE LONG-TERM SUCCESS OF IMPLANT RESTORATIONS

Ph.D. Thesis

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I. PUBLICATIONS

1. Publications related to the subject of the thesis

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II. **<u>Körtvélyessy Gy</u>**, Hangyási DB, Tarjányi T, Tóth Z, Matusovits D, Pelsőczi-Kovács I, Baráth ZL: Static and Dynamic Compression Load Tests of Conically Connected, Screw Fixed Dental Abutment-Implant Assemblies. *Analecta Technica Szegediensia* 2023; 3.1-12.
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2. Other publications related to the subject of the thesis

I. <u>Körtvélyessy Gy</u>, Tarjányi T, Baráth ZL, Minárovits J, Tóth Z: Bioactive coatings for dental implants: A review of alternative strategies to prevent peri-implantitis induced by anaerobic bacteria. *Anaerobe* 2021; 70: e102404.
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II. A szelíd és az agresszív - avagy a válasz az implantátumot, a fejlesztést, a világmindenséget, meg mindent érintő végső kérdésekre In: Szegedi, Tudományegyetem Fogorvostudományi Kar és a Magyar Fogpótlástani Társaság Szegedi Fogorvosnapok 2019. A Magyar Fogpótlástani Társaság XXIII. Kongresszusa - Implantációs és digitális protetika a 21. században: Szegedi Fogorvostalálkozó és Tudományos Konferencia

III. INTRODUCTION

Implantology is a constantly evolving discipline of dentistry. In the second half of the 20th century, research focused on implant design, materials and surgical techniques; while later on, surface modification techniques and minimally invasive procedures were developed to achieve osseointegration as quickly as possible. Following the 2000s, research has focused on prosthetics-guided implant planning, digital prosthodontics and factors influencing long-term implant success. Implant-anchored restorations have a survival rate of 89 - 93% over 10 years, making them a long-term and successful solution.

The development of osseointegration has been shown to depend on the following parameters: 1. implant material; 2. implant design; 3. implant surface; 4. condition and quality of the bone; 5. surgical technique; 6, implant loading conditions. While in the 1960s and 1970s, the focus of studies was on the implantability and osseointegration of implants, currently, the main aim of studies is to determine the factors affecting the long-term success of implant replacements. An important factor for the long-term success of osseointegrated implants is the relationship between implant and abutment.

In my PhD research we were interested in the implant material and design influencing factors which have a significant role in the osseointegration process. The mechanical stresses caused by masticatory forces may vary for different types of implant-superstructure relationships. The loosening of the fixation screw connecting the implant to the abutment and the irreversible deformation of the implant in the long term are both characteristic of loading. Both phenomenons lead to failure of implant restorations.

Implant-based dentures have no harmful effects on neighboring teeth and provide an aesthetic prosthesis that is similar to natural teeth. The load transmission mechanism on osseointegrated dental implants considerably differs from that of natural teeth: in the case of dental implants – that are fixed directly in the cortical and cancellous bone – there is no stress reduction (i.e. stress absorption) as with the case of periodontal ligaments in natural teeth, therefore occlusal forces are transmitted directly to the surrounding bone. As a result of reduced stress-bearing capacity, increased bone resorption rates and consequential peri-implant bone defects may develop more easily. An implant-supported dental restoration is a complex system, where the implant-abutment connection has a fundamental role in the long-term stability of the whole unit. Due to occlusal forces, micro cracks and fractures may develop in the implant or in the connected elements. Recurring mechanical forces may lead to reversible or irreversible changes to implant geometry, in addition, they may lead to vertical and horizontal micro-movements between the implant and the abutment, which may result in screw loosening or screw fracture. The forces acting on the dental prosthesis are distributed, they act on the superstructure, the implant (neck, wall thickness, body), the implant connection and subsequently on the adjacent bone through different mechanisms and at different heights, depending on implant connection design and implant geometry. Different implant connections may considerably affect the aforementioned force distribution.

