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Literature Review

Optimizing Implant Macro-geometry to Improve Primary Stability in Low Bone Density: A Scoping Review

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KEYWORDS

dental implant, implant stability, implant thread design, low bone density

ABSTRACT

Introduction: The design of the implant is a crucial factor that can impact the initial stability of the implant. Nevertheless, the current evidence is inadequate in establishing the most suitable dental implant design for cases with low bone quality to obtain the optimal amount of implant stability despite the availability of various options. **Objective**: The study aimed to perform a systematic review to assess the effect of different implant macro-geometry on primary stability in low bone density. **Methods:** The search strategy included both in vitro and in vivo studies published in PubMed, Cochrane Library, and Scopus from 2015 to 2024. The inclusion criteria were in vitro and in vivo studies, studies that evaluate implant primary stability by implant stability quotient (ISQ), insertion torque (IT), or removal torque (RT) value, studies that compare design thread in low bone density within the same study, and studies published in English. **Results:** 208 manuscripts were retrieved from the electronic literature search, and 11 studies met the eligibility criteria and were selected for this study. **Conclusion:** The results of this review suggested that an implant with a tapered body shape, square thread, and double-threaded feature significantly affects the primary stability of the implant in low bone density. It has become apparent that implant shape and thread geometry are critical parameters when designing new implant designs.

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INTRODUCTION

Implant stability plays a vital role in osseointegration. Osseointegration is the biological process by which an implant integrates with the surrounding bone tissue.[1] Implant stability is categorized into two types: primary stability, achieved through mechanical engagement with the surrounding cortical bone during insertion, and secondary stability, which develops over time through regeneration and remodeling of the bone around the implant.[2] Previous studies have found a direct correlation between primary implant stability and successful osseointegration.[3,4] To establish osseointegration, it is crucial to maintain micro-movements at the interface between the bone and the implant. These micro-movements should generally be kept below 150 microns.[5,6] Implant design, bone density, and surgical procedure of an implant are critical factors in achieving primary stability. Implant shape and implant thread are widely debated variables in implant design among researchers, as they can directly affect the biomechanics of the implant in bone.[7,8]

Achieving primary stability in cancellous bone can be challenging, resulting in a high failure rate.[9] It is accepted that the lowest implant stability is found in type 4 bone. There are reports of failure rates up to 35% in Type 4 bone which has a thin cortical shell and constitutes mainly softer cancellous bone, as in the posterior maxilla compared with Types I, II, and III, which have shown an implant loss of only 3%.[10] Implants that contact only cancellous bone may face difficulties achieving stability and maintaining the bone-implant interface, which is crucial in preventing micromotion and subsequent failure.[11] Several manufacturers have attempted to produce dental implants with more aggressive threads to achieve better stability in low bone density.[10,11]

Many modifications to implant designs have been developed over the years, including the shape and thread of the implant. Selecting an implant that provides sufficient stability in low-quality bone is crucial.[12] Tapered implants provide adequate primary stability in regions with reduced bone quality by creating tight contact between the osteotomy wall and the implant surface. Furthermore, bone perforation is less likely to occur due to the anatomical shape. Although cylindrical implants initially had lower stability after implant insertion, they rapidly gained stability due to early woven bone formation following the blood-clotted gap between the implant surface and osteotomy wall.[1,13] Also, implant threads should be designed to provide favorable stress while minimizing adverse stress at the bone interface. The implant thread should be designed to enhance the stability and contact of the implant with the bone. The optimal implant design should minimize the formation of shear forces and strike a balance between compressive and tensile forces.[14,15]

Several methods have been suggested to assess implant stability. Insertion torque (IT) measurement and resonance frequency analysis (RFA) are the most frequently used methods and have been suggested as techniques to evaluate implant stability due to their reliable results.[16,17] IT measures the frictional resistance to the implant fixture while it moves in the apical direction in a rotating motion along its axis.[18] The IT measurement can be obtained only upon implant placement. Some studies showed that insertion torque scores lower than 20 Ncm predicted a higher failure rate for immediately loaded implants. RFA measures the stiffness and deflection of the implant-bone complex. The value obtained by the RFA device is automatically translated into an index called the implant stability quotient (ISQ), ranging from 1 to 100 , with failure rates increasing when the ISQ is lower than 55. ISQ can be recorded in all phases of prosthetic treatment: upon implant insertion, during the healing phase, and even after the prosthesis has been loaded.[6,19]

