

Developments of Dental Implant Design for Long-Term Success: An Overview

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ABSTRACT

As the bone tissues surrounding implants exhibit varying responses depending on the implant structure and shape, research has been conducted to achieve stable bone responses. Implant design influences not only primary stability through mechanical structures, but also long-term stability through biomechanical mechanisms.

Hence, this paper proposes an ideal implant design with the goals of rapid functional recovery and long-term stability by reviewing the design elements that have evolved with changing trends.

INTRODUCTION

Dental implants have evolved over the past 60 years as restorations to replace natural teeth, with the aim of maximizing their function and enhancing their long-term stability. Since the introduction of Branemark implants, the first osseointegrated implants, in the 1960s, diverse efforts have been exerted to achieve successful implant treatment. In the 1970s, basic surgical guidelines for implants were established, and long-term clinical results of osseointegrated implants were published, providing a clinical foundation for implants^{1), 2)}. In the 1980s and 1990s, various structural designs and surface treatment methods for implants were attempted, leading to a significant increase in implant success rates, ranging from 80% to 90%. After the 2000s, the concept of platform switching emerged, which was recognized to be effective in maintaining crestal bone levels, and has now been adopted in most implant systems.

The macro implant design has also undergone significant advancements. Due to the varying responses of bone tissue depending on the implant structure and shape, such as the design of the implant body, thread, neck, and connection type, research has continued to discover ideal forms that can elicit a more stable long-term bone response. Growing bone, when responding, tends to concentrate primarily on the protruded areas of the implant surface, which can increase stress when occlusal forces are transferred to implants³⁾. According to research by Rieger et al. (1990), implants transfer stress to bone differently depending on their shape in terms of the magnitude and distribution of stress⁴⁾, plus Park et al. (2022) argued that implant system factors must be considered to achieve successful implants⁵⁾ and emphasized the importance of the connection between the implant and the abutment, as supported by several prior studies demonstrating significant differences in bone loss dependent on the connection type^{6), 7)}.

Implant design is also closely related to primary stability, which is known as a prerequisite for achieving the osseointegration of implants and serves as a useful predictor for this^{1), 8)}. During implant placement, the implant body and thread designs can enhance primary stability by controlling the insertion torque. High primary stability not only provides resistance against micro-movements⁹⁾, but also shortens the overall treatment time. It is already widely accepted as an established theory that primary stability is crucial for implant success and long-term stability, as supported by numerous previous studies. Therefore, in the current saturated implant market, selecting well-designed implants is crucial from a treatment and long-term stability perspective.

This paper proposes an ideal implant design with the goals of rapid functional recovery and long-term stability by reviewing the design elements that have evolved with changing trends.

Effects of body design developments

Implants used to be classified into cylinder, press-fit, and screw type implants. In the 1980s, cylinder and press-fit implants were preferred as they have a lower risk of bone necrosis caused by compressive force due to their ease of placement without bone tapping during surgery, and their high initial success rates^{10), 11)}. However, a low bone-to-implant contact (BIC) due to high shear force and fatigue overload acts as a potential risk factor in terms of stability. As a result, studies have reported high implant failure and bone loss rates of over 50% in follow-ups over more than 10 years. Consequently, various designs that have evolved from screw implants now dominate the market^{12), 13)}.

Screw implants are further classified into cylindrical type (parallel type), apically tapered type, fully tapered type, and unique types that do not fit the three other types. The theoretical background behind the emergence of (apically or fully) tapered implants was related to addressing several failure cases associated with "soft bone"¹⁴⁾. Misch (2007) argued that bone quality clearly influenced implant success, and reported that regions such as the maxillary posterior often exhibited poor bone quality of D3 and D4, leading to a higher risk of implant failure^{12), 15)}.

