Dental Implant Design and Its Relationship to Long-Term Implant Success

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The purpose of this review is to evaluate the effects of the biomechanical aspects of dental implant design on the quality and strength of osseointegration, the bone–implant interface, and their relationships to the long-term success of dental implants. The engineering design of implants is based on many interrelated factors, including the geometry of the implant, mechanical properties, and the initial and long-term stability of the implant–tissue interface. There is no one "optimal" design criterion. However, implants can be engineered to maximize strength, interfacial stability, and load transfer by using different materials, surfaces, and thread designs. Limited information is currently available in addressing how implant thread design influences the overall implant success. Therefore, this article reviews and discusses design elements of various dental implant systems currently in use as they affect the quality of osseointegration and their relationship to overall long-term success patterns. (Implant Dent 2003;12:306–317)

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A major advance in dentistry has been the successful replacement of lost natural teeth by osseointegrated implants. Years of clinical experience have fostered a consensus regarding many of the placement criteria and techniques to maximize the chance for long-term implant stability and function.[1] The use of dental implants for the oral rehabilitation of fully and partially edentulous patients has greatly broadened the scope of clinical dentistry, creating additional treatment options in complex cases in which functional rehabilitation was previously limited or inadequate. The predictability and long-term success of dental implants have been well documented, both in removable and fixed prostheses.[2–5] Most of the studies reported have shown multiyear success rates of more than 90% for implants placed in fully edentulous[6–8] or partially edentulous patients.[4,9–14]

Nevertheless, success rates have been reported to vary in different areas of the mouth and in different patients. For example, lower success rates have been reported for maxillary implants than for mandibular implants.[2,15,16] Attempts have been made to understand the factors that could compromise implant success. Factors such as material biocompatibility, implant design and surface, surgical technique, host bed, and the loading conditions have all been shown to influence the implant osseointegration.[17] Available bone volume has long been considered an important factor in achieving implant predictability.[18] Studies showed higher failure rates for implants shorter than 10 mm.[3] Another important influencing factor for implant success is bone density, because higher failure rates have been reported for regions with poor quality bone, eg, the posterior maxilla.[15,19–21]

Consequently, modifications in implant body design and implant surfaces have been suggested to increase the success in poor quality bone by, hypothetically, gaining better anchorage and providing more surface area of load to decrease stress to the softer bone types.[15] In a rabbit study, Carlsson[22] found a more complete bone-to-implant contact around screw-shaped implants than around double cylinders and T-shaped implants. Also demonstrated was the fact that a stronger biomechanical bond was obtained with a rough implant surface than with a similarly shaped, but polished, implant surface. Furthermore, other in vivo studies have agreed that a rough surface is more suitable for implant integration than a comparatively smoother implant surface by demonstrating a higher degree of bone integration.[23–26] Surface roughness can influence the degree of osseointegration. For example, the pattern size and distribution of peaks and valleys that compose the surface roughness can significantly influence the overall intimacy and mechanical interlocking of the bone–implant interface. However, the surface condition is not the only factor that could influence osseointegration. Implant design can affect surgical insertion (eg, stability) and the bone–implant interface after occlusal

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Table 1. Bite Force Transfer Around Natural Teeth and Dental Implants

Authors	Natural Teeth/Dental Implants	Mean Maximum Masticatory Force
Carr and Laney, 1987	Conventional denture	59.6 N
	Implant-supported prostheses	112.9 N
Morneburg and Proshchel, 2002	Implant supported 3-unit FPD	220 N
	Single implant: anterior	91 N
	Single implant: posterior	129 N
Fontijn-Tekamp et al., 1998	Implant-supported prostheses	(unilateral)
	Molar region	50–400 N
	Incisal region	25–170 N
Mericske-Stern and Zarb, 1996	Complete denture/implant-supported prostheses	35–330 N
Van Eijden, 1991	Canine	469 ± 85 N
	2nd premolar	583 ± 99 N
	2nd molar	723 ± 138 N
Braun et al., 1995	Natural teeth	738 ± 209 N
		(Male > female)
Raadsheer et al., 1999	Male teeth	545.7 N
	Female teeth	383.6 N

Comparison of available studies examining masticatory forces generated under varying loading conditions. Study results are reported in Newtons (N) of force unless otherwise indicated. Differences between male and female force generation are noted in applicable studies.

FPD, fixed partial dentures.

loading. Implant design and surface conditions are 2 independent conditions that can alter implant success rates. This article reviews and discusses design elements of dental implants as they affect the quality of osseointegration and their relationship to long-term success.

