The Effect of Implant Design and Bone Quality on Insertion Torque, Resonance Frequency Analysis, and Insertion Energy During Implant Placement in Low or Low- to Medium-Density Bone

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Purpose: This study investigated the effect of implant design and bone quality on insertion torque (IT), implant stability quotient (ISQ), and insertion energy (IE) by monitoring the continuous change in IT and ISQ while implants were inserted in artificial bone blocks that simulate bone of poor or poor-to-medium quality. ***Materials and Methods:*** Polyurethane foam blocks (Sawbones) of 0.16 g/cm^3 and 0.32 g/cm^3 were respectively used to simulate low density and low- to medium-density cancellous bone. In addition, some test blocks were laminated with a 1-mm 0.80 g/cm^3 polyurethane layer to simulate cancellous bone with a thin cortical layer. Four different implants (Nobel Biocare Mk III-3.75, Mk III-4.0, Mk IV-4.0, and NobelActive-4.3) were placed into the different test blocks in accordance with the manufacturer's instructions. The IT and ISQ were recorded at every 0.5-mm of inserted length during implant insertion, and IE was calculated from the torque curve. The peak IT (PIT), final IT (FIT), IE, and final ISQ values were statistically analyzed. ***Results:*** All implants showed increasing ISQ values when the implant was inserted more deeply. In contrast to the ISQ, implants with different designs showed dissimilar IT curve patterns during the insertion. All implants showed a significant increase in the PIT, FIT, IE, and ISQ when the test-block density increased or when the 1-mm laminated layer was present. Tapered implants showed FIT or PIT values of more than 40 Ncm for all of the laminated test blocks and for the nonlaminated test blocks of low to medium density. Parallel-wall implants did not exhibit PIT or FIT values of more than 40 Ncm for all of the test blocks. NobelActive-4.3 showed a significantly higher FIT, but a significantly lower IE, than Mk IV-4.0. ***Conclusions:*** While the existence of cortical bone or implant designs significantly affects the dynamic IT profiles during implant insertion, it does not affect the ISQ to a similar extent. Certain implant designs are more suitable than others if high IT is required in bone of poor quality. The manner in which IT, IE, and ISQ represent the implant primary stability requires further study. *Int J Prosthodont 2015;28:40–47. doi: 10.11607/ijp.4063*

Primary, or initial, implant stability is a prerequisite for osseointegration. It is defined as the biometric stability immediately achieved after implant placement. The lack of primary stability in poor bone quality may result in failure in the long term and is of particular importance when using immediate loading protocols. Primary stability is achieved by reconciling specific determinants such as bone quality, surgical technique, and implant design.[1–8] It is also presumed that bone quality in particular usually defines the adopted surgical technique and the selected implant design. Consequently, various implant designs have been proposed to improve long-term prognoses and to achieve better initial primary stability whenever poor quality bone with a thin cortical layer and loose cancellous bone is the selected implant site.[2,9–13] Different surgical techniques claim enhanced primary implant stability in bone sites with poor bone quality.[14] Moreover, for each implant design, implant manufacturers also recommend specific implant site preparation protocols for soft bone. However, it is not clear how these protocols are developed, let alone the determination of

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Table 1 Classification of Test Blocks; the PIT, FIT, IE, and Final ISQ Values for the Four Different Implants in Each Test Block