The cylindrical type, which is the basic implant form, is inserted by applying compressive forces after under-drilling during surgery. While this type exhibits excellent primary stability in high-density bone, it requires a long healing period of 3-6 months due to a low insertion torque in poor quality bone such as D4. The tapered type ensures a better primary stability in poor bone quality by reducing the drill diameters at the apex while increasing the compressive forces. Recent studies have reported lower surgical trauma during drilling¹⁶⁾, and these factors facilitate rapid osseointegration, enabling immediate placement or immediate loading with a relatively short healing period of 4-8 weeks. Moreover, in cases where

anatomical limitations restrict implant placement, such as thin or concave ridges, the cylindrical type carries a higher risk of perforation at the apex, while the tapered type offers a suitable solution with a decreasing diameter towards the apex.

The difference between apically tapered and fully tapered implants can be observed in their stress distribution mechanisms. Adams (1985) recommended the use of fully tapered implants for stress distribution, as most of the force applied to implants is concentrated on the crestal bone ridge. Rieger et al. (1990) reported that a finite element analysis of six implant types showed that most implants, including the apically tapered type, exhibited stress concentrated around the crestal bone, while fully tapered implants demonstrated a more balanced force distribution. Natural teeth allow for micro-movements thanks to the periodontal ligament, whereas implants do not, leading to a force concentration around the crestal bone. Thus, the fully tapered type has a uniform distribution of compressive forces from the top to the apex of the implant during placement, allowing an even force distribution^{17), 18), 19)}. Notwithstanding, surgeons need to make correct judgments of bone quality as these characteristics may induce excessive compressive forces in highly dense bone.

One important aspect of the tapered type to carefully consider is the shape of the coronal section. While the tapered type structure generally has a wider coronal shape, major manufacturers have recently introduced designs that minimize compressive stress on the cortical bone by reducing the structure that comes in contact with cortical bone (Figure 1) to reduce the risk of bone necrosis and ensure long-term stability²⁰⁾. Representative products include Straumann BLX, Nobel Biocare NobelActive, and MegaGen AnyRidge.

Although most other existing implant products adopt (apically or fully) tapered appearances, there are also implants with unique designs, such as inverted implants (Inverta™, Southern Implants) (Figure 2). Inverted implants lower the possibility of bone necrosis by securing stability at the implant apex and reducing the coronal section, while at the same time maximizing the effect of bone augmentation through facilitating the placement of a larger amount of graft material on both the labial side and in the interdental space. However, since these are specialized products used for severely compromised bone in the anterior region, there may be challenges and limitations for general use and widespread adoption. Nevertheless, if they are used under the appropriate diagnosis of clinicians, they can be beneficial in a wide range of treatments.

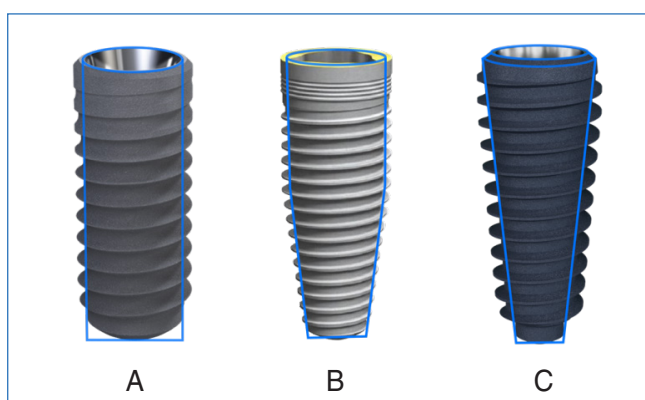


Figure 1. Three types of implant body design. A: Cylindrical implant; B: Apically tapered implant; and C: fully tapered implant.



Figure 2. Unique type of body design.

Effects thread design developments

Threads are used to increase the implant surface area to maximize the initial contact between the bone and the implant, and to enhance the primary stability for better stress distribution at the interface²¹. In the mid-1960s, Branemark implants incorporated V-threads, commonly used in industrial applications, for the purpose of simple fixation²². However, in the 1980s and 1990s, manufacturers

such as Straumann, Ankylos, and BioHorizons introduced products with various thread designs, spurring more research on the function and role of threads.