Biomechanics and Implants

Functions of Implants (Force Transfer). Dental implants are subjected to various force magnitudes and directions during function. Because implants function to transfer occlusal loads to the surrounding biologic tissues, functional design objectives should aim to manage biomechanical loads (through dissipation and distribution) to optimize the implant supported prosthesis function.[27]

The mechanism and efficiency of force transfer by dental implants to contiguous biologic tissues are clearly important determinants in the development of the implant-to-bone/tissue interface and implant longevity. Whether a clinician seeks to gain a better understanding of implant design rationale and/or to implement biomechanics concepts in patient care, a fundamental, yet clinically relevant, understanding of biomechanics is required.[28]

The distribution of force with natural teeth depends on micromovement induced by the periodontal ligament. Force distribution to osseointegrated implant interface differs from natural teeth in that implants do not have micromovement associated with force distribution. Because of the lack of micromovement of implants, most of the force distribution is concentrated at the crest of the ridge.[29] Vertical forces at the bone interface are concentrated at the crestal regions, and lateral forces increase the magnitude of the crestal force distribution.[30]

Prudent control of the biomechanical load on dental implants is imperative to achieve long-term clinical success. The design of the final prosthesis and location of force transmission have a definitive influence on the quantification of induced strains and load partitioning among implants. Alterations to the implant crown location and cusp inclination are suggested to limit implant overload.[31] This is supported by Cehreli et al., who revealed that offset loading increases the magnitude of strains when compared with axial loading. In addition, they believe it is a multifaceted phenomenon when they examined how force has been distributed around implants. This includes, but is not limited to, implant location, angulation, and design of prosthesis.[32]

Biting Forces Generated on Implants. Dental implants are subjected to occlusal loads when placed in function (Table 1). Because loading is increasingly believed to be a determining factor in the treatment outcome, there is a need to further our understanding of the biomechanics of oral implant design. The greatest natural forces exerted against teeth, and thus against implants, occur during mastication and are the result of the action of masticatory muscles. The force is related to the amount and duration of function. Forces acting on dental implants possess both magnitude and direction and are referred to as vector quantities. The maximum bite force decreases as muscle atrophy progresses throughout years of edentulousness. However, this force can increase in the years after implant placement.[33] The muscle strength, masticatory dynamics, and maximum bite force exhibited by adults could all be influenced by sex, muscle mass, exercise, diet, bite location, parafunction, state of the dentition, physical status, and age.[34–37] It has been found that a vertical force in the long axis of an implant of only 10 mm in length with a 4-mm diameter can accept average maximum biting forces to the supporting bone within the physiological strain limits of the bone.[38]

The most common cause of early loss of rigid fixation during the first year of implant loading is the result of parafunction.[27] Parafunctional bruxism or clenching often leads to hypertrophy of the muscles of mastication and increased force. Parafunctional habits (clenching, bruxing, or engaging) can transmit forces to the supporting bone that could result in destructive lateral stresses and overloading.[39] Such loads can vary dramatically in magnitude, frequency, and duration, depending on the degree of the patient's parafunctional habits. Bragger et al.[40] indicated that all of the technical complications in his study were associated with bruxism. Therefore, anticipated occlusal and chewing force should be considered.[41] It has been suggested that most nocturnal parafunctional habits can be ameliorated by acrylic resin nightguards.[39]

The maximum bite force in parafunction is much greater than the natural forces attained during mastication. In normal dentition without implants, mean maximal vertical (axial) bite force magnitudes in humans can be 469 $\pm$ 85 N at the region of the canines, 583 $\pm$ 99 N at the second premolar region, and 723 $\pm$ 138 N at the second molar.[37] In general, maximal bite force in medial and posterior directions was larger than that in corresponding lateral and anterior directions, respectively.[37] Braun et al. also showed the mean maximum bite force to be 738 N with a standard deviation of 209 N. The mean maximum bite force as related to gender was found to be statistically significant, whereas the correlation coefficients for age, weight, stature, and body type were found to be low. Similar results were also reported by Raadsheer et al., who showed average values of the "maximal voluntary bite forces" as 545.7 N in men and 383.6 N in women.[42]

Morneburg and Proshchel measured vertical masticatory forces in vivo using a method that should be insensitive to the location of bite force impact. Their results on implant-supported fixed partial dentures produced a mean total masticatory force of 220 N with a maximum of 450 N. The single abutments experienced mean loads of 91 N (anterior) and 129 N (posterior) with a maximum of 314 N.[43] Fontijn-Tekamp et al. reported similar results.[44] They showed patients with mandibular implant-retained overdentures had maximal unilateral bite forces in men and women ranging from approximately 50 to 400 N in the molar regions and 25 to 170 N in the incisor areas.

The Impact of Occlusal Overload. Dental implants could be subjected to initial loads during the healing stage. These passive mechanical loads are attributed to mandibular flexure, contact with the first-stage cover screw, and/or second-stage permucosal extension. The force of the tongue and oral musculature can generate low loads on implant abutments; however, these could be of greater magnitude with parafunctional oral habits or tongue thrust. Nonpassive prostheses applied to implant bodies during the healing phase could result in mechanical loads applied to the abutment, even in the absence of occlusal loads. Once the dental implant is loaded, the bone reacts to microstrain in different ways. Frost proposed the theory of mechanostat and postulated that bone mass is a direct result of the use of the skeleton.[45] Frost established a mechanical adaptation chart relating trivial loading, physiological loading, overloading and pathologic loading zones to ranges of microstrain. Cell destruction can be seen when the chewing forces are such that they exceed physiological tolerances. This overload zone is reached when microstrains are greater than 3000 units. Excessive occlusal force being generated presents an opportunity for loosening and/or fracture of the implant through bending overload. Bending moments resulting from nonaxial overloading of dental implants can cause stress concentrations exceeding the physiological supporting capacity of cortical bone, leading to an overload situation and various kinds of failures.