Ideally, the reverse torque value does not change under the effect of load forces, nonetheless, screw loosening is a very common problem. It is expected from the implant-connection that the value of the reverse torque does not change due to the occlusal forces, but in reality, the loosening of the screws is also a very common problem. For this reason, there is no clear and ideal decision in terms of the ideal taper angle for the implant-abutment connection. Additionally, these is also a limited understanding whether a change in the value of the taper angle affects the loosening of the screws. During conical fitting, the flexibility of Ti results in a vertical displacement (compression), which may be followed by an irreversible dimensional change (plasticity) in the material of the implant neck. It is important to clarify for clinicians how the degree of conicity affects this material deformation. In addition, this deformation – due to the wedge effect – may cause the microcracking of the surrounding bone, as well as result in crestal bone loss and the loosening of the implant. Increasing the inner wall thickness of the implant body or reducing the diameter of the implant-abutment connection reduces the tension in the peri-implant bone. However, due to the internal geometry, this internal wall thickness may only be increased up to a certain limit; the most commonly used narrow implants are in a diameter range of 3.3-3.8 mm, the implant wall width is less in case of smaller cone angle, which may increase the risk of irreversible dimensional change mentioned in the implant body.

The failure rate of implants due to static and dynamic loads is relatively high (32%) for implants with inadequate primary stability. It is therefore critical to estimate the potential for failure in any given dental implant design. Experimental mechanical testing of dental implants provides useful data for engineers, physicists (involved in implant design) and clinicians. In order to avoid failures in implant systems, it is important to have a detailed understanding about the mechanical behavior of the dental implants prior to their clinical application, which may be assessed via mechanical testing of the connection between the implant and the abutment. Parameters such as maximum allowable mechanical stress and reversible deformation, elastic limit and fracture toughness are key indicators for determining the long-term durability of dental implant systems; thus, static and dynamic mechanical measurements should be performed.

In terms of the mechanical stability of the implant-superstructure connection, in addition to the differences in the raw material and the cone angles, the manufacturing parameters and the dimensional accuracy of the manufactured products also play an important role.

IV. AIMS OF THE STUDY

The mechanical stability of the implant-abutment connection is one of the most important factors for long-term successful implant restorations. In the literature, it has been reported that a conical connection is the most reliable connection type for dental implants. However, there is limited evidence on how the mechanical properties of the implant-abutment connection are influenced by the small or large taper angle of the connection and the quality of the Ti material used for the abutment. Therefore, the aim of our mechanical studies was to simulate the effect of chewing forces on implant-abutment models with different taper angles and to investigate their mechanical stability in order to assess which taper connection represents a long-term, successful and safe solution for small diameter implants. The loosening of the fixig screw between implant and abutment leads to short term dentures and longer-term implant failure, and therefore we investigated how the extension torque values of the fixing screws change under load for implant-abutment models with different taper angles. For which taper-angle connection the highest torque value is retained, i.e. for which one long-term success is likely.

The specific objectives of the study were:

1. Determination of both horizontal and vertical **deformation** of **titanium implants** of **different material** quality (Grade 4 and 5) using a **static mechanical testing protocol**.
2. Determination of whether the **implant material influences** the degree of **screw loosening.** To determine the loosening of fixing screw of implants of different material quality (Grade 4 and 5) using a **static mechanical testing protocol**.
3. Determination of whether **reversible or irreversible deformation** occurs in implant - abutment models with **different conical angle relationships under vertical loading** using a **static mechanical testing protocol**.
4. Determination of whether there is a difference in the **reverse torque values** under **vertical loading** for the fixation screws of **different contact cone angle** models using a **static mechanical testing protocol**.
5. Determination of whether **reversible or irreversible deformation** occurs in implant - abutment models with **different conical angle relationships under vertical loading** using a **dynamic mechanical fatigue protocol**.
6. Determination of whether there is a difference in the **reverse torque values** under **vertical loading** for the fixation screws of **different contact cone angle** models using a **dynamic fatigue testing protocol**.
7. Determination of the **mechanical behavior** of the implant during a **static load with FEA** computational methods, difference of the **mechanical stress** distribution incase of 30 degree and 90 degree along the wall of the implant and at the conical connection
8. Determination of the influence of **design/manufacturing accuracy** on the implant - abutment relationship using **software analytics**.