The influence of implant design on primary stability, particularly in low bone density conditions, is a critical area of research in implant dentistry. Despite the availability of various options, there is insufficient evidence to determine the most appropriate dental implant for use in cases of poor bone quality. The efficacy of a specific implant design in achieving optimal implant stability in cases of low bone density remains unclear. The key objective of this systematic review was to identify and evaluate scientific research to analyze the potential impact of implant macro-geometry, precisely implant shape and implant threads, on the primary stability of implants in low-density bone cases.

METHODS

Search Strategy

The systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA). The PICO question was constructed: in edentulous area with low bone density (P), what are the influences of dental implants (I) with different thread designs (C) on primary stability (O)?". Literature searches were performed in PubMed, Cochrane Library, and Scopus. Articles published from 2015 to 2024 were included. The PubMed search strategy, which was modified as appropriate to be used in other databases, is shown in Table 1. References of selected studies and related reviews for potentially relevant manuscripts were also included.

Table 1. Search strategy

Search	Query
#4	Search: #1 AND #2 AND #3 AND #4 Filters: in the last 10 years, English
#3	Search: ("bone density" OR "low bone density")
#2	Search: ("implant stability" OR "primary stability")
#1	Search: ("dental implant" OR "implant design" OR "implant geometry" OR "implant thread" OR "thread design" OR "thread geometry")

Eligibility Criteria

Manuscripts meeting the inclusion criteria were retrieved and screened through their full texts. The inclusion criteria were as follows: (1) in vitro and in vivo studies, (2) implant primary stability evaluated by ISQ, IT, or removal torque value, (3) comparing design thread in low bone density within the same study, and (4) published in English. The exclusion criteria were (1) finite element analysis, (2) case reports and review articles, (3) studies not reporting bone density and implant stability measures.

Study Selection and Data Extraction

Article selection was conducted by reviewing the titles and abstracts identified through electronic searches. All relevant papers were thoroughly assessed for inclusion. Articles were chosen based on their conformity to the inclusion criteria. Data extraction from the selected studies was performed by recording the following information: year of publication, first author, study design, implant system, number of each type of implant, type of bone, implant body and thread design, method of evaluation, and outcome.

RESULTS

Study Selection and Characteristics of the Included Studies

A total of 208 manuscripts were retrieved from the electronic literature search, including 139 articles from PubMed, 57 articles from Cochrane Library, and 12 articles from Scopus. After removing duplicate publications, reviewing the titles, abstracts, and keywords, and applying the inclusion/exclusion criteria, 16 manuscripts were eligible for further assessment. After complete text evaluation, 10 manuscripts were excluded. Finally, 6 manuscripts were included in this review. The flowchart diagram (Figure 1) summarizes the process of study selection. Table 2 provides an overview of the characteristics of eligible articles. Among the six included studies, all were in vitro studies. Two studies used low-density bovine bone, while the other four studies used low-density polyurethane bone blocks. The number of samples varied from 5 to 60 implants per group. Fourteen types of implants from nine different manufacturers were used. They presented different designs, and their dimensions varied from 3.75 to 4.5 mm in diameter and 10 to 13 mm in length. The most common parameters to measure the stability of an implant in this study were implant stability quotient (ISQ), insertion torque (IT), and removal torque (RTV). The ISQ value ranges from 54.45 to 78.17, the ITV range from 13.8 Ncm to 45.8 Ncm, and the RTV range from 12.4 Ncm to 16.01 Ncm.