Implant*	Test block	Cortical thickness (mm)	Cancellous bone (g/cm^3)	PIT (Ncm)	FIT (Ncm)	IE (J)	ISQ
Mk III-3.75	LD	0	0.16	4.6 (0.4)	4.6 (0.4)	0.94 (0.10)	46.8 (1.1)
	LMD	0	0.32	17.5 (2.4)	17.5 (2.4)	1.99 (0.21)	63.2 (2.3)
	La-LD	1	0.16	14.2 (3.7)	13.7 (2.4)	1.98 (0.54)	57.4 (1.1)
	La-LMD	1	0.32	35.0 (3.7)	34.9 (3.6)	3.45 (0.83)	68.8 (0.8)
Mk III-4.0	LD	0	0.16	4.5 (0.4)	4.5 (0.4)	1.10 (0.18)	45.4 (1.9)
	LMD	0	0.32	17.8 (5.1)	17.8 (5.1)	2.65 (068)	64.6 (3.1)
	La-LD	1	0.16	24.0 (5.8)	24.0 (5.8)	3.16 (0.80)	60.4 (2.2)
	La-LMD	1	0.32	40.0 (2.3)	40.0 (2.3)	5.01 (0.40)	71.0 (1.0)
Mk IV-4.0	LD	0	0.16	10.4 (1.7)	10.4 (1.7)	1.96 (0.27)	50.6 (2.2)
	LMD	0	0.32	47.6 (2.8)	47.6 (2.8)	8.54 (0.43)	65.4 (2.2)
	La-LD	1	0.16	33.5 (2.7)	33.2 (3.2)	9.32 (1.25)	63.0 (1.4)
	La-LMD	1	0.32	69.6 (7.8)	68.8 (6.4)	15.92 (1.81)	73.8 (1.9)
NA-4.3	LD	0	0.16	16.6 (0.8)	16.6 (0.8)	1.53 (0.06)	45.4 (0.9)
	LMD	0	0.32	59.8 (1.9)	59.8 (1.9)	5.14 (0.18)	64.6 (0.5)
	La-LD	1	0.16	56.0 (4.1)	48.1 (5.8)	6.33 (0.75)	62.6 (2.2)
	La-LMD	1	0.32	82.3 (0.7)*	76.6 (3.7)*	9.96 (0.62)*	68.0 (2.8)*

PIT = peak insertion torque; FIT = final insertion torque; IE = insertion energy; ISQ = implant stability quotient; LD = low-density cancellous block; LMD = low- to medium-density cancellous block; La-LD = laminated low-density block; La-LMD = laminated low- to medium-density block.
*Data are from two trials in which implants were fully seated. For the other three trials in which the implants were not fully seated, the PIT was greater than 90 Ncm and the mean ISQ was 61.0 when the torque reached 90 Ncm.

the degrees of primary stability achieved. It is, therefore, difficult to evaluate whether the protocol is really appropriate or whether additional improvements are required.

Simple, clinically relevant noninvasive tests should be used to assess implant stability during surgery. Two measurement methods have been proposed to quantitatively assess primary stability: *(1)* implant insertion torque (IT) and *(2)* resonance frequency analysis that is frequently represented by implant stability quotient (ISQ).[1,15–17] These two measurements also were suggested to represent the bone quality around the implants,[18,19] although their correlation with clinical efficacy, or indeed prognostic merit, in defining primary stability or bone quality remains controversial.[14,17,20–24] Recent studies also suggest that primary stability could be represented by insertion energy (IE) or torque work, which can be calculated from the torque profile during implant placement procedures.[25–27] Because the amount of IT is usually limited by the settings on the machine, surgeons often start with a low torque setting and then incrementally increase the torque whenever an implant cannot be seated completely. Peak insertion torque (PIT) is usually reported although this could be different from the final insertion torque (FIT) applied during the completion of implant placement. Similarly, the IE could be different when the PIT or FIT is similar for an implant placement. Consequently, a correlation between FIT, PIT, and IE in implants of different designs, placed in different bone qualities, needs to be determined before it can be decided which parameters can represent implant stability or bone quality around an implant.

The purpose of this in vitro study was to investigate the following: dynamic changes of IT and ISQ, together with correlations among FIT, PIT, IE, and ISQ in implants of different designs that were placed in artificial bone blocks with a density that simulates poor or poor-to-medium quality bone.

Materials and Methods

Simulated Bone Blocks

Polyurethane blocks (Sawbones, Pacific Research Laboratories) were used to simulate bone with different cancellous densities. As the mean bone mineral density is 0.31 g/cm^3 for the posterior maxilla and 0.55 g/cm^3 for the anterior maxilla,[28] polyurethane foam blocks of 0.16 g/cm^3 and 0.32 g/cm^3 were used to respectively simulate cancellous bone of low and low-to-medium density. Some cancellous test blocks were also laminated by attaching a 1-mm polyurethane layer of 0.80 g/cm^3 density to simulate cancellous bone with a thin layer of cortical bone. Therefore, four artificial bone blocks were prepared: a low-density (0.16 g/cm^3) cancellous block (LD), a low- to medium-density (0.32 g/cm^3) cancellous block (LMD), a laminated low-density block (La-LD), and a laminated low- to medium-density block (La-LMD) (Table 1). Each block measured 60 × 60 × 20 mm (length × width × height).

Fig 1 Implants tested. From left to right: Mk III-4.0, Mk IV-4.0, NA-4.3. The Mk III-3.75 (not shown) has the same profile as Mk III-4.0 but a smaller diameter.

