Effects of Implant Diameter on Implant Stability and Osseointegration in the Early Stage in a Dog Model

Yuning Wang, MDS[1]/Haicheng Wang, PhD[1]/Xiaofan Chen, MDS[1]/Ying Shi, MDS[1]/Zuolin Wang, MD, DDS, PhD[1]

Purpose: To determine the optimal implant diameter under limited bone width by comparing the effects of implants with different diameters on implant stability, peri-implant bone stability, and osseointegration. In addition, to evaluate the reliability of resonance frequency analysis (RFA) in detecting osseointegration and marginal bone level (MBL). ***Materials and Methods:*** Mandibular premolars and first molars of seven beagle dogs were extracted. After 8 weeks, their mandibular models and radiographic information were collected to fabricate implant templates. Implant sites were randomly divided into three groups according to diameter: Ø3.3, Ø4.1, and Ø4.8 mm. Implant stability quotient (ISQ) measurement and radiographic evaluation were performed after surgery (baseline) and at 4, 8, and 12 weeks. Three dogs were euthanized at 4 weeks to observe osteogenesis and implant-tissue interface biology. Four dogs were euthanized at 12 weeks to observe osseointegration. Hard tissue sections were prepared to analyze osteogenesis (fluorescence double labeling) and osseointegration (methylene blue–acid fuchsin staining). ***Results:*** At baseline and at 4, 8, and 12 weeks, the ISQ values of Ø4.1- and Ø4.8-mm implants did not differ ($P > .05$), but both had higher values than the Ø3.3-mm implants ($P < .05$). The mean marginal bone resorption (MBR) associated with Ø3.3-, Ø4.1-, and Ø4.8-mm implants was 0.65 ± 0.58 mm, 0.37 ± 0.28 mm, and 0.73 ± 0.37 mm, respectively. The buccal MBR of Ø4.8-mm implants was significantly higher than that of Ø4.1-mm implants ($P < .05$). The bone-to-implant contact (BIC) percentage at 12 weeks did not differ for any group ($P > .05$). The correlation coefficients between the ISQ and MBL of the Ø3.3-, Ø4.1-, and Ø4.8-mm implants were –0.84 ($P < .01$), –0.90 ($P < .001$), and –0.93 ($P < .001$), respectively, while that between the ISQ and BIC was 0.15 ($P > .05$). ***Conclusions:*** During the early healing stage, the performance of Ø4.1- and Ø4.8-mm implants in terms of implant stability was better than that of Ø3.3-mm implants. Implant diameter may not influence BIC percentage. RFA can be used to evaluate implant stability and MBL but is not suitable to assess the degree of osseointegration. *Int J Oral Maxillofac Implants 2023;38:757–767. doi: 10.11607/jomi.10089*

Keywords: dental implants, diameter, implant stability, osseointegration, resonance frequency analysis

Dental implants have become the gold standard therapy for partially and totally edentulous patients.[1] Osseointegration, a direct and functional connection between ordered living bone and the surface of a load-bearing implant, is vital for implant success.[2,3] A common parameter to estimate osseointegration is bone-to-implant contact (BIC) percentage, and when an implant is osseointegrated, approximately 60% to 70% of the implant surface is in contact with the bone.[4–6] The assessment of osseointegration in the clinical setting is dependent on radiologic analysis (marginal bone stability) and mechanical criteria (implant stability).[7,8] To achieve successful osseointegration, it is essential to guarantee primary mechanical stabilization of the dental implants.[7,9,10] Well-established primary stability after implantation lays a solid foundation for future secondary stability (ie, biologic stability) and dictates the functional load capacity.[6,11]

Tools and methods to assess implant stability can be divided into three types: traditional clinical methods (eg, percussion and radiography), vibration analysis (eg, Periotest and resonance frequency analysis [RFA]), and torque testing (eg, insertion torque [IT] and reverse torque).[12] Among these, RFA has been most extensively used.[13] The Osstell ISQ device, representative of modern RFA devices, uses a SmartPeg to measure the resonance frequency of implant-bone systems and convert the peak amplitude of response into a parameter called the implant stability quotient (ISQ).[14–16] However, the reliability of RFA to identify implant stability and osseointegration remains controversial.[17–19] It seems that RFA is more affected by the implant location and has low sensitivity to the degree of osseointegration.[17] Bone

[1]Department of Oral Implantology & Department of Oral and Maxillofacial Surgery, Stomatological Hospital and Dental School of Tongji University, Shanghai Engineering Research Center of Tooth Restoration and Regeneration, Shanghai, China.

Correspondence to: Dr Zuolin Wang, Department of Oral Implantology & Department of Oral and Maxillofacial Surgery, Stomatological Hospital and Dental School of Tongji University, Shanghai Engineering Research Center of Tooth Restoration and Regeneration, No. 399 Middle Yanchang Rd, Shanghai 200072, China. Email: zuolin@tongji.edu.cn

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architecture, rather than osseointegration, is the main factor influencing implant stability.[20]

Local bone density and thick cortical bone contribute to primary implant stability.[21,22] An increase in cortical bone thickness at the ridge or 3 mm below the ridge (buccal or lingual side) can boost IT and implant stability.[23] Cortical bone anchorage correlates with high IT values, and bicortical anchorage is frequently applied in maxillary sinus floor elevation or during immediate loading of implants to increase primary stability.[24] While cortical bone is essential for implant stability, trabecular bone is considered to be more relevant to peri-implant bone healing.[25]

Implant designs, at both the macro and micro levels, are vital to the osseointegration and mechanical interlocking of the implant-bone interface.[26–28] *Microstructure* refers to the surface morphology of the implant, which is related to bone remodeling at the implant-bone interface.[29] Macrostructure (eg, implant thread, length, and diameter) determines primary stability and peri-implant bone stress distribution.[28] Implant diameter seems to have a greater effect than length on primary implant stability and occlusal force transfer to the bone.[6,30] Total implant surface area increases approximately 20% to 30% for every 1-mm increase in diameter, and a greater surface leads to a more diluted force distribution and less stress on the crestal bone.[6,8,31] Selection of the appropriate implant diameter is fundamental and must match diverse alveolar bone conditions.[32] A suitable implant diameter should not only guarantee ideal implant stability but also favor bone remodeling.

Osteogenesis occurs approximately 4 weeks after implant placement, and it is a repair period in which bone resorption and apposition occur simultaneously.[33,34] The newly formed bone is further modified, and a dense and orderly lamellar structure can be observed along the implant surface at 12 weeks.[33,35] These two periods (4 and 12 weeks) are crucial for osseointegration in the early stage. In the present study, histologic observations were performed at 4 and 12 weeks to evaluate osteogenesis and osseointegration.

A considerable amount of clinical and in vitro research has investigated the independent effect of different diameters on implant stability, marginal bone stability, and osseointegration, whereas few studies have investigated their relationships in vivo.[36–38] To compare the behaviors of different implant diameters on implant stability, marginal bone stability, and osseointegration, implant surgical templates for dogs were fabricated so implant conditions would be as consistent as possible. Three frequently used implant diameters were selected as study objects: Ø3.3 mm (narrow diameter), Ø4.1 mm (standard diameter), and Ø4.8 mm (wide diameter). To monitor the changes in implant stability, ISQ values were recorded every 4 weeks. In addition, the reliability of RFA to detect osseointegration and marginal bone level (MBL) was evaluated.