V. MATERIALS AND METHODS

5.1. Instruments

The static load tests and the dynamic load tests were performed with a fatigue machine (Instron ElectroPuls E3000, Norwood, MA, USA). To measure extension torque, a BMS MS150 electric torque screwdriver (BMS Torque Solutions, Ireland) was used. All load tests were performed at the University of Szeged, Faculty of Dentistry.

5.2. Test modells

For the first static load test, the abutments and implant body models were made from Grade 4 and Grade 5 Ti materials, 3.4 and 3.8 mm in diameter, with the following cone angles: 35°, 55°, 75°, and 90°. A total of n=84 abutment-implant assemblies were used for the first static load tests. At least 3 samples were tested using the same parameter set.

For the first dynamic load test abutments and implant bodies were prepared from Grade 4 Ti in 3.4 mm diameter with the following cone angles: 30°, 45° and 60°. A total of n=21 implant samples were used for dynamic load tests.

Grade 4 Ti implants with 3.4 mm diameter were selected for the second-round static and dynamic tests, with the following cone angles: 24°, 35°, 55°, 75°, and 90°. A total of n=35 implant samples were used for both static and dynamic load tests.

The implant models and abutments were manufactured by Denti System Ltd. (Szentes, Hungary).

5.3. Static load test protocol

5.3.1. The first static load test protocol

At the beginning of our firsth static load tests, the assembly height and implant diameter of an implant abutment were measured before tightening the fixing screw, and the total height was then measured again after tightening the fixing screw to 35 Ncm. The measurement values were recorded. Static loads were then applied. The choice of the load rate was based on the amount of masticatory force applied to a tooth, 100-200-300-400-450-500 N (100 N corresponds to 10 kg weight). The specimens were subjected to successive static loads of different rates for 60 seconds. Total lengths were measured after the loads. After 50 kg load, implant diameter was measured again. The fixing screw connecting the implant to the superstructure was untwisted after the static loads and the extension torque values were measured. The implants and superstructure were reassembled without tightening the fixing screw and the total length and diameter were measured. This connection was then also fixed by tightening the fixing screw to 35 Ncm torque and the total length was measured again. The bolt was tightened again after 60 seconds and the reverse torque value was measured after 24 hours.

5.3.2. The second static test protocol

The implant and the abutment head were tightened with the fixing screw, with a torque of 35 Ncm. The specimens were then placed in a special box, fabricated for this experiment, that held them under the load head during loading. The samples were then pressed by the machine, the force being perpendicular to the surface of the implant abutment. The compression value reading (in N) was obtained by the machine from the position of the loading head. During the load test, the load was gradually increased to 500 N over 20 seconds, and after reaching this peak force, the load was decreased back to 0 N over another 20 seconds. After each load test, the extension torque of the fixing screw were measured by an electric torque screwdriver. From the obtained load curves, resilience and the energy dissipation were calculated from the area under the curve (AUC), with a numerical method.

5.4. Dynamic load test protocols

5.4.1. The first dynamic load test protocol

On each implant our protocol started with tightening the fixing screw between the implant abutment and implant with 35 Ncm torque. After this the assembled implant model samples were put under loads. In the first phase 250 N (equivalent to 25 kg) load over 10 seconds was applied on the implant abutment. The dynamic load test started after this first phase. During the dynamic load test a periodic force with 150 N (equivalent to 15 kg) amplitude sine wave was applied with 15 Hz frequency. This results in a force that varies dynamically over time between 0.1 kN and 0.4 kN. The fatigue test lasted 30000 cycles. After the fatigue testing the 250 N loading force was released over another 10 seconds until zero. After this process each implant and implant head were disassembled by untwisting the fixing screw and during this process the reverse torque was measured.