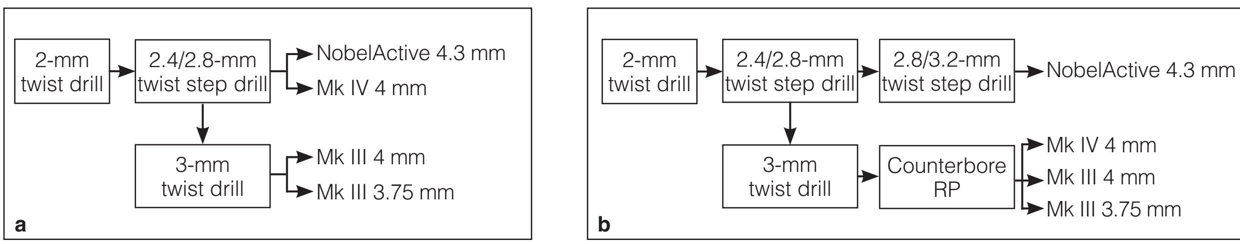


Fig 2 Surgical protocols for the four different implants in **(a)** nonlaminated test blocks and **(b)** laminated test blocks (2-mm twist drill: 32297, 3-mm twist drill: 32267, 2.4/2.8-mm twist step drill: 32261, Counterbore RP: 32283, Nobel Biocare).

Fig 3 A torque wrench connected to a strain gauge transducer indicator, which registers the insertion torque.

Implants

Four different implant designs were used for this study: Mk III-3.75 (28913, Mk III TiUnite; 3.75-mm diameter × 10-mm length, Nobel Biocare); Mk III-4.0 (28920, Mk III TiUnite, 4.0-mm diameter × 10-mm length); Mk IV-4.0 (28934, Mk IV TiUnite, 4.0-mm diameter × 10-mm length); and NA-4.3 (34131, NobelActive, 4.3-mm diameter × 10-mm length, Nobel Biocare) (Fig 1). Mk III-3.75 and Mk III-4.0 are standard parallel-wall implants originally designed for all bone qualities. Mk IV-4.0 and NA-4.3 are tapered implants specially designed for bone of poor quality. For each implant design, five implants were placed into each of the four artificial bone blocks. Each drill hole was separated by 1 cm.

Surgical Protocols and Measurement of the IT and ISQ

Since the drilling protocol affects the measurement of implant IT and ISQ, the surgical protocols for the four different implants placed in test blocks followed the manufacturer's recommendations for soft bone (Fig 2). Five implant insertions were performed in each of the four test blocks for all four implants. During insertion of the implant, the IT and the ISQ were recorded at every successive 0.5-mm of inserted length. The measurements started after 2 mm of an implant had been inserted until it was fully seated. The PIT is the maximum IT value during the insertion procedure. The FIT is the IT value measured at the moment that an implant is fully seated. The IT was measured using a torque wrench (Sensor Development) connected to a strain gauge transducer indicator (TIG-7010; Fig 3) and the ISQ was measured using an Osstell Mentor (Osstell), which displays ISQ values. For each inserted length, three ISQ values were measured and the average was used.

Insertion Energy

In physics, a torque of 1 Nm applied through a full revolution will require an energy of exactly 2π joules. Mathematically, $E = \tau\theta$; where E is the energy, τ is magnitude of the torque, and θ is the angle moved (in radians). Since the thread pitch is 1.2 mm for Mk III-3.75, Mk III-4.0, and Mk IV-4.0 and 2.4 mm for NA-4.3, θ is 2.62 and 1.31 for every 0.5-mm insertion, respectively. Thus, using a trapezoidal integration technique, the area underlying the recorded torque curve (Figs 4 and 5) was calculated and represented the IE.