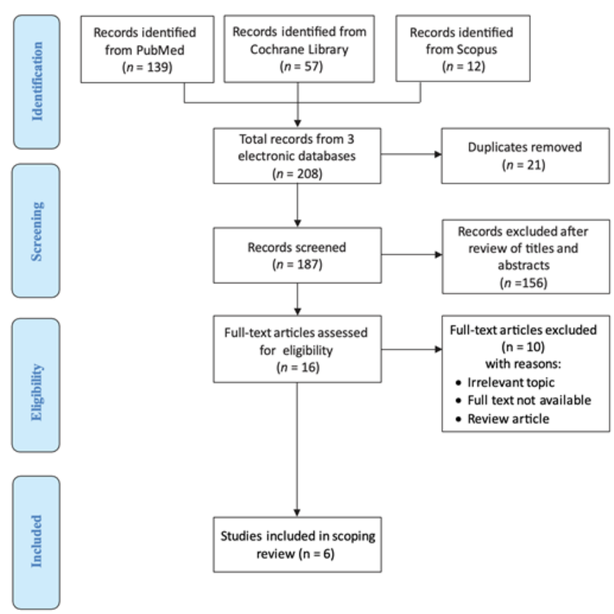

Figure 1. PRISMA flowchart summarizing the selection process of the systematic review.

DISCUSSION

Primary stability is a major concern in successful osseointegration and implant survival. The implant macro-geometry and bone quality are believed to be vital features affecting primary stability.[3,11,20] It is difficult to provide stability when implants are placed in low-density bone. Poor bone quantity and density are the primary risk factors for implant failure due to its correlation with excessive bone resorption and inadequate healing mechanisms.[21] Furthermore, studies have demonstrated that the bone density at the site where the implant is placed directly impacts IT and ISQ. Specifically, a decrease in local bone density is associated with a decrease in IT and ISQ values.[22] All of the selected studies in this research reported the type of implant used and its dimensions, but only four studies reported a comparison of primary stability between tapered and cylindrical implants.