MATERIALS AND METHODS

According to ARRIVE guidelines, this animal study was approved by the review board of the Affiliated Stomatology Hospital of Tongji University. Seven healthy beagle dogs (age: 12 to 18 months; mean weight: 13.2 kg) were selected and raised in Shanghai Jiagan Biotechnology (environmental temperature: 20 ± 2°C; humidity: 55 ± 5%). Implants (Bone Level Implants SLA, Straumann) with diameters of Ø3.3, Ø4.1, and Ø4.8 mm were donated by Shanghai Sichuan Medical Instruments.

Experimetzal Design

A flowchart of the experimental design is presented in Fig 1a. The concrete experimental design and implant distribution were as follows.

Histologic Observation Rime—4 Weeks

Three dogs were euthanized at 4 weeks after implant placement to observe osteogenesis and the implant-tissue interface biology. Each dog received two implants on each side of the posterior mandible. There were 12 implant sites in total, with three different diameters randomly distributed. Clinical observation (ISQ and CBCT measurements) was performed after implant placement (baseline) and at 4 weeks.

Histologic Observation Time—12 Weeks

Four dogs were euthanized at 12 weeks to observe osseointegration. Each dog received eight implants, except for one dog with inadequate alveolar bone that received two implants. The number of Ø3.3-, Ø4.1-, and Ø4.8-mm implants was 8, 10, and 8, respectively. Clinical observation (ISQ and CBCT measurements) was performed at baseline and at 4, 8, and 12 weeks.

Fabrication of the Implant Surgical Templates

Surgical extractions of the mandibular premolars and first molars were performed on beagle dogs under general anesthesia induced by ketamine/xylazine. After 8 weeks, all dogs underwent CBCT to ensure healing of the extraction sites. Impressions of the mandibular arches were made using silicone rubber impression material (Silagum Putty, DMG Dental) and personalized resin trays. The stone casts fabricated from silicone impressions were scanned by a 3D scanner (Open Technologies) then converted to surface tessellation language (STL) data (Fig 1b). Additionally, CBCT data were transformed into Digital Imaging and Communications in Medicine (DICOM) format. DICOM and STL data were imported and matched together in the implant guide design software (RealGuide, 3Diemme). Areas with

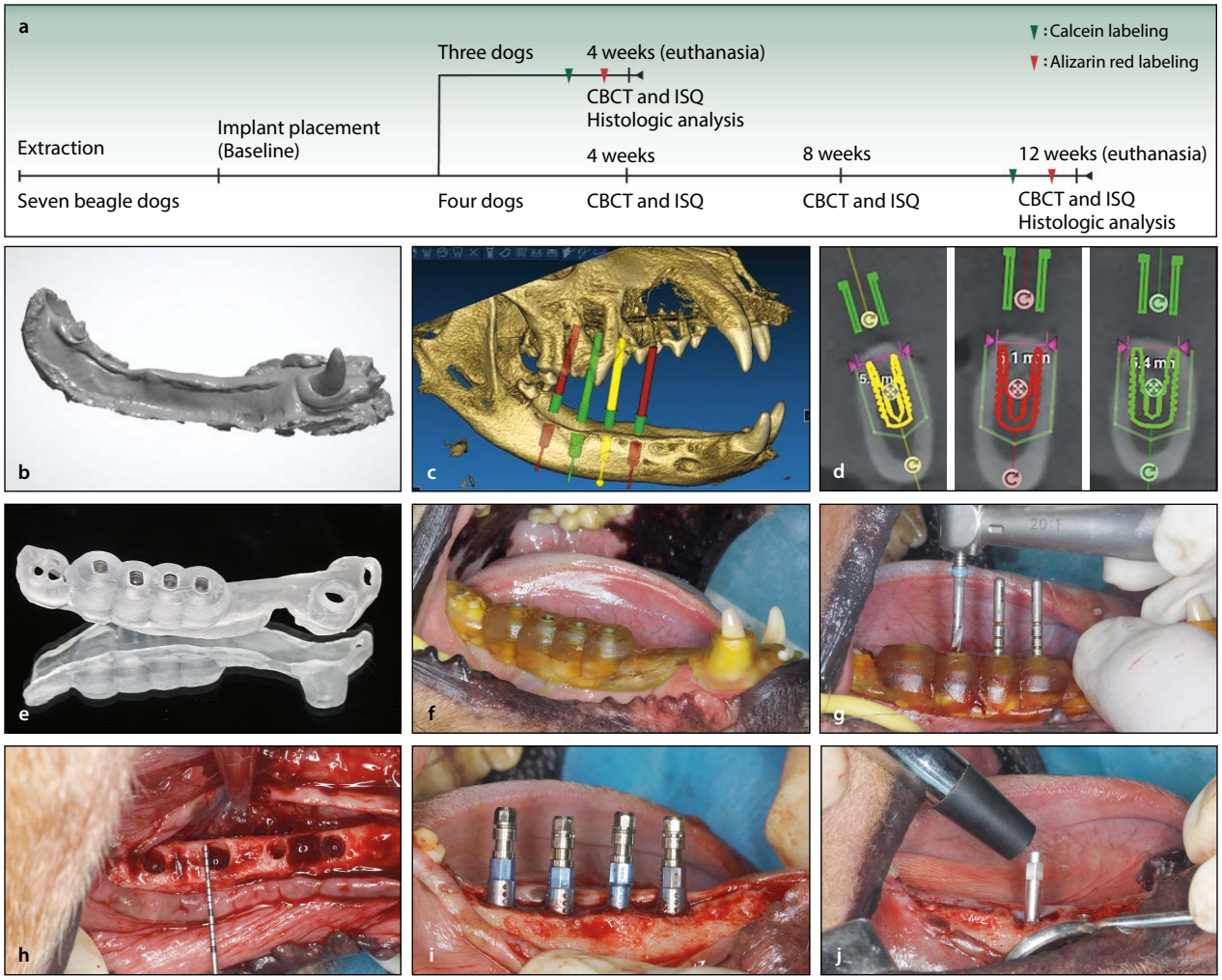


Fig 1 Experimental design and implant surgery procedures. *(a)* Flowchart of the experimental design. *Green triangles:* injection of calcein 14 days before euthanasia; *red triangles:* injection of alizarin red 4 days before euthanasia. *(b)* Model scanning. *(c and d)* Virtual design of implant sites. *Yellow:* Ø3.3-mm implants; *red:* Ø4.1-mm implants; *green:* Ø4.8-mm implants. The safe distance (*green outline border*) was set to 1 mm. *(e)* Implant surgical template. *(f)* Buccal side of the implant surgical template in the mouth. *(g)* Implant osteotomies. *(h)* Bone width was measured using a periodontal probe. *(i)* Placement of implants. *(j)* ISQ measurement.

similar bone width were selected as implant sites, and implants were virtually located at their optimal implant sites (Figs 1c and 1d). Individually customized implant surgical templates that contained four guide sleeves were manufactured by a 3D printer (Fig 1e).

Implant Surgery Procedure

Dogs under general (ketamine/xylazine) and local (lidocaine) anesthesia underwent implant surgery, which was performed with the assistance of the implant surgical template (Figs 1f and 1g). After sequential drilling, an incision was made, and full-thickness flaps were raised. The alveolar bone was trimmed by an osteotomy drill, and implants were subsequently placed (Figs 1h and 1i). Each implant was placed with a healing abutment torqued to 25 Ncm that did not exceed 35 Ncm. Implants that had poor IT were placed with a low-profile cover screw. Flaps were sutured by interrupted suture, and sutures were removed 10 days later. All dogs received analgesics and antibiotics for 5 days.