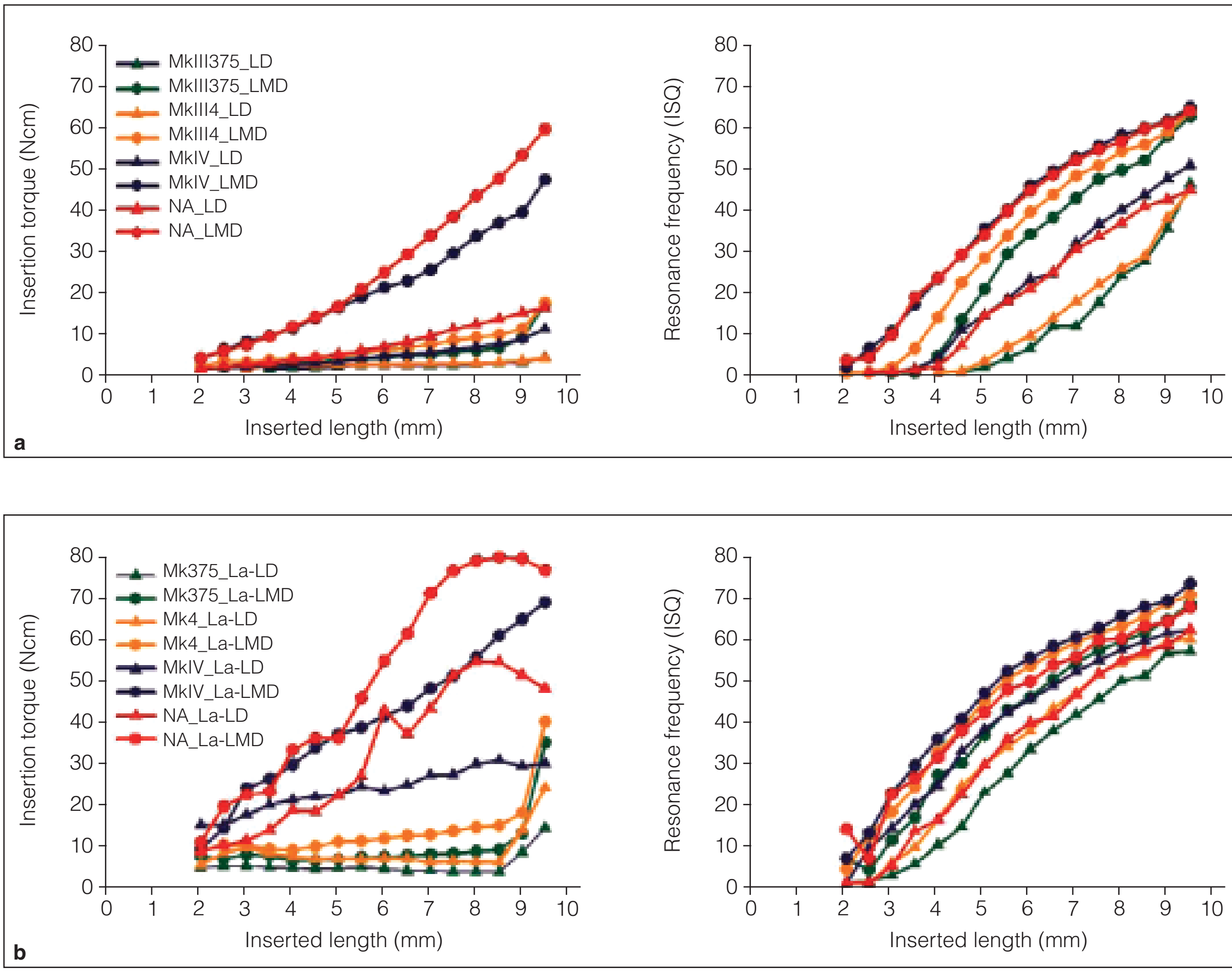


Fig 4 Insertion torque (IT) and implant stability quotient (ISQ) measurements for the four different implants in **(a)** nonlaminated test blocks and **(b)** laminated test blocks of two cancellous densities.

Data Analysis and Statistical Analysis

The means and SDs of the PIT, FIT, and ISQ values were calculated. The statistical analyses were performed using SAS version 9.3 software (SAS Institute). The general linear model (GLM) procedure was used to compare the effect of bone quality (cortical thickness and cancellous density) and implant design on the PIT, FIT, IE, and ISQ values. Post-hoc Bonferroni test was used to compare the mean values. All plots were made using Sigmaplot 11.0 software (GraphPad Software). Differences were considered as significant when $P < .05$.

Results

Implant Stability Quotient Values

The ISQ values were most influenced by the length that an implant is inserted (the amount of implant that is embedded). When the implant was inserted deeper, all of the implants exhibited increasing ISQ values (Figs 4 and 5). For each implant design, the final ISQ values were significantly increased when the density of the test blocks increased or when the 1-mm laminated layer was present (Fig 6).