The four representative thread forms that were initially developed included the V-thread, buttress thread, reverse buttress thread, and square thread, while subsequent modifications of these forms included the trapezoidal thread and spiral thread (Figure 3). Cowin (1989) stated that human bones are strongest under compressive force, approximately 30% weaker under tensile force, and about 65% weaker under shear force²³. V-threads convert masticatory forces comprehensively into compressive, tensile, and shear stress, while square threads produce low shear force and high compressive force, making it the most favorable thread in terms of stability according to some studies²⁴, ²⁵. Among the modified screw shapes, studies have demonstrated that trapezoidal threads produce lower maximum stress values compared to square threads²⁶, which has led to implant designs evolved from trapezoidal threads predominating the current market.

According to previous studies, excessive loads on implants can cause micro-cracks in bone, promoting the formation of osteoclasts that cause bone loss²⁷, plus the accumulation of such microdamage can lead to the formation of larger defects²⁸. Therefore, the thread shape should be designed to minimize unfavorable stress on implants by providing a large contact surface area. The use of sharp-threaded designs can help to protect and preserve newly formed bone cells from excessive compressive forces that can be applied to surrounding bone during implant placement, to ensure fast healing²⁹.

Research on threads has been conducted in terms of shape as well as multiple variables such as the size, pitch, number of helices, and helical angle²⁶, ³⁰, ³¹. As research progressed, the biomechanical importance of threads became apparent³², ³³. According to research findings, reducing the thread pitch values increases the primary stability due to the larger surface area³⁴, ³⁵, while multi-thread designs allow rapid achievement of a strong insertion torque yet can also cause bone damage and generate bone debris³¹. Kong et al. (2006) measured the maximum equivalent stresses for pitch values ranging from 0.5mm to 1.6mm and concluded that a thread pitch exceeding 0.8mm was beneficial in the long term, and that cancellous bone was more sensitive to peak stress than cortical bone in terms of the bone response to pitch values. Thus, there have been various arguments about thread design factors³⁶.

There are also contrasting views on the effect of threads on the secondary stability of implants. Some argue that the stress on the marginal bone differs significantly depending on the thread design, while others claim that the thread design has little effect on marginal bone stress after osseointegration is completed³⁷⁾. The latter view suggests that having a wide thread design is important for achieving primary stability but may not have a significant impact on obtaining secondary stability³⁶⁾. Even if the thread design does not significantly affect secondary stability, it is possible that excessive compressive stress generated during implant placement may affect secondary stability. In 1991, Hider proposed for the first time the possibility of bone loss due to compression necrosis³⁸⁾. Marginal bone has the lowest distribution of blood vessels and is vulnerable to shear forces, making it more prone to bone loss. Therefore, if excessive stress is transmitted to the crestal bone due to micro-thread designs that gain stability from the cortical bone or an aggressive thread design (such as threads that become thicker towards the marginal bone or other designs that may be harmful to cortical bone), excellent primary stability can be achieved through mechanical binding but there is a higher risk of long-term peri-implant cortical bone loss.

For example, micro-threads, first introduced by Astra in the 1990s, are still used by many manufacturers to improve stability in dense cortical bone. There is ample evidence demonstrating the effectiveness of micro-thread designs for enhancing the bone-to-implant contact between micro-threads and cortical bone, thus preventing bone loss³⁹⁾,⁴⁰⁾. However, some studies have found no significant differences in bone loss with or without micro-threads⁴¹⁾,⁴²⁾,⁴³⁾. Small and dense micro-threads may not effectively relieve the stress generated during implant placement and can increase the risk of necrosis if their engagement with the cortical bone is increased from a bone biology perspective.

Therefore, a deep-thread design, where the threads rely on the cancellous bone for primary stability without engaging the cortical bone, appears to be most desirable to minimize bone loss around implants.