Table 2. Characteristics of eligible manuscript

No	Author (Year)	Study Design	Sample Size	Implant System	The type of Bone Evaluated	Implant Macrogeometry	Method of Evaluation	Outcome
1.	Nokar, et al[35] (2019)	In vitro	5 implants per group	1. Zimmer Tapered Screw-Vent (Zimmer) 2. 2. Nobel Replace Tapered (Nobel Biocare) 3. Replace Select Tapered (Nobel Biocare) 4. Dentium Super Line (Dentium)	D4, polyurethane bone block	1. Tapered screw-vent implant (4.1 x 13), with V thread 2. Tapered implant (4.3 x 13), with square thread 3. Tapered implant (4.3 x 13), with square thread 4. Tapered implant (4.5 x 12), with reverse buttress thread and double thread	• Implant stability quotient (ISQ) • Insertion torque (ITV) • Removal torque (RTV)	• Nobel Replace Tapered implants have the highest value of ISQ (mean: 67), which is related to double thread design and square thread. • Dentium Super Line implant has the highest value of ITV (mean: 19 Ncm), which is related to double thread design. • Dentium Super Line implant has the highest value value of RTV (mean: 12.4 Ncm). • All systems had high ISQ, but ITV and RTV were low and not proper for immediate loading in D4 bone. • Dentium Super Line and Nobel Replace Tapered with higher ISQ and ITV are better choices in low bone density to prevent failures in the early healing period.
2.	Krischik, et al[40] (2021)	In vitro	11 implants per group	1. ICX Active Master Implant (Medentis Medical) 2. Conelog Progressive Line Implant (Camlog GmbH)	D4, bovine bone	1. Tapered implant (3.75 x 12.5), with square thread 2. Tapered implant (3.8 x 11), with buttress thread	• Implant stability quotient (ISQ)	• The highest ISQ value was found in ICX Active Master Implant (mean: 71,39). • The square thread design of the implants and under-dimensioned implant bed preparation are effective for better primary stability in cancellous bone.
3.	Degidi, et al[41] (2022)	In vitro	30 implants per group	1. DS Prime Taper (Dentsply) 2. 2. Astra Tech Osseospeed EV (Astra)	D3, bovine bone	1. Progressive tapered implant (4.2 x 11), with self-tapping thread 2. Cylindrical implant (4.2 x 13), with V thread	• Insertion torque (IT) • Implant stability quotient (ISQ)	• DS Prime Taper implant showed higher primary stability in low bone density based on IT values (mean: 39.1 Ncm). • Astra Tech implant has a slightly higher value of ISQ (mean: 78.17) than the DS Prime Tapered implant (mean: 77.22).
4.	Silva, et al[42] (2021)	In vitro	10 implants per group	1. Facility Implant (Neodent) 2. 2.Alvim CM Implant (Neodent)	D3-D4, polyurethane bone block	1. Parallel implant (2.9 mm x 12 mm), with buttress thread 2.Tapered implant (3.5 x 13 mm), with spiral-shaped thread	• Insertion torque (IT) • Implant stability quotient (ISQ)	• Alvim implant showed higher IT (mean: 45.20 Ncm) and ISQ (mean: 74.78) in low bone density. • A tapered implant with robust thread is an indication for cases of low bone density and lower cortical bone thickness.
5.	Sugiura, et al[12] (2020)	In vitro	60 implants per group	1. NobelReplace Straight Groovy (Nobel Biocare) 2. 2.NobelReplaced Tapered Groovy (Nobel Biocare)	Polyurethane bone block: 1. Low-density cancellous bone without cortical bone 2. Low-density cancellous bone with cortical bone 3. Low to medium-density cancellous bone without cortical bone 4. Low to medium-density cancellous bone with cortical bone	1. Cylindrical implant (4.3 x 10 mm), with V thread 2. Tapered implant (4.3 x 10 mm), with buttress thread	• Insertion torque (IT)	• Tapered implants shower significantly higher ITV (mean: 45.8 Ncm) than cylindrical implants in low to medium-density bone with the cortical layered. • Implant displacement of tapered implants was significantly smaller than cylindrical implants. • Tapered implants may be advantageous for improving primary stability in patients with low-density cancellous bone only when crestal cortical bone exists. • Implant stability depended mainly on the bone type, whereas implant design had a limited influence on primary stability.
6.	Comuzzi, et al[17] (2021)	In vitro	40 implants per group	1. Cyroth, AoN Implants 2. 2.Is-Four, AoN Implants	10 PCF polyurethane bone blocks (D4 bone density) with or without 1 mm cortical layer (30 PCF)	1. Cylindrical implant (4 x 10 mm) with reverse buttress thread 2. Tapered implant (4.2 x 10 mm) with V thread	• Insertion torque (IT) • Removal torque (RTV) • Implant stability quotient (ISQ)	• Tapered implants showed higher ITV in D4 bone with cortical layer (mean: 24.62 Ncm) and without cortical layer (mean: 13.80 Ncm). • Tapered implants showed higher RTV in D4 bone with cortical layer (mean: 16.01 Ncm) and without cortical layer (mean: 10.98 Ncm). • Tapered implants showed higher ISQ in D4 bone with cortical layer (mean: 62.35) and without cortical layer (mean: 54.45). • Tapered implants showed characteristics that could lead to clinical application in low-density posterior maxillary sites, even with a drastically decreased bone cortical component.

The findings of this study suggest that under experimental conditions on low bone density, tapered implants were found to have better primary stability than cylindrical implants. In cylindrical implants, the force load is distributed throughout the implant through the parallel walls of the cylindrical implant. However, in a tapered geometry, the force is diverted from the dense cortical bone to the more resilient trabecular bone area, leading to higher forces at the apex. In addition, the tapered implant allows for more lateral compression and stiffness and more favorable compressive forces during placement, improving primary stability in low-density bone.[1,23]

The implants used in this study varied from 3.75 to 4.5 mm in diameter and 10 to 13 mm in length. In addition to implant body shape, other factors such as implant length and diameter also play an essential role in obtaining primary stability.[24] Wider and longer implants generally provide better primary stability due to their increased surface area in contact with the bone and are particularly beneficial in low-density bone, where longer implants can provide better anchorage. A study conducted by Qiu et al. concluded that the diameter of dental implants is more important than implant length in reducing bone stress distribution and improving implant stability under static and immediate loading conditions.[25] Previous studies have shown that implants with a diameter of 5 mm exhibit higher primary stability values compared to those with a diameter of 4 mm, especially in low-density bone.[26] Another study conducted by Li et al. concluded that dental implants with a diameter of 4 mm and a length of 9 mm were the best choice for a screwed implant in Type IV bone.[27]