Insertion Torque and Insertion Energy

Different implant designs exhibited different profiles of the IT during implant insertion (Figs 4 and 5). The Mk IV-4.0 implants and NA-4.3 implants showed an increasing instantaneous IT during implant insertion in all of the test blocks. In contrast, the Mk III implants exhibited unobvious changes in instantaneous IT until the last moment when the platform engaged the test blocks. All of the implants showed an increase in the PIT, FIT, and IE when the density of test blocks increased or when the 1-mm laminated layer was present (Figs 5 and 6, Table 1). Most implants showed a PIT when the implant was fully seated, which meant that the PIT was equal to the

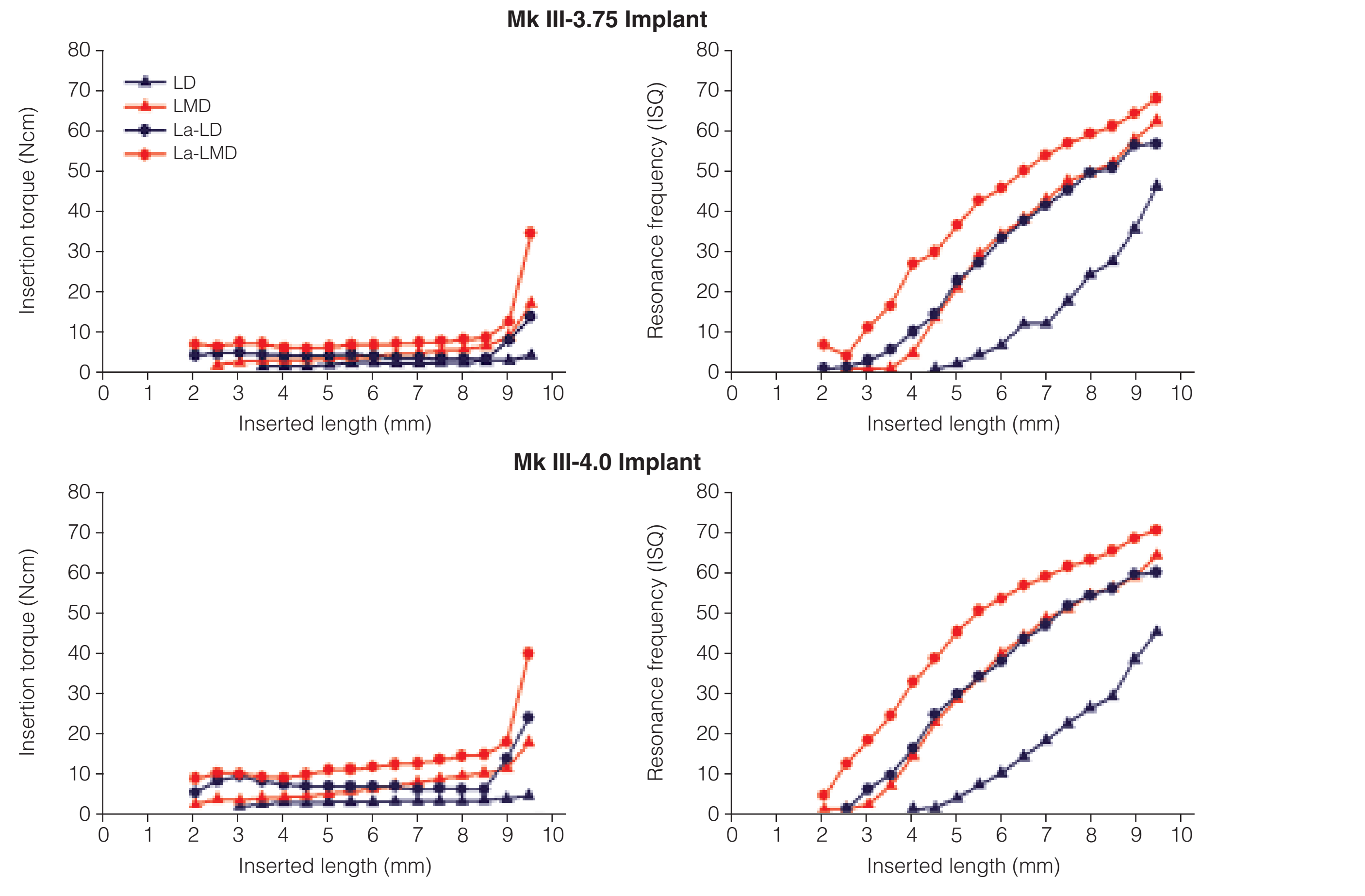


Fig 5 Insertion torque (IT) and implant stability quotient (ISQ) measurements for each implant in four different test blocks.

