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Comparison of the fracture resistance of dental implants with different abutment taper angles

Kun Wang [a], Jianping Geng [b], David Jones [c], Wei Xu [d,*]

[a] *Department of Dentistry, Southwest Hospital, Third Military Medical University, Chongqing 400038, China*
[b] *Institute of Biomedical Engineering, Nanjing Tech University, Nanjing 211800, China*
[c] *MicroStructural Studies Unit, Department of Mechanical Engineering Sciences, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey GU2 7XH, UK*
[d] *Department of Mechanical Engineering Sciences, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey GU2 7XH, UK*

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ABSTRACT

To investigate the effects of abutment taper angles on the fracture strength of dental implants with TIS (taper integrated screwed-in) connection. Thirty prototype cylindrical titanium alloy 5.0 mm-diameter dental implants with different TIS-connection designs were divided into six groups and tested for their fracture strength, using a universal testing machine. These groups consisted of combinations of 3.5 and 4.0 mm abutment diameter, each with taper angles of 6°, 8° or 10°. 3-Dimensional finite element analysis (FEA) was also used to analyze stress states at implant–abutment connection areas. In general, the mechanical tests found an increasing trend of implant fracture forces as the taper angle enlarged. When the abutment diameter was 3.5 mm, the mean fracture forces for 8° and 10° taper groups were 1638.9 N ± 20.3 and 1577.1 N ± 103.2, respectively, both larger than that for the 6° taper group of 1475.0 N ± 24.4, with the largest increasing rate of 11.1%. Furthermore, the difference between 8° and 6° taper groups was significant, based on Tamhane's multiple comparison test ($P < 0.05$). In 4.0 mm-diameter abutment groups, as the taper angle was enlarged from 6° to 8° and 10°, the mean fracture value was increased from 1066.7 N ± 56.1 to 1241.4 N ± 6.4 and 1419.3 N ± 20.0, with the largest increasing rate of 33.1%, and the differences among the three groups were significant ($P < 0.05$). The FEA results showed that stress values varied in implants with different abutment taper angles and supported the findings of the static tests. In conclusion, increases of the abutment taper angle could significantly increase implant fracture resistance in most cases established in the study, which is due to the increased implant wall thickness in the connection part resulting from the taper angle enlargement. The increasing effects were notable when a thin implant wall was present to accommodate wide abutments.

1. Introduction

Most osseointegrated dental implant systems are composed of an endosteal fixture, a component inserted into the jaw bone, and an abutment, connecting the fixture to support or retain the prosthetic superstructure. The abutment is secured to the fixture with a mechanical attachment method and is named the implant–abutment connection. At present, there are a number of implant–abutment connection designs offered by implant companies. They may be classified as either externally or internally connected.

The external hexagonal interface of the original design of the Brånemark system, which is a typical external design, has been in use the longest and has functioned well over the years. Recently, it has been incorporated in a number of competing systems. However, the connection has the mechanical disadvantages of exposing the implant–abutment interface and abutment screw to greater external loads and bending moments, which can lead to screw joint opening and screw loosening [1,2]. Zarb and Schmitt reported the clinical outcome of 274 Brånemark implants with the external connection, and they noted 9 abutment fractures and 53 gold screw fractures over a 4- to 9-year period [3]. In their one-year follow-up study, Jemt et al. reported that the overall success rate was 98.6% for the Brånemark implants, with the most common complications related to loosening gold screws and esthetic complaints [4]. Moreover, problems of screw loosening or fracture are more likely to occur when external connection implants are used to support single-unit restorations, where implants are not splinted and are subjected to multidirectional loading that challenges the external connection components and restoration structural integrity. In a multicenter prospective study on external connection implants for single tooth replacement, the most obvious problem experienced during the first year was related to loosening abutment screws with an incidence of 26% [5]. Becker and colleagues found that retaining screws loosened in 8 of 24 implants restoring single molars with follow-up of 24 months [6].

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* Corresponding author.
E-mail addresses: dentalimplants@163.com (K. Wang), jpgeng2005@163.com (J. Geng), d.g.jones@surrey.ac.uk (D. Jones), w.xu@surrey.ac.uk (W. Xu).

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Since the 1990s, several modifications of the design of the external abutment screw, the material of the screw itself and the coefficient of friction between the mated surfaces, have been made to reduce the connection complications. However, mechanical complications of external connections are not eliminated and still remain a concern in the implant community. In order to overcome the connection problems, a new concept of internal connection was developed. Contrary to the external connection, the internal connection design has a feature that extends from the inferior to the coronal portion of the implant and is located inside the implant body. The internal connection has a mechanical advantage of dramatically reducing screw failures by distributing occlusal forces deep into the implant and shielding the abutment retention screw from excess loading. Further, deep joints in internal connections are more likely to resist bending forces than shallow joints in external connections. Therefore, internal connections have superior joint strength than that of external counterparts [7].

Of various internal connections, the taper integrated screwed-in (TIS) abutment is becoming more popular, which uses simultaneously a screw and a tapered fit to provide mechanical stability. The TIS-type connection offers high resistance to loosening torques, and it has been reported that loosening of the abutment is prevented [8]. Bozkaya and Müftü analyzed the mechanical properties of the TIS-type connection, with the focus on connection stability parameters of tightening and loosening torques [9]. They developed analytical formulas to predict tightening and loosening torque values by combining the equations related to the tapered interface with screw mechanics equations. They found that the value of the coefficient of frictions, taper angles, connection depth and outer radius of the implant were the factors affecting implant–abutment connection stability.