Two of the studies included in this research, Sugiura et al.[12] and Commuzzi et al.[17] demonstrated the relationship between cortical bone and primary stability. They concluded that the presence of cortical bone considerably enhances primary stability, particularly for tapered implants. However, tapered implants may not show the same level of stability as cylindrical implants in low-density cancellous bone without a cortical layer. A study conducted by Prado et al., which evaluated the possible role of cortical bone and implant design in achieving the stability of dental implants, concluded that the presence of cortical bone significantly enhances the primary stability of dental implants.[28] Studies have shown that implants placed in areas with cortical bone exhibit higher insertion torque and better resonance frequency analysis (RFA) values compared to those without cortical bone. Cortical bone provides a mechanical locking mechanism that helps maintain the implant's initial stability. The macro-geometry of the implant, particularly the thread design, also plays a role in this mechanical locking, contributing to the primary stability.[29]

The primary stability of implants is measured by a non-invasive clinical method, such as insertion torque (IT) and implant stability quotient (ISQ). Previous studies have shown that IT values in the 30 to 35 Ncm range correspond to higher rates of new bone growth and increased bone-to-implant contact in low-density bone.[40] ISQ values above 70 are considered ideal for clinical success for single-stage loading of single implants. Furthermore, ISQ values indicate a favorable level of mechanical stability for an implant.[22,31]

In this study, the ISQ value ranged from 54.45 to 78.17 and was higher in implants with square threads. Implant threads are added to maximize initial contact, enhance primary stability and insertion torque, increase the implant's surface area, and increase stress distribution on the interfacial surface. The implant thread converts complex occlusal loads into favorable compressive loads at the bone interface.[32] Implant thread shape has been found to influence the type of force transferred to the surrounding bone. The thread shapes consist of a V-shape, square shape, buttress, and reverse buttress. In square and buttress threads, the axial force is mainly distributed as compressive force, while V-shaped and reversed buttress threads transmit axial force through a combination of compressive, tensile, and shear forces.[33,34]

In addition to the thread shape, other thread design features, such as thread pitch, also affect implant stability. Thread pitch refers to the distance between the center of one thread and the center of the next thread, measured in a parallel direction to the axis of the screw. The impact of thread pitch on implant design factors is significant primarily because it directly affects the surface area. Prior studies have demonstrated that a decrease in pitch results in an increase in surface area, which in turn improves stress distribution. Moreover, stress is more sensitive to thread pitch in cancellous bone than cortical bone.[35]

In one of the studies in this research, the highest IT value was found in double-threaded implants.[36] Thread length and the increased surface area of double-threaded implants contribute to higher insertion torque values than single-threaded implants. Double-threaded implants can positively affect the speed and stability of insertion and thus can be implanted faster than single-threaded implants. A study using an artificial bone model found that double-threaded implants with a 0.6-mm pitch reached maximum torque twice as fast as single-threaded implants with a 1.2-mm pitch. However, higher torque values in double-threaded implants can improve primary stability but also increase the risk of bone damage if excessive.[37]

For immediate loading of an implant, double- and triple-threaded implants are used, and the increased surface area provides greater primary stability.[38] IT value is correlated with implant micromotion. Trisi et al. [39] showed that the maximum IT value in low-density bone could be 35 N/Cm. Each 10 N/Cm increase in IT value decreases the micromotion by about four microns.[36]

This study has several limitations. Among the six included studies, all were in vitro studies that used polyurethane bone blocks or bovine bone to evaluate primary stability. Moreover, the present study only considered the effects of implant shape and implant thread on low bone density, while other factors, such as implant placement techniques, implant diameter, implant length, and surface characteristics, were not considered. Future studies should consider these factors for a more comprehensive understanding of implant biomechanics on poor bone quality.

CONCLUSION

The design parameters of implants, such as the implant body shape and the threads design, directly impact the implant treatment outcomes. Implant therapy can be considered for patients with low bone density if specific precautions are taken. Research indicates that modifying the shape of the implant body, particularly by using a tapered shape instead of a conical shape and using a square thread instead of a V-thread, significantly affects the implant's primary stability in low bone density. It has become apparent that implant shape and thread geometry are critical parameters when designing new implant designs.

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