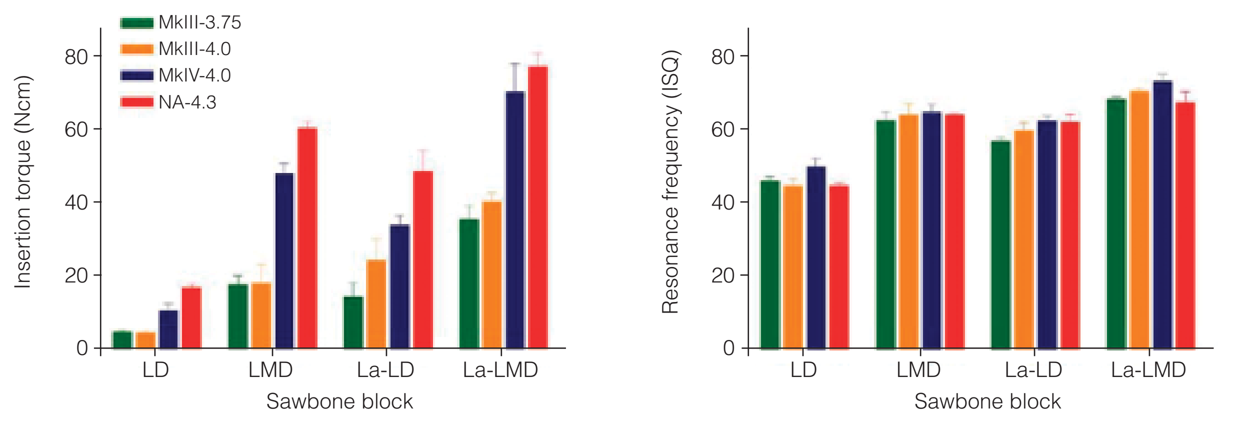
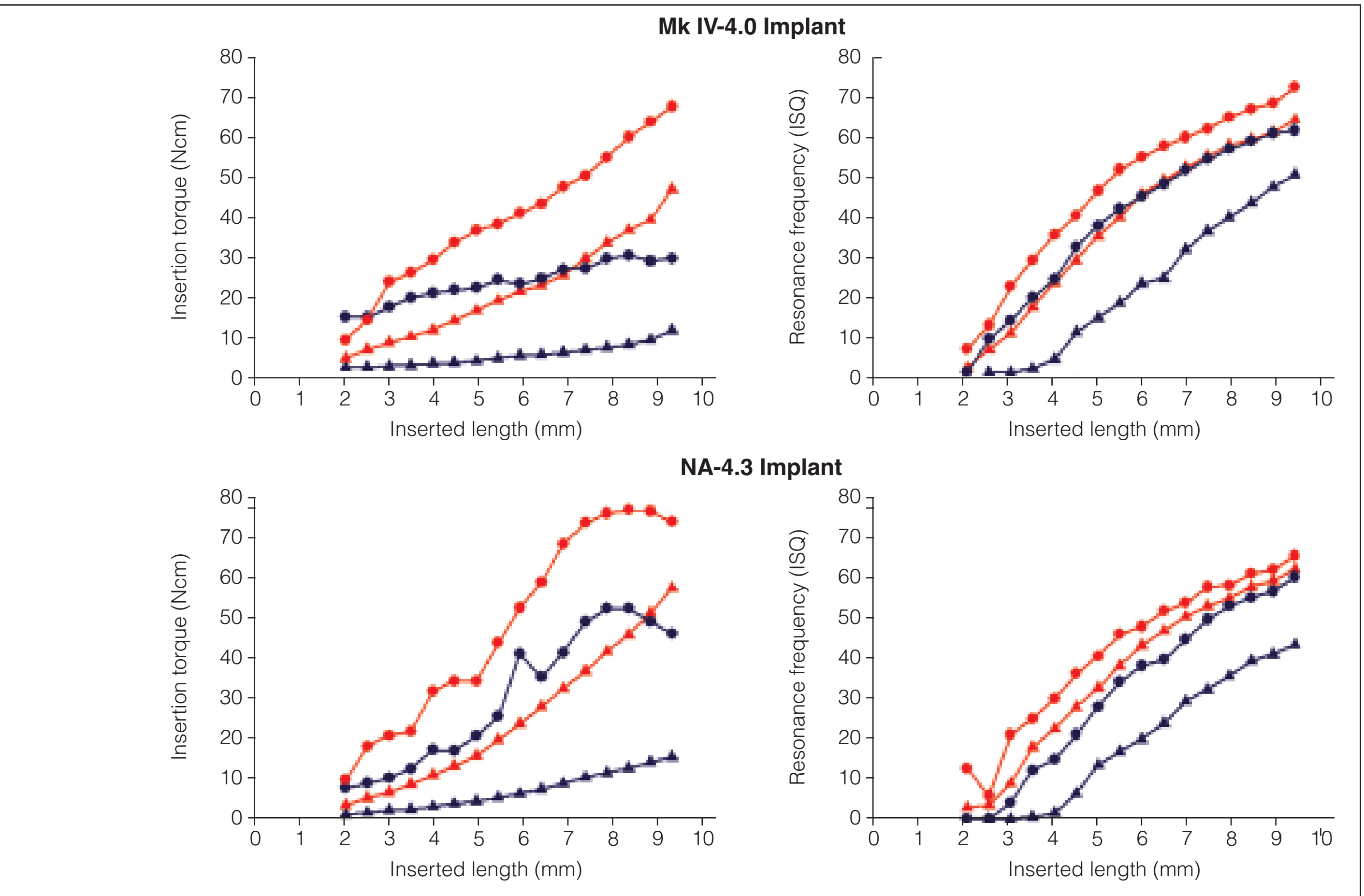


