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Optimally oriented grooves on dental implants improve bone quality around implants under repetitive mechanical loading

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ABSTRACT

The aim was to investigate the effect of groove designs on bone quality under controlled-repetitive load conditions for optimizing dental implant design. Anodized Ti-6Al-4V alloy implants with −60° and +60° grooves around the neck were placed in the proximal tibial metaphysis of rabbits. The application of a repetitive mechanical load was initiated via the implants (50 N, 3 Hz, 1800 cycles, 2 days/week) at 12 weeks after surgery for 8 weeks. Bone quality, defined as osteocyte density and degree of biological apatite (BAp) *c*-axis/collagen fibers, was then evaluated. Groove designs did not affect bone quality without mechanical loading; however, repetitive mechanical loading significantly increased bone-to-implant contact, bone mass, and bone mineral density (BMD). In +60° grooves, the BAp *c*-axis/collagen fibers preferentially aligned along the groove direction with mechanical loading. Moreover, osteocyte density was significantly higher both inside and in the adjacent region of the +60° grooves, but not −60° grooves. These results suggest that the +60° grooves successfully transmitted the load to the bone tissues surrounding implants through the grooves. An optimally oriented groove structure on the implant surface was shown to be a promising way for achieving bone tissue with appropriate bone quality. This is the first report to propose the optimal design of grooves on the necks of dental implants for improving bone quality parameters as well as BMD. The findings suggest that not only BMD, but also bone quality, could be a useful clinical parameter in implant dentistry.

Statement of Significance

Although the paradigm of bone quality has shifted from density-based assessments to structural evaluations of bone, clarifying bone quality based on structural bone evaluations remains challenging in implant dentistry. In this study, we firstly demonstrated that the optimal design of dental implant necks improved bone quality defined as osteocytes and the preferential alignment degree of biological apatite *c*-axis/collagen fibers using light microscopy, polarized light microscopy, and a microbeam X-ray diffractometer system, after application of controlled mechanical load. Our new findings suggest that bone quality around dental implants could become a new clinical parameter as well as bone mineral density in order to completely account for bone strength in implant dentistry.

1. Introduction

Implant therapy has been one of the most secure and reliable treatments for ensuring the success and longevity of oral rehabilitation. Dental implants are constitutively subjected to repetitive loads, including functional loads such as mastication and swallowing, and parafunctional loads such as clenching, grinding, and tapping movements. On the other hand, bone loss of less than 0.2 mm annually after the first year of the implant is necessary for therapeutic success [1]. Indeed, marginal bone loss around dental implants seriously disfeatures aesthetic profiles and hinders successful outcomes. One study using finite element analysis reported that load stress is concentrated mainly on the neck of bone around implants [2], and other studies have indicated that stress distribu-

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tion is affected by differences in implant neck design [3–5]. In addition, some animal studies conducted to investigate the effects of bite force have reported that mechanical load affects the marginal bone level around dental implants [6–8]. Taken together, these previous findings suggest that the marginal bone architecture around implants is influenced by implant neck designs and mechanical load. However, because the amplitude, frequency, cycle and duration of bite force are difficult to control, little evidence has been reported regarding the net effect of implant design on bone around dental implants under appropriate load conditions.

Microthreads have been widely used in dental implants because of their ability to reduce marginal bone loss by enhancing mechanical stability between bone and implant [9]. Rough surfaces and microthreads promote stress anchoring and transmission at the bone/implant surface by increasing the bone/implant contact area [5]. Currently, several kinds of dental implants with microthreads in their neck are commercially available worldwide. However, bone quality around microthreads, which may be related to the mechanical stability of implants, has not been well documented, and microthread design has not been optimized based on bone quality [10].

Bone quality, which has been defined as "the sum of all characteristics of bone that influence the bone's resistance to fracture [11]", is completely independent of bone mineral density (BMD), and many clinical studies have indicated that increases in BMD following treatment with *anti*-resorptive drugs do not reflect a proportional reduction in relative fracture risk [12], which suggests that bone quality plays an essential role in determining bone strength [13]. In a consensus statement issued by the National Institutes of Health (NIH), bone quality was defined more concretely as bone architecture, bone turnover, bone mineralization and micro-damage accumulation [13]. In implant dentistry, however, bone quality is still considered equivalent to bone density on radiographic assessments [14,15]. Although the paradigm of bone quality has shifted from density-based assessments to structural evaluations of bone, clarifying bone quality based on structural bone evaluations remains challenging in implant dentistry because devices capable of accurately evaluating bone structure have yet to be developed.