Resonance Frequency Analysis

Implant stability was assessed by an Osstell ISQ device according to the manufacturer's instructions at baseline and every 4 weeks after surgery (Fig 1j). The final ISQ of an implant was the average of recorded values in four directions (mesial, distal, buccal, and lingual).[39] For implants with soft tissue coverage, the position of the implant was partially visible through the thin mucosa; it could also be detected by a probe.

Radiologic Analysis

Each beagle dog underwent CBCT imaging (Accuitomo, J Morita) at baseline and every 4 weeks after surgery.

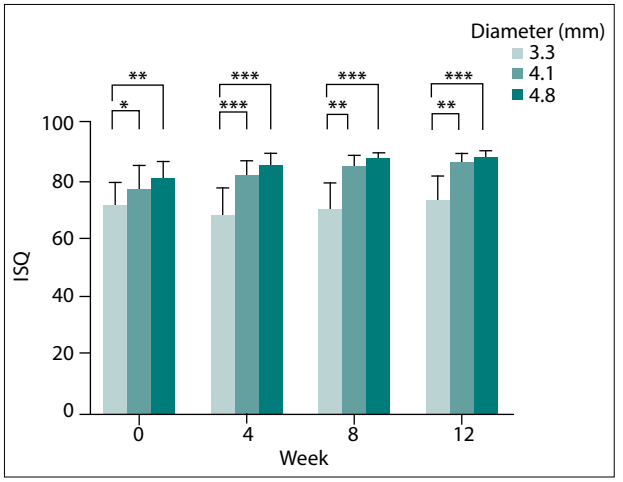


Fig 2 Influence of implant diameter on ISQ. *$P < .05$, **$P < .01$, ***$P < .001$.

The operating voltage was 90 kV, the current 3.0 mA, and the exposure time 17.5 seconds. The primary slice thickness was 1 mm, and a 0.5-mm slice increment was used. The MBL was the distance between the most coronal BIC and the implant platform level.[40] Marginal bone resorption (MBR) was the distance between the peri-implant bone level at implant placement and the peri-implant bone level at 12 weeks. The mean MBR was the average of MBR values in four directions (buccal, lingual, mesial, and distal) and so was the mean MBL. The residual bone thickness (buccal/lingual) of implants at baseline was measured at 1 mm below the alveolar crest. The measurements were performed by image analysis software (Image-Pro Plus 6.0, Media Cybernetics).

Fluorescence Double Labeling

To observe dynamic bone remodeling of implants, calcein (C0875, Sigma-Aldrich) and alizarin red (A3882, Sigma-Aldrich) solutions were injected subcutaneously into the necks of the beagle dogs 14 and 4 days before euthanasia, respectively. The injection concentrations of calcein and alizarin red solutions were 20 mg/mL and 10 mg/mL, respectively. The doses of calcein and alizarin red solutions were 10 mg/kg and 20 mg/kg, respectively. The dilution solution was 0.9% NaCl containing 2% $NaHCO_3$. The pH of the dyes was adjusted to 7.4, after which they were filtered into sterile containers by Millipore filters. Before use, dyes were stored at 4°C. Tissue sections were observed under a laser confocal microscope (Nikon). The mineral apposition rate (MAR) was calculated by dividing the distance from the outer edge of red fluorescence to the outer edge of green fluorescence by the injection time interval of these two drugs.

Morphometric Analysis

According to the group allocation, dogs were euthanized at 4 and 12 weeks after implant surgery. The mandibles of the beagle dogs were removed, and tissue specimens containing implants were fixed in 4% formaldehyde for 24 hours. After an ascending series of alcohol dehydration, the undecalcified specimens were embedded in light-curing resin (Technovit 7200 VLC, Kulzer). Blocks were sectioned buccolingually, and tissue sections were ground (Ekakt) to approximately 50 µm.

After collecting the confocal images, histologic sections were stained with methylene blue–acid fuchsin (DB0088, Leagene) and observed under a light microscope (Nikon). Full views of the implants were observed under a stereoscopic microscope (Zeiss). The area between two adjacent implant threads was regarded as the region of interest (ROI). Image analysis software (Image-Pro Plus 6.0, Media Cybernetics) was used to quantify the following parameters:

1. BIC (%): BIC was calculated by dividing the total length of the implant surface in direct contact with the bone by the whole implant perimeter.[1]
2. Bone volume fraction (BV/TV, %): BV/TV was determined as the average percentage of bone present in the ROI.[41]

Statistical Analysis

All measurement data are expressed as mean ± SD. Shapiro-Wilk test was used to assess data with a normal distribution. Homogeneity of variance was also assessed using Levene test. If data did not conform to normal distribution or homoscedasticity, a nonparametric test (Kruskal-Wallis) was used to evaluate the statistical differences of intra- and intergroup data (ISQ, MBR, MAR, BIC, and BV/TV). Spearman correlation coefficient (ρ) was used to evaluate the correlation between MBR and residual bone thickness as well as the correlation between ISQ and BIC. Pearson correlation coefficient (r) was used to evaluate the correlation between ISQ and MBL. Statistical analysis was performed by SPSS version 26.0 (IBM). $P < .05$ was regarded as statistically significant.

RESULTS

Three implants (1 of each diameter) of a dog whose observation time was 4 weeks showed fibrous healing and were excluded from the analysis. All other implants achieved good osseointegration.

Table 1 Average Bone Width, Marginal Bone Resorption (MBR), Residual Bone Thickness, and Correlation between MBR and Residual Bone Thickness (Spearman's Correlation Coefficient)

	Implant diameter (mm)						Correlation between MBR and residual bone thickness	*P* value
	3.3		4.1		4.8			
Bone width (mm)	5.20 ± 0.37		5.55 ± 0.41		5.83 ± 0.42			
	Buccal	Lingual	Buccal	Lingual	Buccal	Lingual		
Residual bone thickness (mm)	0.87 ± 0.49	0.95 ± 0.40	0.82 ± 0.29	1.24 ± 0.44	0.59 ± 0.32	1.33 ± 0.35	0.72	*P* < .001
Mean MBR (mm)	0.65 ± 0.58		0.37 ± 0.28		0.73 ± 0.37			

Data are expressed as mean ± SD.