Fig 6 Final insertion torque (FIT) *(left)* and final implant stability quotient (ISQ) *(right)* values for different implants in bone of different quality.

FIT. However, with the 1-mm laminated test blocks (La-LD, La-LMD), the NA-4.3 implants showed a PIT of 0.5 to 1 mm before the implants were fully seated, and the FIT was less than the PIT (Figs 4 and 5). It is worthy of note that three NA-4.3 implants could not be fully inserted in the La-LMD block because the IT had exceeded 90 Ncm when only 7 to 8 mm of the implants were inserted.

A significant linear correlation between FIT and IE could be found for each implant design (NA-4.3:



$r^2 = 0.777$; Mk IV-4.0: $r^2 = 0.863$; Mk III-4.0: $r^2 = 0.970$; Mk III-3.75: $r^2 = 0.894$) (Fig 7). It is worth noting that NobelActive-4.3 showed a significantly higher FIT, but a significantly lower IE, than Mk IV-4.0. Several implant-bone block combinations showed the FIT around 40 Ncm but the IE in the range of 2.5 to 10 J.

Relation Between ISQ and IT

A positive linear correlation could be observed between FIT and ISQ (Table 1) in each implant design. However, no correlation could be observed when data from all of the implants was pooled.

Discussion

While different drilling protocols may affect IT and ISQ values,[4,6,13] this study investigated these parameters by following the manufacturer's recommendations for soft and soft-to-medium bone qualities. The employed continuous monitoring technique showed that implant design affects the IT profile during insertion. The three implant designs with an implant flange at the platform (Mk III-3.75, Mk III-4.0, and Mk IV-4.0) always showed the highest IT values at the end of the insertion, so their FIT values were equal to the PIT values. In the presence of cortical bone, the FIT value for the two Mk III implants increased suddenly, which may be due to their parallel-wall design and the impingement of the implant flange on the crestal cortical bone. These results are inconsistent with the observations at several parallel-wall and tapered implant designs observed in a previous study.[2] The NA-4.3 implant is a tapered implant, which was developed to increase the primary stability of the implant in an implant site with poor bone quality or an extraction socket. It has no implant flange, like the other implants with internal connections, and its implant width is constricted from the major diameter of 4.3 mm to 3.9 mm at the platform interface. These characteristics explain why the PIT values for the NA-4.3 implants occurred 2 mm before the implants were fully seated and the FIT values were less than the PIT values. Theoretically, the FIT may represent the target primary stability—it is undesirable to have a much higher PIT during implant placement before it is fully seated.