It has been stated that overloading of an oral implant can result in loss of the marginal bone or even complete loss of osseointegration.[1,2,46,47] Initial breakdown of the implant–tissue interface generally begins at the crestal region in successfully osseointegrated endosteal implants, regardless of surgical approaches (submerged or nonsubmerged).[21,48] Early crestal bone loss on average of 1.5 mm is often observed after the first year of function followed by an annual bone loss after the first year of less than 0.2 mm.[6] Six plausible etiologic factors are hypothesized, including surgical trauma, occlusal overload, peri-implantitis, microgap, biologic width, and implant crest module.[49] Based on currently available literature, the reformation of biologic width around dental implants, microgap if placed at or below the bone crest, occlusal overload, and implant crest module could be the most likely causes of early implant bone loss. Furthermore, it is important to note that other contributing factors such as surgical trauma and peri-implantitis could also play a role in the process of early implant bone loss.[49]

Implant overload can be caused by a multitude of factors, including suboptimal implant design and size, an insufficient number of implants to support the restoration, improperly splinted abutments, violation of conventional prosthetic limitations for natural dentition, excessively cantilevered pontics; splinting to natural dentition (even with a stress-breaking attachment), improperly positioned implants, the wrong type of restoration for the clinical condition, loss of supporting bone, excessive parafunctional forces, and nonmaintenance of the components.[47] Crestal bone loss as well as loosened screws are frequently the first detectable signs of implant overload and warrant immediate action. To eliminate or reduce the excessive stress at the crestal bone–implant interface is a goal accomplished by balancing the whole arch, reducing occlusal contacts to the area of the implant-supported regions, and shortening or eliminating cantilevers whenever possible. This uniquely specific occlusal philosophy of endosteal implant prostheses has been referred to as "implant-protected occlusion."[30] Implant orientation and the influence of load direction, the surface area of implants, occlusal table width, and protecting the weakest area are blended together from a biomechanical rationale to provide support for a specific occlusal philosophy.[30]

Appropriate implant design selection through careful treatment planning is imperative to lower the magnitude of loads imposed on the vulnerable implant-to-bone interface. The following section will review design elements that could affect the force transfer and the quality of osseointegration.

Design Elements Affecting Force Transfer and Osseointegration Quality

History of Design. The three-dimensional structure of the implant, with all the elements and characteristics that compose it, is referred to as the implant design. The type of prosthetic interface, the presence or absence of threads, additional macroirregularities, and the shape/outline of the implant are considered some of the most important aspects of implant design. Dental implants can be categorized into threaded and nonthreaded, cylindric, or "press-fit" designs. Implant companies have been using a plethora of additional features to accentuate or replace the effect of threads. These features include vents, grooves, flutes, indentations, and perforations of various shapes. Implants can be hollow or solid, with a parallel, tapered/conical, or stepped shape/outline and a flat, round, or pointed apical end.[50]

Methods for the Assessment (Mechanical Tests, Histology). The effects of implant design elements on the quality and strength of osseointegration can be validated through several assessment methods. To prove the value of one design feature over another, outcome variables such as histologic assessments and mechanical testing have been the main methods used.

There are generally 3 types of biomechanical tests: pull-out, push-out, and torque measurement. Push-out and pull-out tests are indicated with cylindric or press-fit implants, whereas threaded implants are more effectively tested with the counter-torque or reverse-torque test. Thread volume fill and number of cells in contact with the implant surface are 2 other variables frequently reported in histomorphometric studies.[51,52]

With reference to an implant's ability to transfer occlusal stresses at the interface, a common method of testing the mechanical performance is by using a pull-out or push-through test. The results of such tests are often reported in terms of holding power or shear strength. Implants in a screw shape will resist push-out, but this shape requires a bond if it is to resist torsion, which tends to loosen the implant along the threads. Removal torque testing measures the resistance to loosening of the implant, not necessarily to occlusal load conditions. Push-out and removal torque force are both proportional to the interfacial shear strength. The interfacial strength ranges from 9 to 19 MPa for cortical bone and 2 to 6 MPa for trabecular bone after 12 weeks of insertion in various animal models.[53] However, these results showed that surface roughness and texture could be a primary factor in the anchorage of dental implants. The interfacial tensile strength of titanium is 2.5 MPa on average, whereas hydroxyapatite-coated titanium might not be much better.[53] On the other hand, several other studies demonstrated that hydroxyapatite (HA) is superior to sandblasted, large-grit, acid-etched (SLA), titanium plasma spray (TPS) and/or machined surfaces.[26,54]