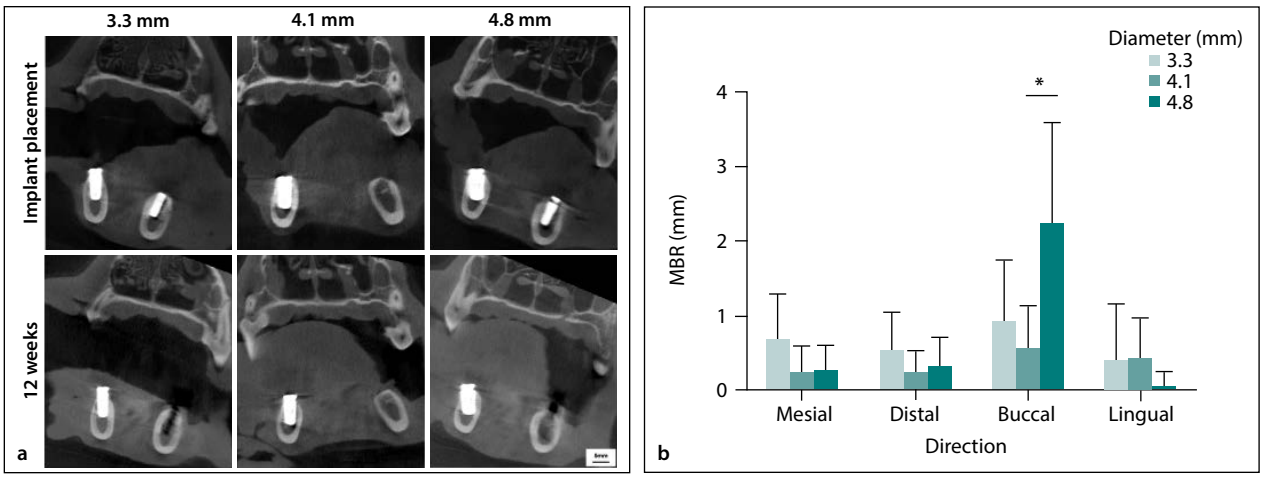


Fig 3 Radiologic analysis. *(a)* CBCT images of implants in cross-sectional views. *(b)* MBR of Ø3.3-, Ø4.1-, and Ø4.8-mm implants in four directions (mesial, distal, buccal, and lingual). *$P < .05$.

Influence of the Implant Diameter on Implant Stability

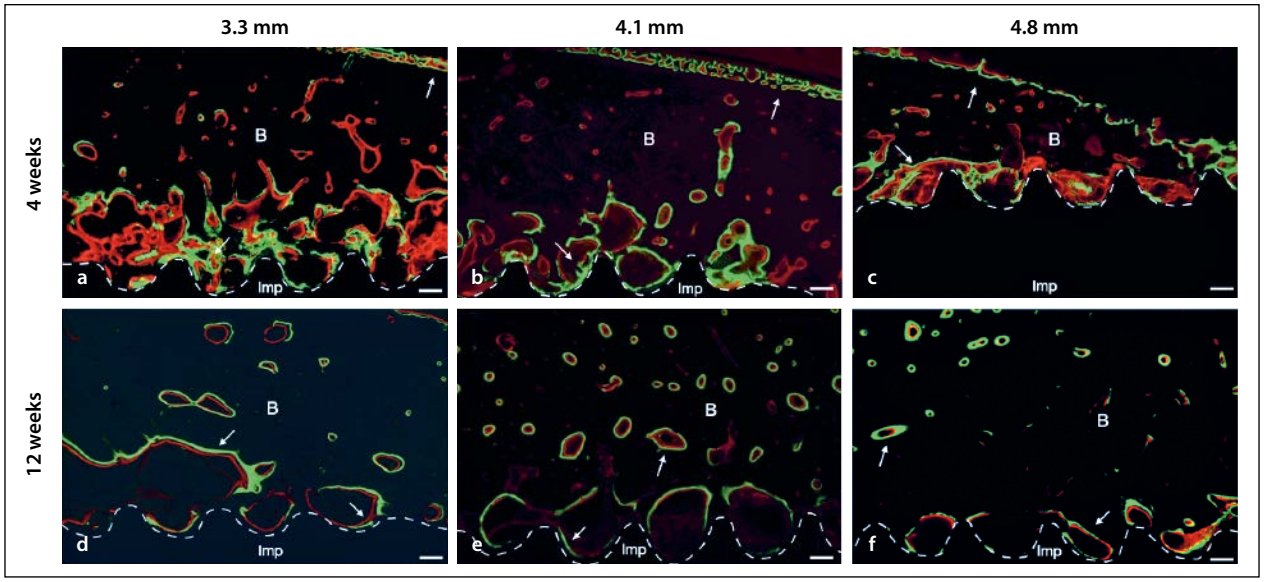
Preoperative CBCT scans showed type II bone at implant sites, which was related to ideal primary stability. The primary ISQ values of the Ø3.3-, Ø4.1-, and Ø4.8-mm implants were 71.67 ± 2.21, 77.50 ± 2.09, and 80.55 ± 1.77, respectively. Throughout the observation period, ISQ values increased except for a slight decrease for Ø3.3-mm implants at 4 weeks after surgery. For the final measurement (at 12 weeks), ISQ values of Ø3.3-, Ø4.1, and Ø4.8-mm implants reached 73.38 ± 2.77, 86.40 ± 0.83, and 88.25 ± 0.65, respectively. At baseline and every 4 weeks after surgery, the ISQ value of Ø3.3-mm implants was significantly different compared to that of Ø4.1- and Ø4.8-mm implants ($P < .05$), but there was no significant difference between ISQ values for Ø4.1- and Ø4.8-mm implants ($P > .05$; Fig 2).

Influence of the Implant Diameter on Peri-implant Bone Stability

Postsurgical CBCT images showed that all implants were in ideal positions. After 12 weeks of healing, implants achieved good osseointegration (Fig 3a). The mean bone width (buccolingual) values of Ø3.3-, Ø4.1, and Ø4.8-mm implants were 5.20 ± 0.37 mm, 5.55 ± 0.41 mm, and 5.83 ± 0.42 mm, respectively. The residual bone thickness and mean MBR values of all implants are presented in Table 1. The MBR increased gradually with the decrease of residual bone thickness at 1 mm below the alveolar crest ($P < .001$). Because of the thinner residual bone thickness, the buccal MBR of Ø4.8-mm implants was significantly higher than that of Ø4.1-mm implants ($P < .05$; Fig 3b).

Influence of the Implant Diameter on Osteogenesis and Osseointegration

The confocal imaging system showed dynamic bone remodeling of implants, which was labeled by calcein and alizarin red fluorescence. The fluorescent labels represented the deposition of mineralized matrix at the injection time. At 4 weeks, there were intensive green and red fluorescent labels close to the implant surface and subperiosteal cortical bone, indicating active mineralization surrounding the implant and periosteum (Figs 4a to 4c). At 12 weeks, fluorescent labels were concentrated in the surrounding alveolar bone and were