In our previous studies, the preferential orientation of biological apatite (BAp) crystal and collagen fibers (hereafter BAp *c*-axis/collagen fibers) was proposed as a new index for assessing bone quality [16–19]. BAp, which is one of the main inorganic components of hard tissue, crystallizes on the type-I collagen, which is a main organic component, so that the BAp *c*-axis is almost parallel with the direction of the collagen fibers [20]. Preferential orientation refers to nano-scale anisotropic organization in a vector form (consisting of the direction and magnitude of bone tissue), which is not adequately described by the BMD as a scalar parameter. Regardless of BMD, bone shows a wide variety of orientation distribution depending on type and anatomical location [16], which results in its anisotropic mechanical performance. Therefore, BMD alone cannot be used to fully evaluate the mechanical properties of bone. A combination of BMD and preferential orientation might be highly beneficial in the assessment of bone function.

In the fields of dentistry and implant dentistry, the mandible bone is a primary focus. In our previous studies, the preferential orientation degree of BAp *c*-axis/collagen fibers was applied to evaluate mandible function and the development of dental implants [17,19]. Similar to the long bone, which shows unidirectional orientation along the longitudinal axis [16], the mandible basically shows uni-directional orientation of BAp along the mesiodistal axis; however, the direction of maximum orientation was initially reported to change locally to the biting direction just beneath the teeth [16]. This suggests that mechanical load alters anisotropy in the microstructural arrangement of bone and affects other mechanical properties. Therefore, BAp and collagen orientation are highly important in the development of dental implants because they directly transfer mechanical load to the host bone tissue through mastication.

In addition, osteocytes are known to play a substantial role in modifying the macro- and microstructures of bone based on mechanosensation and mechanotransduction [21,22], even though the way in which osteocytes regulate bone structure remains a matter of debate. Nonetheless, focusing on osteocytes in an attempt to understand alterations in bone quality around dental implants seems worthwhile.

The aims of the present study were to investigate the effect of implant neck groove designs on bone quality under controlled repetitive mechanical loading and to determine the optimal implant design by evaluating bone microarchitecture around implants using light microscopy, polarized light microscopy, and a microbeam X-ray diffractometer (μXRD).

2. Materials and methods

2.1. Implant neck designs

Anodized Ti-6Al-4V alloy dental implants with three grooves around the neck were used (3.7 × 6.0 mm; Kyocera Co. Ltd., Kyoto, Japan). On the implants, +60° and −60° grooves, defined as 60° downward and upward directions to a plane perpendicular to the long axis, respectively, were introduced by machining (Kyocera Co. Ltd., Kyocera, Japan) (n = 14 each). The pitch and depth of the grooves were 400 μm and 200 μm, respectively (Fig. 1a).

2.2. Implant placement

Fourteen adult Japanese white rabbits (mean weight: 3.85 ± 0.24 kg) were obtained for use in this study (Biotek Co. Ltd., Saga, Japan). First, 56 Ti-6Al-4V screws (Kyocera Co. Ltd.) were used to anchor a custom-made loading device (Higuchi Co. Ltd., Nagasaki, Japan). The implants with −60° grooves were placed in the tibial metaphysis of a randomly selected side of each rabbit, and the implants with +60° grooves were placed in the other side. Two anchor screws were placed in both sides of the implant 2 mm from the implant surface. Implant placement was performed unicortically under a combination of local and general anesthesia (35 mg/kg ketamine and 5 mg/kg xylazine, respectively). The study protocol was approved by the Ethics Committee for Animal Research of Nagasaki University, and animals were treated in accordance with the guidelines for Animal Experimentation of Nagasaki University.

2.3. Loading protocol

All implants received healing abutments at 12 weeks after implant placement. The 14 rabbits were then randomly divided into two groups. In an experimental group (n = 7), both implants in each rabbit were subjected to a cyclic mechanical load in accordance with that used in our previous study [19]. Briefly, the implants were subjected to a mechanical load of 50 N with a frequency of 3 Hz for 1800 cycles which is equivalent to chewing and swallowing cycles in humans [23], 2 days/week for 8 weeks using a loading device supported by two lateral screws on each implant under general anesthesia. The load direction was parallel with the long axis of the implants. The rabbits in the other group (n = 7) served as controls and were not subjected to a mechanical load (Fig. 1b).