Research of thread shape has been performed exploring the use of orthopedic bone screws placed into cadaveric bovine or canine long bones. In general, the holding power is a function of the test configuration, cortical thickness[55] and the number of threads engaged,[56] properties of the bone adjacent to the screw thread, and the major diameter of the screw. Reports differ regarding the relative importance of the thread profile. Koranyi et al. found little difference between thread types, whereas others stated that the interface strength does depend on thread shape.[55,56]

It has been shown that roughened titanium surfaces can improve the clinical prognosis of implants by achieving a higher percentage of bone–implant contact and higher removal torque values in mechanical testing as compared with the traditional, smooth titanium surface.[57,58] However, high surface roughness alone is not the only criteria to consider for optimal osseointegration, and the scope of this article does not focus on surface roughness. The following section reviews available studies addressing the effects of implant shape, diameter, length, and thread design on osseointegration of the bone to implant interface.

Effects of Shape, Diameter, and Length. The macrodesign or shape of an implant has an important bearing on the bone response; growing bone concentrates preferentially on protruding elements of the implant surface such as ridges, crests, teeth, ribs, or the edge of threads, which apparently act as stress risers when load in transferred.[59] The shape of the implant determines the surface area available for stress transfer and governs the initial stability of the implant. Finite element analysis studies of implants indicate that bone stress distributions and magnitudes vary with implant shape.[29,60] It is known and accepted that bone responds differently to different types of loading and is weakest under shear loading conditions.[61] Bone is strongest when loaded in compression, 30% weaker when subjected to tensile forces, and 65% weaker when loaded in shear.[62] Therefore, an attempt is made to limit the shear force resulting from the least resistance to fracture. Transforming shear forces into more resistant force types at the bone interface is the purpose of incorporating threads into the implant design as a surface feature. Smooth cylinder implant bodies result in essentially a shear type of force at the implant-to-bone interface. Surface features such as threads are incorporated into the design to transform the shear loads to more resistant force types. It is for this reason that most implant designs are threaded, because the thread shape is particularly important in changing force at the bone interface. The available thread shapes of square, V-shaped, and reverse buttress are intended to reduce the development of shear at the dental implant–tissue interface so as to improve long-term success.[63]

The significance in increased implant length or its ability to achieve osseointegration is not found at the crestal bone interface, but rather in initial stability and the overall amount of bone–implant interface. The increased length can provide resistance to torque or shear forces when abutments are screwed into place. However, the increased length does little to decrease the stress that occurs at the

Table 2. The Influence of Implant Lengths on Long-Term Success Rate

Study	Year	System	No.	Length	Duration	Success Rate
Quirynen et al.	1991	Brånemark	1273	7 mm	7 yrs	87.4%
				10 mm		93.2%
				13 mm		99.0%
Lekholm et al.	1994	Brånemark	558	7 mm	5 yrs	93.6%
				10 mm		89.7%
				13 mm		94.2%
Buser et al.	1997	ITI	2359	8 mm	7 yrs	91.4%
				10 mm		93.4%
				12 mm		95%
ten Bruggenkate et al.	1998	ITI	253	6 mm	6 yrs	94% (survival)
Ferrigno	2002	ITI	1286	8 mm	10 yrs	89.6%
				10 mm		91.6%
				12 mm		93%

Comparison of available studies examining the influence of implant fixture length on longitudinal implant success. All studies report implant success rates unless otherwise noted. Only longitudinal studies of 5 years in length or greater were included in this comparison.

transosteal region around the implant at the crest of the ridge or change its ability to achieve osseointegration.[27]

Table 2 compares the long-term success rates of different lengths of implants. In general, the use of short implants has not been recommended because it is believed that occlusal forces must be dissipated over a large implant area for the bone to be preserved.[64] Less favorable success rates for shorter implants were observed in clinical studies.[65–70] By the use of engineering statics, the amount of force transferred to the crestal bone from a horizontal occlusal load, relative to the implant length necessary to support that load, was analyzed for hypothetical instances when the implant was embedded in a uniform mass of bone and when it was bicorticated. The analysis revealed that implants longer than 12 mm will not significantly reduce force transfer proportionately to the increased length.[71] On the other hand, ten Bruggenkate et al.[72] evaluated short ITI implants of 6 mm and reported a cumulative survival rate at 6 years of 94%. This study recommended that short implants should be used in combination with longer implants, especially when used in the less dense bone that is often seen in the maxilla.