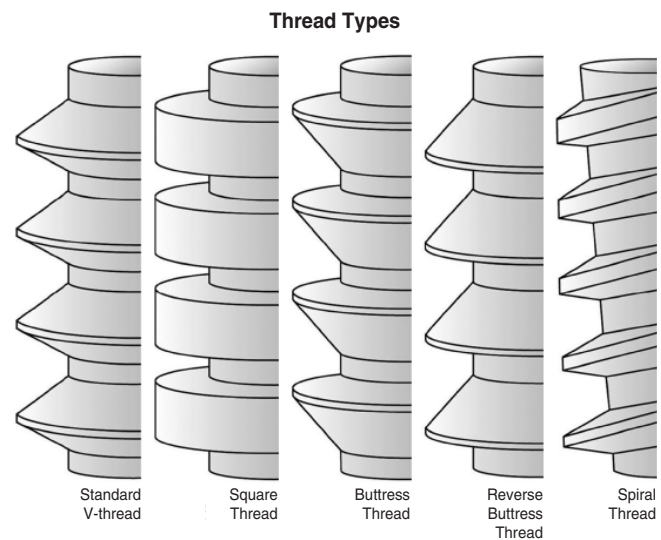


Figure 3. Typical implant thread patterns used in the past. Adapted from 'The effect of thread pattern upon implant osseointegration', by Abuhussein et al. *Clinical oral implants research*, 2010, 21.2: 129-136.

Effects of implant-abutment connection developments

1. External connection

In general, the connection between the implant and the abutment is classified into external and internal connections. An external connection means the implant and abutment are connected outside the implant. Originally, Branemark implants were developed for edentulous patients, so they had an external connection to facilitate the connecting of a metal bar to the arch. However, as the demand for partial restorations gradually increased from edentulous cases to single tooth cases, it became necessary to improve the connection. Branemark's external connection is based on a passive contact between the implant and the abutment using the flat contact surface of the butt joint, yet this results in various clinical complications, such as abutment screw loosening, fractures, and micro-movements at the implant-abutment interface⁴⁴⁾,⁴⁵⁾. Thus, to minimize such problems, recently launched external-type implants have introduced connection methods including a prosthetic index and anti-rotation mechanisms.

2. Internal connection

Internal connections were proposed to connect implants and abutments inside the implant to overcome the limitations of external connections. Whereas external connections are vulnerable to lateral force due to their 90° connection angle, internal connections offer strong resistance against lateral force due to their angulated interface, which enables effective distribution of masticatory pressure through a large connection area. Moreover, internal connections allow the interface to be sealed, thereby preventing potential microbial colonization and addressing a concern associated with external connections.

Internal connections can be grouped into slip fit and friction fit types based on the contact mechanism at the interface. A friction fit achieves tight integration using the local frictional forces generated between the implant and the abutment during their connection and is characterized by a gap-free interface. Meanwhile, a slip fit, also known as a passive fit, includes micro-gaps at the interface, thereby eliminating the generation of frictional forces. In the past, Straumann, Astra Tech, and Ankylos utilized friction fit connections, while Core-vent, 3i, and Nobel Biocare introduced implants with slip fit connections, and the adoption rates of the two connection types were similar. However, currently, friction fit connections are more widely used^{(46), (47), (48)}.

3. Friction fit internal connection

Once implants start to function, lateral pressure is exerted on them, and this causes micro-movements of the abutment creating small gaps at the connection interface. These micro-gaps serve as a habitat for microorganisms, leading to the leakage of toxins into the surrounding bone that can cause infection and impair the long-term stability⁽⁶⁾. A friction fit connection induces cold welding via the compressive and frictional forces generated during the abutment connection, achieving effective sealing at the interface. In particular, the conical sealing method, introduced by Astra in 1993, positions micro-gaps between the implant and the abutment closer to the central axis and further away from the adjacent marginal bone, thereby lowering the risk of microbial contamination and leading to relatively low bone loss rates (Figure 4)⁽⁷⁾.