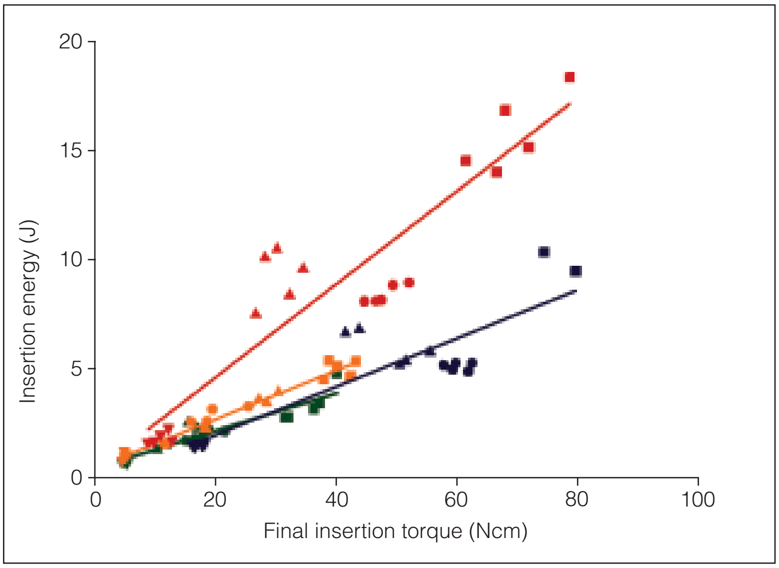


Fig 7 Correlation between FIT and IE. Five measurements were made per implant design per test block (except NA-4.3 in La-LMD). Each color represents an implant design (green: Mk III-3.75, orange: Mk III-4.0, red: Mk IV-4.0, blue: NA-4.3). Each symbol shape represents a type of test block(▼: LD, ●: LMD, ▲: La-LD; ■: La-LMD).

This study supports the observations that implant IT and ISQ values increase in the presence of cortical bone or increased cortical thickness.[6] For most implant designs, the IT or ISQ values ascend in order from the lowest to the highest value in the following sequence: LD, La-LD, LMD, and La-LMD. The data suggest that although a cortical layer is important, an increase in the cancellous density may actually supersede the role of the thin cortical bone in providing a higher IT or ISQ value.

In this study, some of the FIT did not reach 30 Ncm while the IT of three NA-4.3 implants reached 90 Ncm and could not be seated completely. These observations suggest that better surgical protocols for each implant design may be necessary. However, in vivo studies are required to verify these in vitro observations. Similar insertion difficulties were observed in a clinical evaluation of NA dental implants.[29] In the present study, the NA-4.3 implants showed a larger PIT than the FIT in laminated blocks and still have a FIT as high as 59.8 Ncm in nonlaminated LMD blocks. An in vivo study would be able to verify these results and explore whether a wider preparation at the cortical bone can reduce the PIT while maintaining a high FIT. Although the bone blocks were selected to simulate the low-density and low- to medium-density cancellous bone,[28] additional studies may also be needed to verify whether this was an appropriate simulation since three NA-4.3 implants could not be placed successfully.

It is also important to note that the ISQ values of the three NA-4.3 implants were 58, 62, and 63 when the IT exceeded 90 Ncm. Therefore, the ISQ values appeared to depend more on the inserted length of the implant and did not parallel the high IT ones. Since an implant may not fully contact the bone in immediate implantation, these data suggest that an implant with a similar design to the NA-4.3 implant could show a high IT but low ISQ value if it is placed into an extraction socket. It would also be interesting to evaluate the micromotion of the implants to clarify whether IT or ISQ actually represent the primary stability in this case. Although increasing the PIT may reduce the level of implant micromotion in a single implant design,[7,8] clarification is needed to determine whether the same IT, ISQ, or IE values of different implant designs represent similar primary stability.

Recent studies explored the feasibility of IE or work as a new primary stability parameter.[25,26] A similar FIT may have different IE or work if the torque curve profiles are different during implant placements. This study showed a significant linear correlation between FIT and IE for each implant design, although there were different implants showing similar FIT around 40 Ncm, but quite different IE (Fig 7). The significance of IE needs clarification. Furthermore, additional in vitro and in vivo studies are needed for each implant design to investigate the best surgical protocols that ensure primary stability and the final implant treatment outcomes.

Conclusions

It appears that the presence of cortical bone as well as implant design significantly affects the dynamic IT profiles during implant insertion, while not similarly affecting ISQ profiles. Certain implant designs may be more suitable for specific selections than others if high IT in bone with poor quality is required, when using the surgical protocols recommended by the manufacturers. The modification of these surgical protocols to achieve a high ISQ and optimal IT deserves future study, together with the manner in which IT and ISQ values can be employed to reliably represent implant primary stability.

Acknowledgments

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