The surface area of each implant support system is directly related to the width and height of the implant. Wider root-form implants have a greater area of bone contact than narrow implants of similar height and design resulting from their increased circumferential bone contact areas.[27] As a result of the fact that occlusal load to the implant causes most stress at the crest of the ridge, the crest of the ridge is where initial bone loss occurs. As a result, width appears to be more important than height of the implant once a minimum or optimal height has been obtained for initial fixation and resistance to torque.[64,71]

The posterior regions of the mouth can sustain greater forces, yet often present poorer bone density. The longest implants are typically inserted into the anterior regions of the mouth, where forces of less magnitude and superior bone quality are normally present. A common biomechanical approach, often presented to decrease risk factors in such regions, is to increase implant surface area primarily by focusing on diameter. However, this increases surface area by only 30% for conventional thread designs despite the fact that forces increase by >300% in the posterior regions. A change in implant diameter and thread design could increase surface area by >300%. Such increases in surface area could decrease stresses to the crestal bone regions and reduce both crestal bone loss and early loading implant failure.[73]

Winkler et al. studied the influence of implant diameter and length on implant success rate.[74] Their results on 3-year survival and stability of various implant lengths (7 mm, 8 mm, 10 mm, 13 mm, and 16 mm) and diameters (3–3.9 mm and 4–4.9 mm) were 90.7% for the 3- to 3.9-mm diameter and 94.6% for the 4- to 4.9-mm group. Survival ranged from 66.7% for the 7-mm implants to 96.4% for 16-mm implants. Overall, the shorter implants had statistically lower survival rates as compared with longer implants, and 3- to 3.9-mm diameter implants had a lower survival rate as compared with 4- to 4.9-mm implants. However, there was no significant difference in crestal bone loss for the 2 different implant diameters between placement and uncovering.

Effects of Thread Design/Geometry. Threads are used to maximize initial contact, improve initial stability, enlarge implant surface area,[75] and favor dissipation of interfacial stress.[76] Thread depth, thread thickness, thread face angle, thread pitch, and thread helix angle are some of the varying geometric patterns that determine the functional thread surface and affect the biomechanical load distribution of the implant.[27] The influence of the threads can be easily understood as the greater the number of threads that are present as well as the greater the depth of the threads, the more functional surface area that is available.

Thread shapes in dental implant designs include square, V-shaped, and buttress (Fig. 1). The face angle of the thread can change the direction of load from the prosthesis to a different force direction at the bone. Under axial loads to a dental implant, a V-thread face is comparable to the buttress

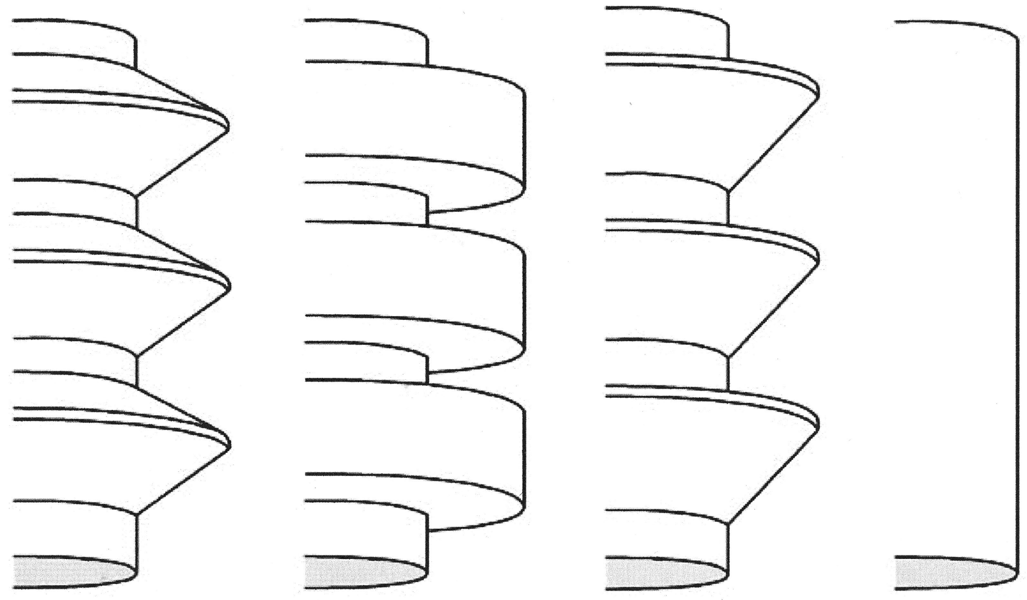

Fig. 1. Standard thread shapes in dental implant design. V-thread (Nobel Biocare, Paragon, 3i, Calcitek, ITI), square thread (Biohorizons), buttress thread (Steri-Oss), and cylindrical (nonthreaded).

thread when the face angle is similar and is usually 30°.[77] A square thread design (as opposed to the standard V-shaped or buttress thread) has been suggested to reduce the shear component of force by taking the axial load of the prosthesis and transferring a more axial load along the implant body to compress the bone. Increased cellular inflammatory responses have been observed under nonaxial, shear loading when compared with axial loading conditions.[78] Hence, it was suggested to avoid nonaxial, shear loading whenever possible. Therefore, design considerations that reduce the development of shear at the dental implant–tissue interfaces might improve long-term success, particularly in weak and low-density bone sites.[63]