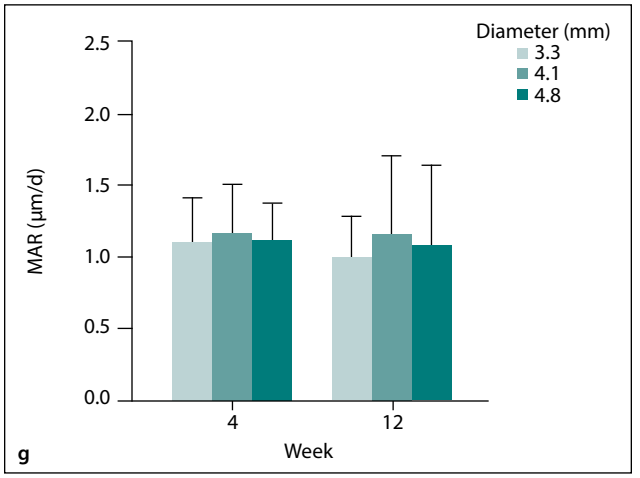


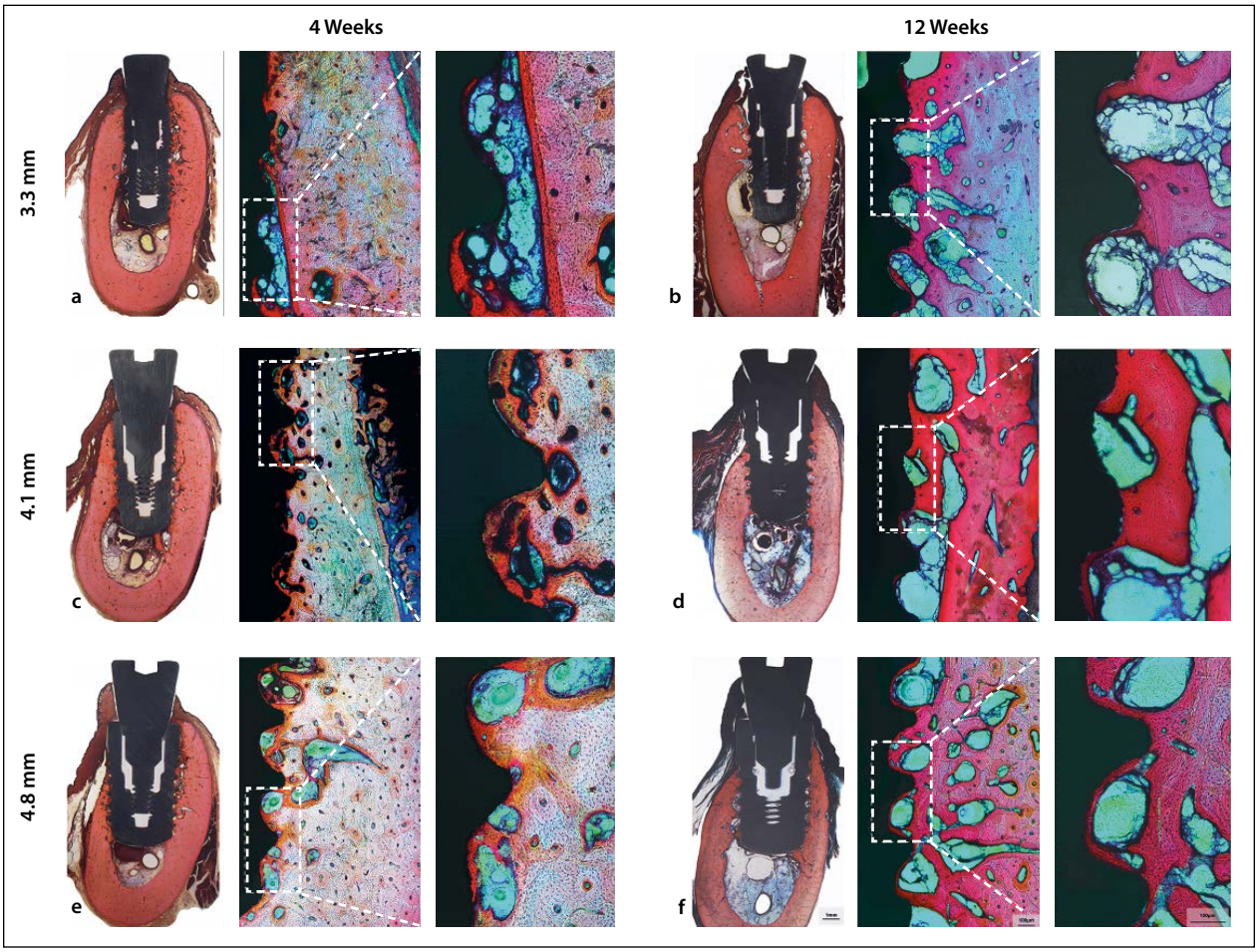
Fig 4 Influence of implant diameter on bone mineral apposition rate (MAR). *(a to f)* Fluorescence double labeling, B: bone; Imp: implant. The *white arrows* depict active bone mineralization; the *white dotted lines* identify the boundaries of implants. *(g)* MAR of Ø3.3-, Ø4.1-, and Ø4.8-mm implants at 4 and 12 weeks.

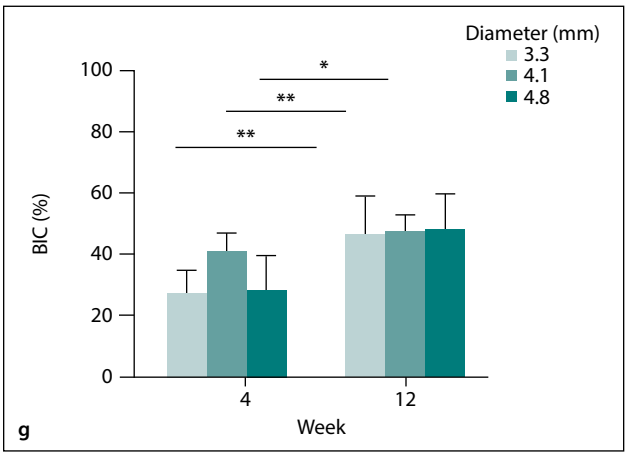
less visible on the implant surface (Figs 4d to 4f). There was no significant difference in MAR between the three implants at 4 and 12 weeks ($P > .05$; Fig 4g).

At 4 weeks, new bone formation was observed on the implant surface, as indicated by methylene blue–acid fuchsin staining. The trabecular structure of woven bone connected the original bone and implant surface. There was an obvious boundary between new forming bone (orange red) and original bone (light red; Figs 5a, 5c, and 5e). At 4 weeks, the BIC values of Ø3.3-, Ø4.1-, and Ø4.8-mm implants were 27.75% ± 6.62%, 40.84% ± 5.84%, and 28.50% ± 10.72%, respectively. With the increase of bone mineral density, implants contacted the mature bone tissue directly (Figs 5b, 5d, and 5f). At 12 weeks, implants achieved good osseointegration, and the BIC values of Ø3.3-, Ø4.1-, and Ø4.8-mm implants reached 46.91% ± 12.48%, 47.72% ± 5.22%, and 48.51% ± 11.43%, respectively, which were higher than the BIC values at 4 weeks ($P < .05$). There was no statistical difference in BIC and BV/TV values at 4 or 12 weeks among the three implants (Figs 5g and 5h). The BV/TV value of Ø3.3-mm implants at 12 weeks was higher than that at 4 weeks ($P < .01$; Fig 5h).

Correlations of the ISQ with MBL and BIC

The correlation between ISQ and mean MBL in four directions (buccal, lingual, mesial, and distal) was analyzed at 12 weeks, and strong negative correlations were observed among all three implants. The correlation coefficient between ISQ and MBL of the Ø3.3-, Ø4.1, and Ø4.8-mm implants were –0.84 ($P < .01$), –0.90 ($P < .001$), and –0.93 ($P < .001$), respectively (Fig 6a). The decrease of ISQ values was related to the descending crestal bone. The most rapid change in ISQ values was observed with Ø3.3-mm implants, whereas the slowest change was observed with Ø4.8-mm implants. There was no correlation between ISQ values and BIC ($\rho = 0.15$, $P > .05$; Fig 6b).