5.4.2. The second dynamic load test protocol

After the second static load test, the same samples were used for further fatigue tests. On each implant, the first step of our measurement was the tightening of the fixing screw that holds together the implant abutment and the implant, with 35 Ncm torque. Following this, the implants were put under loading. In the first phase, the fatigue machine loaded with 0.25 kN (equivalent to 25 kg) force over 10 seconds on the abutment. The dynamic load test started following the first phase; during the test, a 0.15 kN (equivalent to 15 kg) amplitude sine wave was applied with 10 Hz frequency. This resulted in a dynamically changing force between 0.1 kN and 0.4 kN over time. The fatigue test lasted 15,000 cycles. After the fatigue test was done, the force was released over another 10 seconds. Following this process, each implant and abutment were unscrewed and the torque was measured.

5.5. Finite element analysis (FEA)

A preliminary FEA was performed to examine the mechanical stress occurring in the implant, in case of different cone angles. For the purposes of FEA, the COMSOL Multiphysics 5.5 software (COMSOL Inc., Burlington, MA, USA) was utilized. For the study, the 24° and 90° cone angle implant and abutment models were modelled, based on the manufactured samples that were presented in this study. In our analysis, the implant and the abutment model were interpreted as one body with perfect tight fit. The number of elements (tetrahedra) were 10589, with a mesh volume of 63.06 mm^3, average element quality of 0.5975 and element volume ratio of 1.29E-4, respectively. The mesh was created and adjusted by the built-in physics-controlled sequence of the COMSOL software, while element size was set to normal in the settings.

The implants with the smallest (24°) and greatest (90°) cone angle cases available for us were chosen to be included in the FEA. The models were compressed with 400 N at the top, and the Ti material parameters were the following: density: 4500 kg/m^3, Young’s modulus: 110 GPa, and Poisson’s ratio 0.34. The Yield limit of the CP 4 Ti was considered as 480 MPa.

5.6. Inaccuracies due to manufacturing parameters

The mechanical parameters of the test models used in the study, as well as their parameter tolerances, have a significant impact on the performance of the products. All devices used in our study were designed using the Creo Parametric 5.0 software. As part of our investigation, with the help of the design software implant parts were drawn with the acceptable tolerances of the parameters, we compared the tight fit case with the manufactured extreme but still tolerated fit case. With this test, we validated a connection to the extent of vertical deviations in the case of elements manufactured to the worst tolerance values in the opposite direction of the products compared to the ideal, exact size pieces.

5.7. Statistical analysis

Results of the measurements were presented as mean±SEM (standard error of the mean). Statistical analyses were performed using IBM SPSS 23.0 (IBM Corp., Somers, NY, USA) software; one-way analysis of variance (ANOVA) followed by Tukey HSD post hoc tests were performed on the measured values. During analyses, p values < 0.05 were considered statistically significant. A linear regression was performed on the measured data, and the fit equation with the R^2 values were determined.

VI. RESULTS

6.1. Static load results

6.1.1. The first round of static load tests

During the first static mechanical loading tests, the lengths of the abutment implant assemblies were measured after applying 0, 100, 200, 300, 400, 450 and 500 N compression forces. Overall, no significant differences were shown between the behaviours of implants from Grade 4 and Grade 5 raw materials in the case of connections with different taper angles (35°: $p = 0.562$; 55°: $p = 0.666$; 75°: $p = 0.235$; 90° $p = 0.944$). The largest strain was obtained for the 35° angle connections, for both Grade 4 and Grade 5 assemblies, respectively. After the application of 500 N compression load, the reverse torque was measured upon disassembling the implant and abutment parts. The reverse torque values consistently increased with the conical angle, i.e., the lower values were observed for the 35° conical angle case, while the highest for the 90° case. On the other hand, no significant differences were noted when comparing the reverse torque values of grade 4 and 5 implants with the same conical angle ($p > 0.05$).

Diameter changes of the implant models corresponding to different loads (0, 300, 500 N) were examined, during which, diameter values were measured at three locations. No significant differences were found between the case of the different Ti grades.

The result of the first static measurements showed that the smaller the cone angle between the implant and the superstructure, the greater the diameter increase of the implant at the conical closure under load. As a result, the mechanical stress value of the implant body on the bone will be higher, that is, more stress is transferred to the bone, which may lead to increased bone resorption.