The original Branemark screw, introduced in 1965, had a V-shaped thread pattern as a means of placement into a threaded osteotomy.[1] The original design has been modified over the years to allow for simpler, more efficient placement and better load distribution. The concept of "double-threaded" or "triple-threaded" implants have recently been introduced (eg, Nobel Biocare USA Inc., Yorba Linda, CA; Paragon & Calcitek, Centerpulse Dental Inc., Carlsbad, CA). These implants are believed to thread faster into the osteotomy site to provide initial increased stability. They require more torque for placement. Type IV cancellous bone is the primary indication for use.[50] However, the number of threads, the depth of threads, and the overall functional surface area is exactly the same, whether the implant body has double or triple threads. These terms refer to the process of making the implant body. Instead of an instrument making one thread of 0.6 mm for each turn in the vice, 2 or 3 points make 2 or 3 grooves at the same time. These 2 or 3 independent, external threads start 180° apart and are also 0.6 mm apart. They spiral around the implant body at a steeper angle than conventional implant threads, but act as one thread. In other words, the single thread moves 0.6 mm for each rpm and the double thread moves 1.2 mm for each rpm even though the surface area to load is exactly the same. So although providing the same surface area, each 360° turn seats the implant 1.2 mm instead of the 0.6 mm in standard threads. This allows for full seating of an implant in half the time. As a result of the tapered shape of the implant apex, higher apical torque bone compression occurs during the last revolution of placement, increasing implant rigidity and stability.

The standard V-shaped thread (eg, Paragon/Calcitek; Centerpulse Dental Inc.; 3I, 3i Implant Innovations, Inc., Palm Beach Gardens, FL; ITI, The Strauman Co., Waltham, MA; and Nobel Biocare, Nobel Biocare USA Inc.), called a "fixture" in engineering, has 10 times greater shear loads on bone compared with a square thread with parallel major and minor diameters.[27] Square thread shape (eg, Biohorizons; Biohorizons Implant Systems, Birmingham, AL), called a power thread in engineering, has an optimized surface area for intrusive, compressive load transmission, resulting in a lower strain profile to bone. Buttress thread shape is optimized for pull-out loads and has parallel major and minor diameter.[79] The reverse buttress thread design (eg, Steri-Oss, Steri-Oss Inc., Anaheim, CA) has fewer threads and less thread depth. Despite the suggested differences in force transfer to bone from their use, no controlled clinical studies comparing the 3 thread designs are available.

Another recent approach has been the introduction of a rounded thread design that claims to induce "osteocompression." In dentistry, controlled functional osteocompression is the

Table 3. Implant Success Rates by Implant Design

Implant Design	System	No.	Maxilla (no.)	Mandible (no.)	Overall (no.)
V-Thread	Branemark	35	91.7% (18)	95.4% (18)	93.9% (28)
	ITI	17	92.5% (6)	95.5% (7)	96.3% (12)
Nonthreaded	IMZ/Interpore	5	96.3% (1)	96.8% (3)	94.2% (3)
Buttress thread	Steri-Oss	3	93.76% (3)	95.9% (3)	94.9% (3)
Square thread	Biohorizons	3	99% (3)	99% (3)	99% (3)

Comparison of available studies examining implant success rate stratified by thread design, implant system, and placement location. All studies report implant success rates unless otherwise noted.

* No. represents the number of longitudinally evaluated studies. A minimum number of 3 studies were evaluated in this comparison to limit investigator bias.

compaction created by the tapping procedure. Functionally, there is always applied force acting on bone modified by an implant design, and there is always resisting force acting on the implant through the viscoelastic properties of trabecular structure. Through biomechanical events in bone, osseous tissue can be stimulated within physiological limitations by implant design to develop along the lines of compressive forces dependent on the implant load-bearing area to sustain equilibrium. A sinusoidal thread design (eg, LaminOss immediate-load implant; Impladent Ltd., Holliswood, NY) has shown, in animal histologic observation, lamellar bone achieved by the function of osteocompression.[80] This implant design allows bone to be molded and compacted circumferentially. Future human clinical research would be necessary to provide a meaningful statistical analysis to validate the importance of this implant design and the function of osteocompression.[81]

Hoshaw conducted an experimental animal study to examine the bone modeling and remodeling response of interfacial tissues near screw-shaped V-threaded titanium dental implants (Nobel Biocare® Branemark) under different mechanical loading conditions.[82] The study has shown that threaded implants had higher remodeling rates and less mineralized bone formation when loaded with axial force than the nonloaded threaded implants. The general elevation in bone modeling and remodeling activity observed near loaded implants supports Frost's mechanostat theory and is consistent with the idea that these responses were triggered by tissue microdamage as a direct consequence of the applied loads. She speculated that this cortical bone remodeling around the implants could be an attempt to provide an improved strain orientation of the bone to loads.

Square-thread design implants showed, in a 4 beagle dog animal study, that bone grew between the threads, closely adapted to the implant, and that the inferior aspect of the test implant threads were apposed by more bone than the coronal aspect.[63] These results suggest a biologic advantage for the compressive load transfer mechanism for this thread design. This observation was further supported in the case report.[79] As a result of limited sample size, additional histologic reports and clinical data are required to confirm the observations made in this study. However, limited information is currently available in examining the influence of the buttress thread design on the implant success. Future studies comparing these 3 different implant thread designs are certainly indicated.