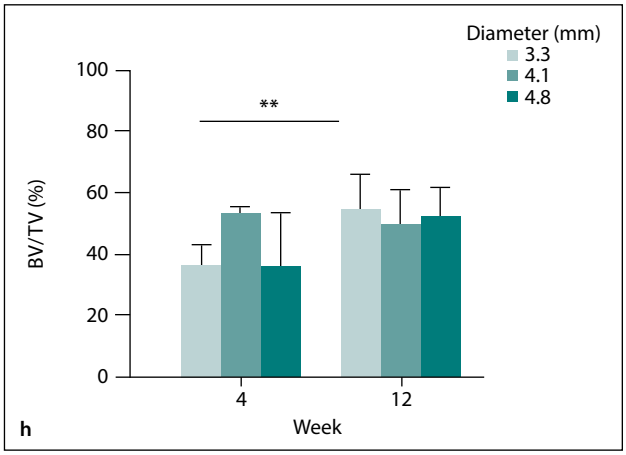


Fig 5 Influence of implant diameter on osseointegration. *(a to f)* Representative methylene blue–acid fuchsin histologic sections of Ø3.3-, Ø4.1-, and Ø4.8-mm implants at 4 and 12 weeks. *Left:* overall view of implants; *middle:* ×40 magnification; *right:* ×100 magnification. BIC *(g)* and BV/TV *(h)* assessment of Ø3.3-, Ø4.1-, and Ø4.8-mm implants at 4 and 12 weeks. *$P < .05$, **$P < .01$.

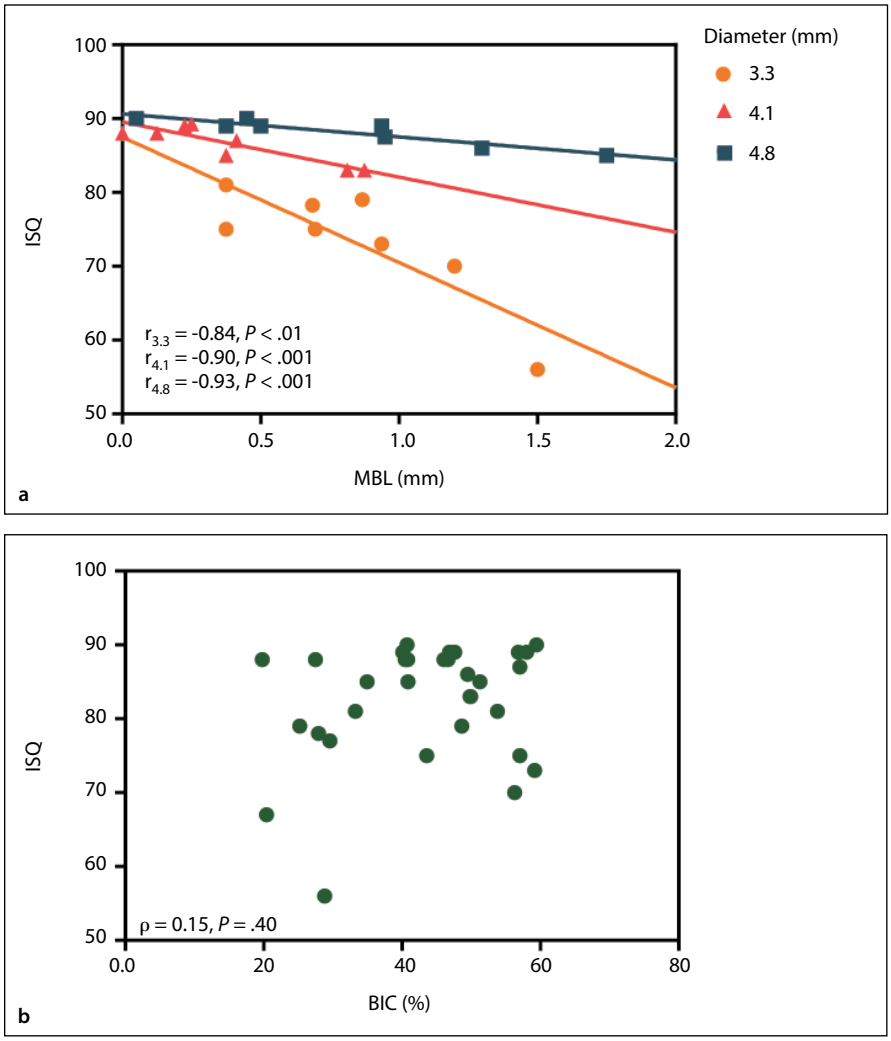


Fig 6 Correlations of ISQ with MBL and BIC. *(a)* Correlation between ISQ and mean MBL at 12 weeks. *(b)* Correlation between ISQ and BIC.

DISCUSSION

Correlations among implant diameter, implant stability, and osseointegration have been controversial.[42–44] While a wider implant achieves a greater implant surface, which increases implant stability and BIC, it can also invade the original bone, which increases the risk of MBR.[6] Therefore, the behaviors of implants with different diameters on implant stability, marginal bone stability, and osseointegration should be comprehensively considered when choosing the optimal implant diameter.

In the present study, most implants achieved high primary stability, which may be related to the thick cortical bone of dogs. Regarding healing of the surrounding bone, the ISQ of Ø3.3-mm implants placed in cancellous bone temporarily decreased at 4 weeks. From implant placement to 12 weeks, ISQ values of Ø3.3-mm implants were always lower than those of Ø4.1-mm and Ø4.8-mm implants, and there was no statistical difference between ISQ values in Ø4.1-mm and Ø4.8-mm implants, which was consistent with the findings of a previous clinical study.[45] The lack of difference in ISQ values between Ø4.1-mm and Ø4.8-mm implants may be related to the cortical bone placement of implants. The stiffness of the implant-bone interface was crucial in determining the ISQ values.[36]

Once osseointegration of an implant begins, the diameter is no longer the dominant factor influencing implant stability.[46] However, the implant diameter significantly influences strain level and strain concentration of the alveolar crestal bone, and wider-diameter implants may exert excessive pressure on the buccal alveolar crestal bone.[47] A 1-mm increase in diameter leads to a decrease in crestal bone level of approximately 0.11 mm.[48] Compared to standard implants, wide-diameter implants have an excellent survival rate with lessened MBL.[29] In the present study, postoperative

CBCT scans at 12 weeks showed various degrees of crestal bone resorption associated with most implants; this was related to the impact of the maxillary molar teeth of dogs. Among the three implant diameters, the Ø4.8-mm implants had the thinnest residual bone thickness, which generated the greatest MBR. When the available alveolar bone was adequate, narrow implants behaved better than wide implants in terms of maintaining the surrounding bone mass and reducing the risk of gingival recession.[49]

At the beginning of the osseointegration process, osteoblasts from the trabecular bone and inner surface of the cortex migrate to the implant surface.[50] After 1 week, a thin layer of osteoid forms along the implant and immature bone tissue is deposited along the original bone and implant surface.[51] The immature bone matrix and bone lining cells together serve as the ossification center, and osteogenesis can occur simultaneously on the implant surface (direct osteogenesis) and bone margin (distant osteogenesis).[52] In the present study, double fluorescence staining showed active bone formation along the implant thread surface and distal subperiosteal cortical bone at 4 weeks, which confirms that osteoblasts migrate from the trabecular bone and subperiosteal cortical bone. Methylene blue–acid fuchsin staining of implants showed immature woven bone along the edge of the implant thread, and the direction of osteogenesis extended from the surrounding bone tissue to the implant surface, which was consistent with the findings of a previous study.[53]

With bone remodeling, woven bone gradually deposits and transforms into lamellar bone, and the mechanical stability of implants is gradually replaced by biologic stability.[54] In the present study, mature bone tissue was in direct contact with the implant at 12 weeks, as observed under microscopy. Osseointegration was time dependent, and the BIC values of Ø3.3-, Ø4.1-, and Ø4.8-mm implants at 12 weeks were higher than those at 4 weeks. The BIC values among Ø3.3-, Ø4.1-, and Ø4.8-mm implants showed no significant differences at 4 or 12 weeks. Some studies similarly concluded that diameter did not influence BIC.[41,44,55] Biomimetic bone materials were used previously to analyze the relationship between implant diameter and BIC, with the same conclusion.[56] These results may be relevant to the measurement type of BIC, which cannot reflect the overall BIC area due to the formula mode of the 2D longitudinal section of an implant.