6.1.2. The second round of static load tests

During the second static load tests, the device recorded the vertical compression of the abutment in to the implant and force. As the force gradually increased, a linear relationship was observed with the compression, i.e. the load was in the elastic region of Ti. Different conical angle implant-abutment connections showed different load curves, i.e. there were differences in how the compression increased due to the load. The smallest compression was obtained with a cone angle of 75°, while the highest was in the case of 35°.

The compression rate of implants with different cone angles were compared at the highest static force value. Significant differences among the mean compression rates of implants with different cone angles were seen ($p = 0.021$); however, based on post hoc analyses, only the 35° and 75° cone angle implants were significant different (0.067 ± 0.008 mm vs. 0.044 ± 0.003 mm; $p = 0.032$).

After the deload, the irreversible vertical compression of the implant and the abutment was determined. Our results showed no significant differences between the different cone angles ($p = 0.08$). Cone angles of 24°, 35° and 90° showed a similar mean irreversible compression rate of ~ 0.022 mm; on the other hand, the 75° cone angle case showed the lowest irreversible vertical compression.

From the area of the load curves, resilience and energy dissipation were determined. The different cone angles cases showed significant differences both in the case of resilience ($p = 0.02$) and energy dissipation ($p = 0.01$). Highest resilience values were found in case of 24° (38293 ± 2640 J/m^3), and 35° (40221 ± 5194 J/m^3) and interestingly, the 75° cone angle case showed the lowest resilience value (25748 ± 1357 J/m^3). The dissipated energy showed a similar order, 24° (17165 ± 2325 J/m^3) and 35° (16014 ± 3333 J/m^3) were the highest, and the 75° (6129 ± 731 J/m^3) case was the lowest.

6.2. Dynamic load results

6.2.1. The first round of dynamic load tests

During the dynamic load test, the fatigue testing machine recorded the loading head position from which, compression strain of the implants with different conical angles (30°, 45° and 60°) can be determined. It was observed that there is a permanent deformation in the material, as the loading and unloading curves did not coincide. However, due to the elastic properties during the unloading phase, the material can still partially recover its length. It was also studied whether there were any differences in the impression of the implant head into the implant body during the fatigue cycles. The loading-unloading nature of this test revealed that most of the impression occur in the very first cycles, while it remains constant in the subsequent cycles; this is shown as the curves immediately begin to shift to larger displacement values, and after that there is no essential change between the loading-unloading cycles. Thus, the samples suffered elastic deformation mainly after this early phase.

Final displacement values – indicating irreversible impressions of the abutments into the implant bodies – were also measured with the dynamic testing machine, following the dynamic test. The highest impression value was measured for the 30° case (0.047± 0.002 mm), while the lowest value was found in the 60° case (0.039±0.001 mm), respectively; observed differences between the conical angle groups were statistically significant ($p < 0.001$).

After the dynamic loading test, reverse torque values were also measured upon disassembling the implant head and implant body. Similar observations were obtained to our previous measurement, the lowest torque values were shown in for the 30° conical angle case, while the highest were seen for 60°; significant differences were noted among the mean reverse torque values; significant differences were observed between the average torque (p=0.003) in case of 30° (18.7 ± 1.01 Ncm), 45° (21.25 ± 0.67 Ncm) and 60° (24.03 ± 0.59 Ncm). Additionally, based post hoc test, a significant difference between the 30° and 60° conical connections (p = 0.043) was verified, while this was not the case for the 30° vs. 45° and 45° vs. 60° comparisons.

6.2.2. The second round of dynamic load tests

During the dynamic load test, the fatigue machine recorded the load head position, which was in a direct relationship with the vertical compression of the implants (i.e. how much the abutment slipped into the implant structure). The device also recorded the given force values over time, therefore load-compression graphs could be analyzed. It may be observed that there are different degrees of average vertical compression based on the different conical angle. The highest compression was measured in the case of 35° and 55° while the lowest was at the 75° and 90° conical angle implants. Due to the elastic properties during the deload, the material may still deform back. The vertical compression occurred in the very first cycle, while it remains constant thereafter, in the beginning of the compression cycles, there was a sudden rise in compression and after that there was no change in compression rate.