The majority of recent implant systems incorporate an Astra-type (bone level) morse tapered connection combined with each manufacturer's technology (Table 1). Major manufacturers such as Straumann, MegaGen, and Bicon have also adopted an interface angulation of 15° or less to maximize the frictional force for mechanical binding. The smaller the angulation of the implant connection, the higher the interface surface area enhancing the microbial sealing effect and implant strength as the implant coronal wall becomes thicker⁽⁴⁹⁾. Among implants on the market, Bicon's 1.5° tapered connection has the smallest angulation⁽⁵⁰⁾. Bicon implants are also known for secure connections void of movement when the abutment is connected using only friction, even without a screw connection. This has led some clinicians to claim that Bicon's 1.5° connection is the most ideal form. Yet, as the connection angulation decreases, prosthesis jamming can occur and the adjustable angle can be decreased during prosthetic connection, limiting the prosthetic restoration. Therefore, it is crucial to choose the appropriate connection that can accommodate a smaller angulation along with convenient prosthetic delivery.

Consequently, internal-type implants with friction fit connections and appropriate interface angulations, yet minimal microbial leakage potential, need to be selected for long-term implant stability as this type of connection is designed for both strength and prosthetic restoration.

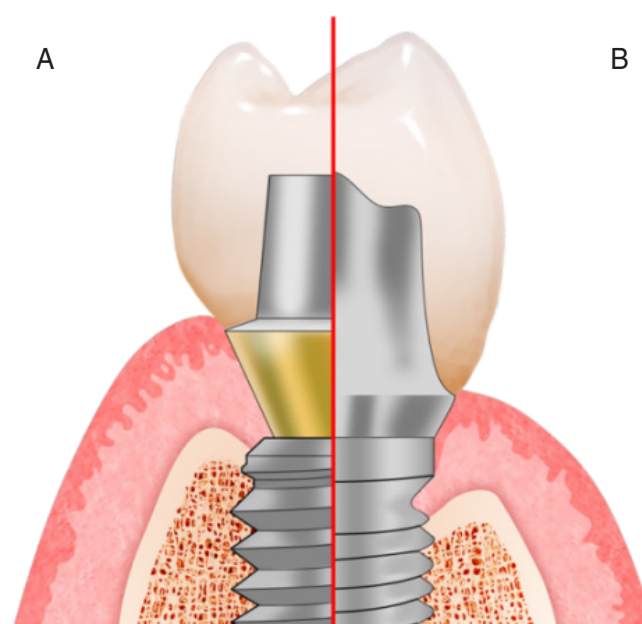


Figure 4. Microbial sealing effect according to implant-abutment connection type; A: Internal conical connection; and B: External connection.

No.	Angle of connection interface	Manufacturer	Brand	Implant system
1.	15° morse taper	MegaGen Straumann	MegaGen Straumann	BLUEDIAMOND BLT
2.	12° morse taper	Nobel Biocare	Nobel Biocare	NobelActive
3.	11° morse taper	Dentium Dentsply Sirona Osstem	Dentium Astra Tech Osstem	SuperLine II Astra Tech implants TS system
4.	7.5° morse taper	Camlog	Camlog	CONOLOG
5.	7° mosre taper	Straumann	Straumann	BLX
6.	5.7° morse taper	Dentsply Sirona	Ankylos	Ankylos implants
7.	5° morse taper	MegaGen	MegaGen	AnyRidge
8.	1.5° morse taper	Bicon	Bicon	Bicon implants

Table 1. Friction fit internal connection types

CONCLUSION

The structure and shape of implant design can lead to strong primary stability. However, designs that rely excessively on support from cortical bone can potentially lead to cortical bone necrosis in the long term. In order to achieve primary stability for both rapid restoration of masticatory function and long-term stability, it is important to have implant body and thread designs that acquire stability from cancellous bone. Furthermore, an internal friction fit-type connection, designed for both strength and prosthetic restoration, can provide an excellent long-term clinical prognosis with firm support for the implant and prevention of microbial leakage.

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