A strong negative correlation between MBL and ISQ was observed in Ø3.3-, Ø4.1-, and Ø4.8-mm implants in this study, which was consistent with findings by Monje et al.[1] However, there was no correlation between BIC and ISQ. Although RFA has been widely used as a clinical parameter to evaluate implant stability, the reliability of RFA is still controversial.[18] Ito et al[57] demonstrated that there was no correlation between BIC and RFA but that the marginal bone around the neck of an implant could more effectively impact ISQ. A statistical correlation between ISQ and BIC was found in a retrospective clinical study.[37] The different aforementioned conclusions may be related to the effects of multiple factors on ISQ.

CONCLUSIONS

Overall, the performance of the Ø4.1- and Ø4.8-mm implants was better than that of the Ø3.3-mm implants in terms of primary stability and subsequent secondary stability. This excellent performance in terms of implant stability is closely related to cortical bone anchorage. In terms of the performance of marginal bone stability, Ø4.1-mm implants showed good peri-implant bone stability. Thinner original cortical bone led to greater bone resorption observed with Ø4.8-mm implants, and nonsubmerged healing contributed to the obvious bone resorption observed with Ø3.3-mm implants. It seems that before osseointegration, a narrow-diameter implant is more affected by the external environment than standard- and wide-diameter implants. During the early healing stage, the implant diameter may not influence BIC. RFA can be a way to assess implant stability and MBL, but it cannot detect the degree of osseointegration. The present study also provided insight into the creation of an implant surgical template that can be used as a reference method for future research.

This research study had some limitations. First, due to the small sample size of the 4-week group, statistical analyses of BIC and BV/TV at 4 weeks were not reliable; a larger sample size is needed to confirm these results. Second, the present study lacked occlusal load on the implant, and observation time was short; it would be interesting to study the impact of implant diameter on implant stability, peri-implant bone stability, and osseointegration over a longer period of time.

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REFERENCES

1. Monje A, Insua A, Monje F, Munoz F, Salvi GE, Buser D. Diagnostic accuracy of the implant stability quotient in monitoring progressive peri-implant bone loss: An experimental study in dogs. Clin Oral Implants Res 2018;29:1016–1024.

2. Guglielmotti MB, Olmedo DG, Cabrini RL. Research on implants and osseointegration. Periodontol 2000 2019;79:178–189.
3. Branemark PI, Hansson BO, Adell R, Breine U, Lindstrom J, Hallen O. Osseointegrated implants in the treatment of the edentulous jaw. Experience from a 10-year period. Scand J Plast Reconstr Surg Suppl 1977;16:1–132.
4. Folkman M, Becker A, Meinster I, Masri M, Ormianer Z. Comparison of bone-to-implant contact and bone volume around implants placed with or without site preparation: A histomorphometric study in rabbits. Sci Rep 2020;10:12446.
5. von Wilmowsky C, Moest T, Nkenke E, Stelzle F, Schlegel KA. Implants in bone: Part II. Research on implant osseointegration: Material testing, mechanical testing, imaging and histoanalytical methods. Oral Maxillofac Surg 2014;18:355–372.
6. Mish CE, Resnik RR. Available bone and dental implant treatment plans. In: Resnik RR. Mish's Contemporary Implant Dentistry, ed 4. Mosby, 2021:415–435.
7. Palaskar JN, Joshi N, Shah PM, Gullapalli P, Vinay V. Influence of different implant placement techniques to improve primary implant stability in low-density bone: A systematic review. J Indian Prosthodont Soc 2020;20:11–16.
8. Quesada-Garcia MP, Prados-Sanchez E, Olmedo-Gaya MV, Munoz-Soto E, Vallecillo-Capilla M, Bravo M. Dental implant stability is influenced by implant diameter and localization and by the use of plasma rich in growth factors. J Oral Maxillofac Surg 2012;70:2761–2767.
9. Arosio P, Arosio F, Di Stefano DA. Implant diameter, length, and the insertion torque/depth integral: A study using polyurethane foam blocks. Dent J (Basel) 2020;8:56.
10. Ueda N, Takayama Y, Yokoyama A. Minimization of dental implant diameter and length according to bone quality determined by finite element analysis and optimized calculation. J Prosthodont Res 2017;61:324–332.
11. Huang H, Wu G, Hunziker E. The clinical significance of implant stability quotient (ISQ) measurements: A literature review. J Oral Biol Craniofac Res 2020;10:629–638.
12. Monje A, Ravida A, Wang HL, Helms JA, Brunski JB. Relationship between primary/mechanical and secondary/biological implant stability. Int J Oral Maxillofac Implants 2019;34:s7–s23.
13. Zanetti EM, Pascoletti G, Cali M, Bignardi C, Franceschini G. Clinical assessment of dental implant stability during follow-up: What is actually measured, and perspectives. biosensors (Basel) 2018;8:68.
14. Andreotti AM, Goiato MC, Nobrega AS, Freitas da Silva EV, Filho HG, Pellizzer EP. Relationship between implant stability measurements obtained by two different devices: A systematic review. J Periodontol 2017;88:281–288.
15. Kastel I, de Quincey G, Neugebauer J, Sader R, Gehrke P. Does the manual insertion torque of smartpegs affect the outcome of implant stability quotients (ISQ) during resonance frequency analysis (RFA)? Int J Implant Dent 2019;5:42.
16. Norton MR. The influence of low insertion torque on primary stability, implant survival, and maintenance of marginal bone levels: A closed-cohort prospective study. Int J Oral Maxillofac Implants 2017;32:849–857.
17. Liu Y, Sorensen JA, Shen IY. Challenges of using resonance frequency analysis to identify stability of a dental implant placed in the mandible. Int J Oral Maxillofac Implants 2021;36:e7–e21.
18. Gupta RK, Padmanabhan TV. Resonance frequency analysis. Indian J Dent Res 2011;22:567–573.
19. Bischof M, Nedir R, Szmukler-Moncler S, Bernard JP, Samson J. Implant stability measurement of delayed and immediately loaded implants during healing. Clin Oral Implants Res 2004;15:529–539.
20. Hoekstra JWM, van Oirschot BA, Jansen JA, van den Beucken JJ. Innovative implant design for continuous implant stability: A mechanical and histological experimental study in the iliac crest of goats. J Mech Behav Biomed Mater 2021;122:104651.
21. Merheb J, Vercruyssen M, Coucke W, Quirynen M. Relationship of implant stability and bone density derived from computerized tomography images. Clin Implant Dent Relat Res 2018;20:50–57.
22. Pai UY, Rodrigues SJ, Talreja KS, Mundathaje M. Osseodensification—A novel approach in implant dentistry. J Indian Prosthodont Soc 2018;18:196–200.
23. Di Stefano DA, Arosio P, Cappare P, Barbon S, Gherlone EF. Stability of dental implants and thickness of cortical bone: Clinical research and future perspectives. A systematic review. Materials (Basel) 2021;14:7183.
24. de Oliveira Nicolau Mantovani AK, de Mattias Sartori IA, Azevedo-Alanis LR, Tiossi R, Fontao F. Influence of cortical bone anchorage on the primary stability of dental implants. Oral Maxillofac Surg 2018;22:297–301.
25. Mavrogenis AF, Dimitriou R, Parvizi J, Babis GC. Biology of implant osseointegration. J Musculoskelet Neuronal Interact 2009;9:61–71.
26. Lee CT, Chen YW, Starr JR, Chuang SK. Survival analysis of wide dental implant: Systematic review and meta-analysis. Clin Oral Implants Res 2016;27:1251–1264.
27. Javed F, Romanos GE. The role of primary stability for successful immediate loading of dental implants. A literature review. J Dent 2010;38:612–20.
28. Steigenga JT, al-Shammari KF, Nociti FH, Misch CE, Wang HL. Dental implant design and its relationship to long-term implant success. Implant Dent 2003;12:306–317.
29. Junker R, Dimakis A, Thoneick M, Jansen JA. Effects of implant surface coatings and composition on bone integration: A systematic review. Clin Oral Implants Res 2009;20 (suppl 4):185–206.
30. Noaman AT, Bede SY. The effect of bone density measured by cone beam computed tomography and implant dimensions on the stability of dental implants. J Craniofac Surg 2021;33:e553–e557.
31. Brink J, Meraw SJ, Sarment DP. Influence of implant diameter on surrounding bone. Clin Oral Implants Res 2007;18:563–568.
32. Lee CT, Chen YW, Starr JR, Chuang SK. Survival analysis of wide dental implant: Systematic review and meta-analysis. Clin Oral Implants Res 2016;27:1251–1264.
33. Byrne G. Implant-tissue interfact biology. In: Fundamentals of implant Dentistry. Wiley-Blackwell, 2014:23–41.
34. Rossi F, Lang NP, De Santis E, Morelli F, Favero G, Botticelli D. Bone-healing pattern at the surface of titanium implants: An experimental study in the dog. Clin Oral Implants Res 2014;25:124–131.
35. Mei S, Dong F, Rahman Khan MS. Effects of biomineralization on osseointegration of pure titanium implants in the mandible of beagles. J Oral Maxillofac Surg 2018;76:2104e1–2104e10.
36. Satwalekar P, Nalla S, Reddy R, Chowdary SG. Clinical evaluation of osseointegration using resonance frequency analysis. J Indian Prosthodont Soc 2015;15:192–199.
37. Scarano A, Degidi M, Iezzi G, Petrone G, Piattelli A. Correlation between implant stability quotient and bone-implant contact: A retrospective histological and histomorphometrical study of seven titanium implants retrieved from humans. Clin Implant Dent Relat Res 2006;8:218–222.
38. Romanos GE, Delgado-Ruiz RA, Sacks D, Calvo-Guirado JL. Influence of the implant diameter and bone quality on the primary stability of porous tantalum trabecular metal dental implants: an in vitro biomechanical study. Clin Oral Implants Res 2018;29:649–655.
39. Diaz-Sanchez RM, Delgado-Munoz JM, Serrera-Figallo MA, Gonzalez-Martin MI, Torres-Lagares D, Gutierrez-Perez JL. Analysis of marginal bone loss and implant stability quotient by resonance frequency analysis in different osteointegrated implant systems. Randomized prospective clinical trial. Med Oral Patol Oral Cir Bucal 2019;24:e260–e264.
40. Lee CT, Sanz-Miralles E, Zhu L, Glick J, Heath A, Stoupel J. Predicting bone and soft tissue alterations of immediate implant sites in the esthetic zone using clinical parameters. Clin Implant Dent Relat Res 2020;22:325–332.
41. Exposto CR, Oz U, Westgate PM, Huja SS. Influence of mini-screw diameter and loading conditions on static and dynamic assessments of bone-implant contact: An animal study. Orthod Craniofac Res 2019;22 Suppl 1:96–100.
42. Degidi M, Daprile G, Piattelli A. Primary stability determination by means of insertion torque and RFA in a sample of 4,135 implants. Clin Implant Dent Relat Res 2012;14:501–507.
43. Horwitz J, Zuabi O, Peled M. Resonance frequency analysis in immediate loading of dental implants. Refuat Hapeh Vehashinayim (1993) 2003;20:80–88,104.
44. Jimbo R, Janal MN, Marin C, Giro G, Tovar N, Coelho PG. The effect of implant diameter on osseointegration utilizing simplified drilling protocols. Clin Oral Implants Res 2014;25:1295–1300.