The samples only deformed elastically mainly after this early phase. At the end of the fatigue test, the compression was gathered before the deload phase. Based on the result of the vertical compression at the end of the dynamic load, significant differences were observed among the different cases ($p = 0.029$); comparative analyses showed that there is a significant difference between the 35° and 75° (0.049 ± 0.004 mm vs. 0.037 ± 0.002 mm; $p = 0.011$), and in case of 55° and 75° conical angle implants (0.046 ± 0.003 mm vs. 0.037 ± 0.002 mm; $p = 0.009$). After the dynamic loading test, the permanent deformations were also measured: the loading head unloaded the samples and fixed the final position; based on the results, there were significant differences between the average permanent deformities ($p = 0.032$).

After the dynamic load test, the lowest torque needed to roll apart the abutment and implant were also measured. Lowest torque values were noted for the 24° case (13.1 ± 1.26 Ncm), while the highest was for the 90° case (29.4 ± 1.1 Ncm). Significant differences were observed between the mean torque both in the case of static and dynamic load tests, ($p < 0.001$ in both cases). With the exception of the 24°- and 35°-degree conical angle connections ($p = 0.384$ and $p = 0.994$), there were significant differences among every other case both after the static and dynamic load test ($p < 0.05$).

6.3. Finite element analysis

The FEA showed a pronounced difference between the two selected cone angle implant models in von Mises stresses. In the case of 24°, the calculated mechanical stress presenting in the implant was roughly 3-times greater than in the case of 90°. Also, around 130 MPa of mechanical stress was concentrated in the upper third of the implant, with the highest stress values seen at the conical surface. The barrel-shaped horizontal deformation is observed in the case of the 24° connection, while this barrel-shaped deformation is not observed in the case of the 90° connection. In the case of an implant with a 90° taper angle, the mechanical stress of around 60 MPa was evenly distributed on the implant wall, and the mechanical stress peaked at the taper connection. The highest mechanical stress value noted was around 300 MPa in the case of 24°, while it was only around 160 MPa in case of the 90° conical angle case. To evaluate mechanical stress, a line was defined on the conical surface between the abutment and the implant body.

Furthermore, we also added a diagram of the mechanical stress distribution along the implant height on the side which shows the stress in the wall of the implant. Here it can be seen that clearly the stress is much higher on the implant wall in the case of the 24° implant model, corresponding to values near 120 MPa, while the stress values were only around 60 MPa in the case of the 90° model.

6.4. Inaccuracies due to manufacturing parameters

Several implants on the market from different manufacturers were examined, but with the same internal design, and measured a ±1° cone angle difference. For the implants in our samples, a taper angle tolerance of +0/-0.5° was accepted, but during the production of the samples, a deviation close to zero degrees is preferable. For the abutments, the same tolerance of 0/+0.5° was acceptable.

Our software comparison shows that when considering the worst possible tolerance fields, the height difference of our model for the 24° implant - abutment connection is 0.0271 mm compared to the ideal, while for the 90° connection it is only 0.003 mm.

VII. DISCUSSION

The aim of our study was to understand the effect of different taper-angle implant abutment relationships on the long-term survival and clinical success of dental implants. During our investigation, two issues were identified: on the one hand – according to the results of the mechanical tests – the screw loosening, as well as the horizontal deformation, based on the measurements and the results of the FEA.

The results of our mechanical tests conclude that as the cone angle of the implant superstructure connection increases, the extraction torque of our fixing screw decreased proportionally, i.e. the larger the connection angle, the loosening of the screw under load was smaller. The management of screw loosening is a common issue in clinical practice; the change in the torque is affected by the continuous, periodical repeating loads. Our static and dynamic results both showed the highest change in case of lower conical angles. This resulted in the decrease of the reverse torque needed to take apart the implant and the abutment. However increasing the conical angle of the abutment improved the results, i.e. it has led to lower rates of compression and less decrease in the case of the small angle cases.