Longitudinal Studies on Implant Success

A large number of varying criteria for implant success have been published over the last 25 years with each being a better reflection of the continually evolving science of implantology. It could well be that no single set of criteria would address all implant systems in all patients when attempting to judge longitudinal or even individual success rates. However, some generalized factors have been well established as guidelines:

- Immobility of the implant fixture.
- Regular radiographic assessment of the fixture using a paralleling technique.
- Absence of peri-implant radiolucency as assessed with radiography.
- Stable marginal bone levels after the first year of implant placement and loading.
- Absence of infection, pain, neuropathy, and paresthesia.
- Ability to properly restore the fixture so as to improve patient function above what existed before implant rehabilitation.
- Stable functional performance for an interval equal to or longer than alternative available therapies.
- Patient satisfaction with function and esthetics.

We recently combined the data from 104 longitudinal studies reporting on implant success rates (unpublished data). These studies were selected from published manuscripts in refereed journals found in a search of the National Library of Medicine from 1981 to 2000.

Calculation of average success rates for area-specific implant rehabilitation, including maxillary and mandibular success rates as well as overall implant success, are presented in Table 3. From Table 3 it would appear that the overall maxillary success rate is, on average, approximately 3% lower than that of the mandible. Additionally, the success rates for the maxilla have a wider range of percentages reported, whereas the mandibular success rates are not quite as varied. However, the square thread design is the exception with success rates in the maxilla and mandible being equal and also the highest success rates reported. The overall success rates are the lowest for the V-shaped thread and the nonthreaded design. However, more longitudinal studies are needed for the nonthreaded, buttress, and square thread designs in making these comparisons. The overall implant success rate for all areas of the oral cavity, as estimated from these longitudinal studies, is approximately 95.5%.

Conclusions

It is imperative that a greater understanding of the parameters that govern the long-term success of implants be developed. The design of an "optimal" implant requires the integration of material, physical, chemical, mechanical, biologic, and economic factors.[83] Implant success is primarily a function of biomaterials and biomechanical factors. The objective of implant research remains the development of an implant that can be placed in a simplified manner to osseointegrate in as short a period as possible. It should also be reliable as well as relatively inexpensive. Continued research is essential if these objectives are to be met to engineer the "optimal" implant design.

Although there is currently no clearly superior dental implant design, a number of controllable parameters are important when considering oral implant rehabilitation.

Bone Volume and Implant Length

The amount of bone available for implant placement, fixture length and diameter have all been shown to influence implant predictability and success. When selecting potential areas for implant rehabilitation, consideration should be given to maximize the amount of available bone, allowing for placement of longer (≥10 mm) and wider diameter (≥4 mm) implant fixtures.

Bone Density and Implant Surface Area

In areas with poorer bone quality and density (notably the posterior maxillary areas), emphasis should be given to maximizing implant surface area contact with available bone, because there are currently no methods available to change regional bone density. Thread design, surface roughness, length and diameter of the implant fixture have all been shown to influence the surface area available for bone contact. Selecting implant characteristics that maximize the available surface area for bone contact can be considered important in successful implant rehabilitation of poor-quality bone sites. For example, the literature suggests that a coated, square-threaded, 10+-mm long, 4+-mm diameter implant fixture would fare better than a machined, cylindrical, <10-mm long, <4-mm wide implant fixture when placed in areas of low bone quality and density.

Loading Forces

Because implants are most susceptible to fracture and failure when exposed to shear forces, the implant design should incorporate features that best transform tensile and shear masticatory forces. Thus, threaded implants are preferential to cylindrical implants as a result of their ability to minimize undesirable force components. Within threaded designs, there is some evidence suggesting that square-shaped thread designs are better able to dissipate shear forces, transforming them to more desirable axial loading. Prosthetic engineering of the final implant appliance also greatly influences the distribution of masticatory force during function. Particular attention should be given to evenly distributing masticatory load, protecting implant occlusion through splinting fixtures and using natural teeth as heavy occlusal stops, avoiding steep cuspal inclines in implant appliances, avoiding prosthesis cantilevering, and assuring that the proper number of implants are placed for the span of missing dentition.

Parafunctional Habits

Because bruxism and grinding have been demonstrated to adversely affect long-term implant stability and success, careful consideration should be given to identifying and managing parafunctional behaviors. It is often advisable to provide a bite guard for those implant patients having a positive history of parafunctional activity.

Overall, implant rehabilitation can provide a highly successful esthetic and functional treatment option. Through careful adherence to established protocol and techniques of surgical and prosthetic implant rehabilitation, clinicians can confidently and enthusiastically recommend implant therapy to their patients as a successful, superior treatment that has no equal in today's dental therapy.