45. Guler AU, Sumer M, Duran I, Sandikci EO, Telcioglu NT. Resonance frequency analysis of 208 Straumann dental implants during the healing period. J Oral Implantol 2013;39:161–167.
46. Veltri M, Gonzalez-Martin O, Belser UC. Influence of simulated bone-implant contact and implant diameter on secondary stability: A resonance frequency in vitro study. Clin Oral Implants Res 2014;25:899–904.
47. Mijiritsky E, Mazor Z, Lorean A, Levin L. Implant diameter and length influence on survival: Interim results during the first 2 years of function of implants by a single manufacturer. Implant Dent 2013;22:394–398.
48. French D, Grandin HM, Ofec R. Retrospective cohort study of 4,591 dental implants: Analysis of risk indicators for bone loss and prevalence of peri-implant mucositis and peri-implantitis. J Periodontol 2019;90:691–700.
49. Shin SW, Bryant SR, Zarb GA. A retrospective study on the treatment outcome of wide-bodied implants. Int J Prosthodont 2004;17:52–58.
50. Garg AK. Bone biology, osseointegration, and bone grafting. In: Implant Dentistry: A Practical Approach, ed 2. St Louis: Mosby, 2010:193–211.
51. Pellegrini G, Francetti L, Barbaro B, Del Fabbro M. Novel surfaces and osseointegration in implant dentistry. J Investig Clin Dent 2018;9:e12349.
52. Choi JY, Sim JH, Yeo IL. Characteristics of contact and distance osteogenesis around modified implant surfaces in rabbit tibiae. J Periodontal Implant Sci 2017;47:182–192.
53. Beutel BG, Danna NR, Granato R, Bonfante EA, Marin C, Tovar N. Implant design and its effects on osseointegration over time within cortical and trabecular bone. J Biomed Mater Res B Appl Biomater 2016;104:1091–1097.
54. Grzeskowiak RM, Schumacher J, Dhar MS, Harper DP, Mulon PY, Anderson DE. Bone and cartilage interfaces with orthopedic implants: A literature review. Front Surg 2020;7:601244.
55. Witek L, Parra M, Tovar N, Alifarag A, Lopez CD, Torroni A. Effect of surgical instrumentation variables on the osseointegration of narrow- and wide-diameter short implants. J Oral Maxillofac Surg 2021;79:346–355.
56. Hsu JT, Shen YW, Kuo CW, Wang RT, Fuh LJ, Huang HL. Impacts of 3D bone-to- implant contact and implant diameter on primary stability of dental implant. J Formos Med Assoc 2017;116:582–590.
57. Ito Y, Sato D, Yoneda S, Ito D, Kondo H, Kasugai S. Relevance of resonance frequency analysis to evaluate dental implant stability: Simulation and histomorphometrical animal experiments. Clin Oral Implants Res 2008;19:9–14.