It has been well documented that the implant–abutment connection is the weakest part in terms of the whole implant mechanical strength, especially for the internal connection designs which have a thin fixture wall at the connecting parts [10]. As for the TIS-type connection, those abovementioned connection parameters can also affect its mechanical strength. Nowadays, different taper angles have been used by different manufacturers in their TIS-type implants. However, there is only limited information that can be found in the literature about the relationship between taper angles and the mechanical strength of implants. The purpose of the present in vitro research was to compare the compressive fracture strength of dental implants with different abutment taper angles. In addition to the experimental tests, 3-dimensional finite element analysis (3D-FEA) was carried out to evaluate the stress state of implant–abutment connection areas as a function of different abutment taper angles.

2. Material and methods

2.1. Sample preparation for mechanical tests

For this in vitro investigation, thirty prototype cylindrical titanium alloy (Ti–6Al–4V) implants divided into six groups ($n = 5$) were fabricated using a BUMOTEC S-191 V (Bumotec SA, Switzerland) CNC (computer numerical control) machining center. The manufacturing dimensional tolerances were set to 10 μm. To the best of the authors' knowledge, this accuracy tolerance level should be sufficient to satisfy the testing requirements for the present study [11].

2.2. Overview of implant specimen designs

The TIS-type dental implant specimens used in this study can be divided into three parts: implant body, abutment, and the restorative part. The latter two parts were simplified into one section of the superstructure. The implant body had a diameter of 5.0 mm and length of 13.0 mm. It consisted of two parts: the 2.0 mm-height of the non-threaded highly polished cylindrical neck and an 11.0 mm-height of the threaded part. The threaded part featured a triangular thread design with a uniform 0.3 mm thread depth and 0.6 mm thread pitch. The superstructure part started from the TIS abutment and gradually widened to be the coronal restorative part, which was simplified into a combination of a cylinder (4.5 mm-diameter, 5.5 mm-height) and a hemispherical dome (Fig. 1). Two different abutment diameters, 3.5 mm and 4.0 mm, at the implant platform level were designed. The abutment connection part had a depth of 3.0 mm and taper angles of 6°, 8° and 10°. For the purpose of brevity, each specimen was named by two hyphenated numbers, representing the abutment diameter and taper angle, respectively. Thus 5.0 mm-diameter implants had names of 3.5-6, 3.5-8, 3.5-10, 4-6, 4-8, and 4-10, respectively.

2.3. Overview of the static test set-up

The implant specimens were investigated in a test setup fabricated according to the ISO 14801 static testing standard (Fig. 2). The implants were embedded and secured in a custom jig, which was made up of an aluminum alloy cylinder and a stainless steel block. An internal threaded hole in the depth of 10 mm was cut in the center of the aluminum alloy cylinder to accommodate test implants, and the stainless steel block functioned as a holder for the aluminum alloy cylinder. Implants were inserted into the threaded hole to a depth of 10 mm in a manner simulating 3.0 mm of the crestal bone loss. The jig carrying implant specimens was fixed onto the universal testing machine (Model 6025; Instron, Canton, MA, USA) in such a way that specimens were loaded with a 30° oblique force recommended by the ISO 14801 standard. Off-axis loading was applied to the hemispherical cap of each implant by a flat indenter, ensuring the distance from the center of the hemisphere cap to the cylinder surface (clamping plane) was 11.0 mm. Therefore the moment arm was defined as $11.0 \text{ mm} \times \sin 30°$ (5.5 mm). The ISO 14801 was followed by ensuring unconstrained movement of the loading member transverse to the loading direction. This was achieved by a socket fit joint between the loading member and the test machine structure. The joint was close to the load cell and was approximately 200 mm away from the lower end of the flat indenter. The abutments were tightened to the implants with a torque value of 35 N cm using the BTG60CN-S torque gauge (Tohnichi, Tokyo, Japan). Ten minutes after the torque tightening, the test was carried out with a crosshead speed of 0.5 mm/min until the implant fractured or exhibited a significant amount of plastic deformation. This kind of irreversible deformation is determined by fitting the load–displacement curves with the regression lines, and the force at which the load–displacement curve first deviates by 10% from the regression line will be recorded as an indicator for initiation of significant plastic deformation [12].

2.4. Statistical analysis & fracture analysis

Throughout the loading, the raw data of force–displacement values were recorded by the computer. Data were subsequently used to determine the maximum load levels and create force–displacement curves. The mean and standard deviations of the fracture forces or the maximum deformation forces were determined, and Tamhane's multiple comparison test was used to assess differences between groups. The level of significance was set as $P < 0.05$.

After the mechanical testing, macrofracture mode analysis was performed to identify different fracture modes for all the specimens. Further fractographic analysis was performed using a scanning electron microscope (SEM) (JEOL, JSM-7100F, Japan). For SEM evaluations implants were cleaned and dried. Digital images of the specimens were recorded at various magnifications to evaluate the fracture surfaces.

2.5. Finite element analysis

Numerical simulations were carried out to evaluate the mechanical properties of the implants with different abutment taper angles with