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Zum Aufbau von Zahnimplantaten und dessen Auswirkungen auf den Langzeiterfolg einer Implantierungsbehandlung

ZUSAMMENFASSUNG: Innerhalb vorliegender Abhandlung sollte untersucht und bewertet werden, inwieweit sich biomechanische Eigenschaften eines Zahnimplantates in der Qualität und Stärke der Knochengewebsintegration, an der Schnittstelle zwischen Knochen und Implantat niederschlagen und inwieweit diese Faktoren den Langzeiterfolg einer Zahnimplantierungsbehandlung beeinflussen. Viele miteinander in Verbindung stehende Faktoren bestimmen den Konstruktionsaufbau der Zahnimplantate. Dazu gehören: die Implantatgeometrie, die mechanischen Eigenschaften und die anfängliche sowie die langfristige Stabilität der Schnittstelle zwischen Implantat und Gewebe. Somit gibt es nicht das eine, bestimmende und 'optimale' Kriterium, das über den Implantataufbau zu bestimmen hat. In der Entwicklung der Implantate wird allerdings versucht, die maximale Stärke des Implantats selbst, die höchst mögliche Stabilität an den Schnittstellen und die maximale Belastbarkeit durch die Auswahl spezieller Materialien, Oberflächen und Fadenbeschaffenheiten zu erreichen. Da als erwiesen gelten kann, dass die Aufbauelemente die Qualität der Knochengewebsintegration und damit den Langzeiterfolg der Implantierung beeinflussen kann, befasst sich diese Arbeit mit den Aufbauelementen verschiedener, aktuell verwendeter Zahnimplantatsysteme und diskutiert deren Vor- und Nachteile sowie die langfristigen Erfolgsaussichten.

SCHLÜSSELWÖRTER: Zahnimplantate, Biomechanik, Aufbau, Knochengewebsintegration

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Diseño de implantes dentales y su relación con el éxito del implante a largo plazo

ABSTRACTO: El propósito de esta revisión es evaluar los efectos de los aspectos biomecánicos del diseño de implantes dentales sobre la calidad y solidez de la oseointegración, la interfaz entre el hueso y el implante y su relación con el éxito a largo plazo de los implantes dentales. El diseño de ingeniería de los implantes se basa en muchos factores interrelacionados: la geometría del implante, las propiedades mecánicas, y la estabilidad inicial y a largo plazo de la interfaz entre el implante y el tejido. No existe un solo criterio de diseño "óptimo". Sin embargo, se pueden fabricar implantes para maximizar la solidez, la estabilidad interfacial y la transferencia de la carga al utilizar materiales, superficies y diseños de la rosca diferentes. Existe actualmente información limitada que se ocupa sobre cómo el diseño de las roscas del implante influencia el éxito general del implante. Por lo tanto, este trabajo evalúa y analiza los elementos del diseño de varios sistemas de implantes dentales actualmente en uso según afectan la calidad de la oseointegración y su relación con el éxito general a largo plazo.

PALABRAS CLAVES: implantes dentales, biomecánica, diseño, oseointegración

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O Design do Implante Dentário e sua Relação com o Sucesso do Implante a Longo Prazo.

SUMÁRIO: O propósito deste estudo é avaliar os efeitos dos aspectos biomecânicos do design do implante dentário na qualidade e resistência da ósteointegração, a interface do implante ósseo e suas relações com o sucesso a longo prazo dos implantes dentários. A engenharia do design dos implantes é baseada em muitos fatores inter-relacionados, incluindo: a geometria do implante, propriedades mecânicas, e a estabilidade inicial e a longo prazo da interface do tecido do implante. Não existe critério "ótimo" de design. Mas, implantes podem ser desenvolvidos para maximizar resistência, estabilidade interfacial e transferência de carga com a utilização de diferentes materiais, superfícies e desenhos de linha. Informação limitada está atualmente disponível no tocante em como os desenhos de linha influenciam o sucesso do implante de maneira geral. Entretanto, este estudo revê e discute os elementos do design de vários sistemas de implante dentário atualmente em uso e como eles afetam a qualidade da ósteointegração e sua relação geral com padrões de sucesso a longo prazo.

PALAVRAS-CHAVE: implantes dentários, biomecânica, design, ósteointegração.

デンタル・インプラントのデザインと長期的成功の関係

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要約：この研究の目的は、デンタル・インプラントのデザインの生体力学的効果が骨統合と骨-インプラント境界の質と強度に与える影響を調べ、それとデンタル・インプラントの長期的成功との関係を知ることにあった。インプラントの力学的デザインは、インプラントの外面的形態や力学的性質、またインプラントと組織の間の長期的安定など、相互に関連する多くの要因によって決定される。「もっとも重要な」デザイン条件がひとつだけ存在するということはありえない。しかし、強度、境界面の安定性や応力伝達性能においてもっとも優れたインプラントを、異なる材料、表面、threadのデザインを採用することによって設計することは可能である。インプラントthreadのデザインがその全般的な成功にどのような影響を与えるかについての情報は、現状では限定されている。本論文では、現在使用されている各種のデンタル・インプラント・システムのデザインを要点的に論じ、それと骨統合への影響・長期的成功のパターンとの間の関連を調べることに重点が置かれた。

キーワード：デンタル・インプラント、生体力学、デザイン、骨統合

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