Both the first static and first dynamic measurements reveal the same results. It can be stated that the conical closure was also clearly visible in the case of the implant-superstructure connection with different tapers. There is also a direct proportionality in the case of the reverse torque, i.e., the larger the cone angle of the connection, the greater the reverse torque value we measured.

Screw loosening of taper-connected implants, i.e., a loose state of the clip between the implant and the retaining screw, can be a significant problem, as the screw loosening increases the risk of removal of dentures and the possibility of screw failure. Screw loosening of implants can be traced back to various reasons, such as incorrect tension of the screw, excessive load on the screw, a defect in the material or size of the fixation screw, wear between the implant and the fixation screw, or continuous slippage of the screw due to continuous loading. Therefore, it is important that the implant and retaining screw are properly secured and that dentists inspect the suprastructure and implants to prevent screw loosening.

The reversible and irreversible shape deformations of titanium implants can have a significant impact on the success of the implant surgery and the long-term stability of the implant. In reversible deformation, deformation occurs during surgery or subsequent loading (mastication) due to the elasticity of the titanium implant, but the implant returns to its original shape when the load is removed. This type of shape deformation is usually associated with micro- and macro-deformations due to loading, which can lead to fatigue fracture in the long term. During irreversible shape deformation, the implant does not return to its original shape, even after the load is removed. This is usually due to exceeding the yield point or excessive deformation during surgery. Irreversible deformation can have a serious effect on the stability of the implant, as the shape of the implant changes and, as a result, the implant does not fit properly with the implant bed. In order to prevent irreversible deformity, dentists must be careful to choose the right size and shape of implant and carefully plan and perform surgical procedures. Planning, with pre-planning and simulation, plays an important role in selecting the right sized and shaped implants for the patient and ensuring the correct fit of the implant to the implant bed. Performing professional procedures and using appropriately chosen implants can reduce the risk of irreversible shape deformations and improve the long-term stability of the implants.

Irreversible vertical deformation may also cause compression of the implant and the abutment, if the taper angle of the connection is small, a phenomenon that may be exacerbated by manufacturing inaccuracy, i.e. the height of the implant and superstructure may change as a result of the load. In this case, the occlusal height also decreases, thereby changing the occlusion, which leads to further biological (malocclusion, traumatic occlusal forces, peri-implant bone loss, temporo-mandibular dysfunction) and mechanical (screw loosening, fracture, superstructure deformation, fracture) issues. The inaccuracy of the taper angles of the implant and the abutment has a considerable influence on the compression under load. The greater the dimensional error from manufacturing, the greater the conical surface shrinkage. In our results the inaccuracy of the taper angles of the implant and the abutment has a significant influence on the compression under load as well. The greater the dimensional error from manufacturing, the greater the impression of the abutment into the implant body along the conical surfaces.

Based on the FEA methodology and models, many studies showed that implant geometry, bone quality, and site of implant placement affect load transmission mechanisms, thereby subsequently also affecting peri-implant bone resorption. Maximum stress areas may be located at the implant neck, and possible overloading could occur in the form compression in the compact bone (due to lateral components of the occlusal load) and in the form tension at the interface between cortical and trabecular bone (due to vertical intrusive loading components). Load transmission may also occur in the abutment-implant interface zone, which may also lead to the above mentioned phenomenon. Our FEA analyses also confirmed that the implant-abutment connection greatly influences the distribution of forces in different ways at different heights between the implant and the bone. In the FEA, the mechanical stress was better distributed over the entire surface of the implant in the case of the 90° implant-abutment connection, compared to the 24° connection. Regarding the 24° connection, the mechanical stress was greatest in the area where the cones meet, which represents the part of the implant with the smallest wall thickness; in addition, in the case of the 24° model, not only vertical but also horizontal deformation occurs. This horizontal deformation may lead to peri-implant bone resorption in the cortical bone. When the taper angle is increased, more of the load is transferred to the implant wall than to the fixing screw. For this reason, the higher load on the smaller taper angle resulted in greater screw loosening, as more force is transmitted to the screw.

The formation of biological width after implant placement is an important factor in the prevention of peri-implant bone loss. Adaptation and remodeling of these soft tissues may have considerable roles in facilitating secondary stability and the long-term survival of implants, as they absorb forces that act on the implant, thus reducing the transmission of forces acting on the jawbone. The forces acting on the dental prosthesis are distributed and continue to affect the superstructure, the implant, the implant connection and the bone. Through the implant-abutment connection, which mentioned may cause loosening of the fixing screw, irreversible vertical compression and overloading of the bone in different ways at different heights depending on the design.

In order to achieve long-term implantation success – from a mechanical point of view – it may be crucial that the prosthetic phase takes place at the implant or abutment levels. Important examples from clinical practice may include situations with a large axis deviation, where the contact part of the abutment is reduced in the dental technique phase in order to facilitate the placement of the restoration. However, this may have a detrimental effect on the fit between the implant and the abutment, thereby changing the distribution of masticatory forces between the implant body and the surrounding bone; in many cases, this may lead to the breakage of the retaining screw of restoration or the fracture of the bridge itself. The implant-abutment relationship affects the indications in which the implants may be used. It is extremely important that in the case of special indications (immediate implantation, immediate loading, or cracking technique) that the implant-abutment connection should serve the best possible force distribution on the surface of the implant, i.e. transfers the masticatory force to the bone on the largest possible surface.

In summary, according to our mechanical tests, the amount of fixing screw loosening changes significantly with the change in the taper angle of the connection. The larger the angle of the implant-superstructure connection, the smaller is the screw loosening due to loading.

As a result of our finite element analyses, it can be concluded that in the case of connections with a smaller taper angle, the masticatory forces acting on the implants was concentrated on the upper third of the implant-body; this may result in horizontal, irreversible deformation in the implant neck, which could lead to increased risk of cortical bone resorption. While in the case of a larger taper angle, the masticatory force is evenly distributed over the body of the implant.

Long-term and safe rehabilitation of edentulous patients still has numerous challenges, due to the numerous variables that affect implant survival and patient satisfaction; thus, all advances aiming for the optimalization of prosthodontic treatment may have considerable real-world implications for clinical practice. Our studies aimed to highlight the importance of the implant-abutment relationship – that is, the effect of conical angles and the Ti grade of the implants – in the context of screw loosening and irreversible deformation, both being detrimental for durable restorations. Overall, it was demonstrated that increasing the taper angle of the connection has an inverse relationship with screw loosening; these findings were further supported by finite element simulations, suggesting that the accumulation of masticatory forces, which may result in horizontal deformation in the implant neck, is more likely for smaller angles. To ensure high secondary stability and clinical satisfaction, judicious treatment planning is critical, which includes implant design. Therefore, further studies to confirm and complement the existing body of evidence is definietly warranted.

VIII. NEW FINDINGS

a. **Conical angle, but not implant material affected implant behaviour and reverse torque values under static loading:** under a static compressive load of 500 N, implant deformation (numerical, but no significant difference), resilience (significant differences) and dissipated energy (significant differences) decreased consistently, while values of the reverse torque, increased consistently (significant differences) with increasing conical angles. Implant composition (titanium Grade 4 vs. 5) had no significant effect on vertical or horizontal deformation or reverse torque values.

b. **Conical angle affected implant behaviour and reverse torque values under dynamic fatigue:** during dynamic fatigue tests, vertical compression (significant differences) and irreversible deformation (significant differences) was highest for the

35° conical angle, but decreased consistently, while values of the reverse torque increased consistently (significant differences) with increasing conical angles.

c. **Higher conical angles resulted in lower mechanical stress values and more advantageous stress distribution in our finite element model:** during FEA, the calculated von Mises stress for the 24° implant was considerably higher than in the 90° case (highest stress values: 300 MPa vs. 160 MPa). A horizontal barrel-shaped deformation was observed in the model with the 24° conical angle connection, which was not shown for the 90° case.

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