Resonance Frequency Measurement of Implant Stability In Vivo on Implants with a Sandblasted and Acid-Etched Surface

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Purpose: *To determine the changes in stability as a reflection of early healing around single-stage, roughened-surface implants in humans utilizing resonance frequency analysis (RFA). RFA makes use of a transducer, attached to an implant, which is excited over a range of sound frequencies with subsequent response analysis.* ***Materials and Methods:*** *Twenty patients had 1 to 4 implants placed in the posterior maxilla or mandible. Bone type was classified into 1 of 4 groups according to the Lekholm and Zarb index (1985). RFA was used for direct measurement of implant stability on the day of implant placement and consecutively once per week for 6 weeks and at weeks 8 and 10.* ***Results:*** *Twenty-seven ITI SLA implants placed in the premolar and molar regions of the maxilla and mandible were evaluated. Early failure occurred with 1 implant related to parafunction. The remaining 26 implants were distributed as follows: 29.6% in Type 1 bone, 37% in Type 2 or 3 bone, and 33.3% in Type 4 bone. The lowest mean stability measurement was at 3 weeks for all bone types. The percentage decrease in stability from baseline to 3 weeks was highest for Type 4 bone (8.6%), as was the percentage increase in stability from 3 to 10 weeks (26.9%). A Bonferroni adjusted Student t test comparison of bone groups at each time point revealed highly significant differences between implant stability in Types 1 and 4 bone at 3 weeks ($P = .004$) and a moderately significant difference between Types 2, 3, and 4 bone ($P = .08$) at 3 weeks. Implant stability did not change significantly during the 10-week period in Type 1 bone ($P > .10$). With the same test, by 5 weeks, no bone groups showed any difference in implant RFA measurements ($P = 1.0$).* ***Discussion:*** *This study demonstrated the lowest values for implant stability at 3 weeks after placement for all bone types. This effect was statistically significant and most pronounced in Type 4 bone.* ***Conclusion:*** *There was no significant difference in the pattern of stability changes among different bone types after 5 weeks of healing.* INT J ORAL MAXILLOFAC IMPLANTS 2003;18:641–651

Key words: *bone, clinical trials, dental implants, early healing, endosseous dental implantation, implant stability, resonance frequency analysis*

Since the days of the Etruscans 2,500 years ago, efforts have been made to develop a dental replacement that is implanted in bone.[1] Most implants were dismal failures because of the lack of biocompatibility of the materials used. It was not until 1965 that Brånemark and coworkers[2] achieved osseointegration with titanium implants in the mandible. The term *osseointegration* was defined as "the direct structural and functional connection between ordered living bone and the surface of a load-carrying implant." Osseointegration has also been defined in clinical terms as "a process in which clinically asymptomatic rigid fixation of alloplastic materials is achieved and maintained in bone during functional loading."[3] Primary stability occurs at the time of implant placement and is related to the level of primary bone contact.[4] It is influenced by the length, geometry, and surface area of the implant

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and by the bone-to-implant contact area.[5] Other factors include the ratio of cortical to trabecular bone and the placement technique. Secondary stability is the result of the formation of secondary bone contact of woven and then lamellar bone. During healing, as primary bone contact decreases, secondary bone contact increases.[4] Primary and secondary stability in healed bone has typically been clinically assessed via tapping the implant in a lateral direction with 2 opposing mirror handles.[6] Although this is a widely practiced clinical technique, there is little evidence in the literature to suggest that this method is valid. A clearly perceived need for a quantitative method to measure implant stability exists.[5]

A quantitative method for describing the stability of an object in a solid medium is through vibration analysis. Vibration analysis of an implant with subsequent measurement of an implant's vibratory oscillation can be divided into 2 categories: transient excitation and continuous excitation.[7] Manual percussion is the simplest form of transient vibration analysis. The Periotest (NIVA, Charlotte, NC) is another transient excitation tool designed originally to assess tooth mobility by measuring the damping characteristics of the periodontal ligament of a tooth to establish a quantitative value for its mobility.[8] However, when the Periotest is applied to the implant, the values obtained represent only a narrow range over the scale of the instrument,[9] thereby indicating a lack of sensitivity in the measurement of implant stability.

Dynamic vibration analysis of implant stability employs a continual excitation of the implant. The pulsed oscillation waveform was developed by Kaneko[10] to measure mechanical vibration characteristics of the bone-implant interface in vitro. In this technique, a high-energy pulse is repeatedly applied to the implant with probes containing piezoelectric elements, and the resonance frequency (RF) is measured. In a series of publications, Meredith and coworkers[11,12] reported on the use of a transducer that could be directly attached to an implant body or to the abutment on the implant. Resonance frequency analysis (RFA) offers a clinical, noninvasive measure of stability and presumed osseointegration of implants. Initial in vitro studies demonstrated the ability of the device to assess changes in interfacial stiffness.[5] Clinically, RF values have been correlated with changes in implant stability during osseous healing, failure of implants to integrate, and the supracrestal dimensions of the implant.[13–16] The results of a recent histomorphometric study suggested that RF values correlated well with levels of bone-implant contact.[17] These findings support the use of RFA in assessing changes in the bone healing and osseointegration process following implant placement.

The objective of this clinical study was to gain insight into the pattern of stability changes and therefore early healing around single-stage, roughened-surface implants in humans. Although differences in primary stability and healing levels at abutment placement have been established between areas of varying bone density with a machined, screw-type implant, a closer examination during the first 2 1/2 months of healing in different bone types will further an understanding of the varying qualities of bone and their impact on implant stability.

A prospective human clinical trial was designed with the aim of applying the noninvasive RFA technique to the clinical measurement of the early healing of ITI SLA (sandblasted, large-grit, and acid-etched) solid-screw implants (Straumann, Waldenburg, Switzerland). The first hypothesis was that RFA can be used clinically to detect changes in implant stability during the early healing period for nonsubmerged, roughened-surface implants. The second hypothesis was that RF values show varying stability patterns based on the bone type surrounding the implant and the implant location.

MATERIALS AND METHODS

Patient Data

This human clinical trial was designed as a prospective study to measure implant stability with an RF analyzer (Osstell; Integration Diagnostics, Savedalen, Sweden) at the time of implant placement and up to 10 weeks postplacement. The study population consisted of active dental patients seeking treatment at the University of Texas Health Science Center at San Antonio (UTHSCSA). This population provided 20 patients between the ages of 22 and 75 years (5 men and 15 women). At the initial screening appointments, the subjects' medical and dental histories were reviewed and inclusion/exclusion criteria were confirmed (Fig 1). Only patients requiring between 1 and 4 standard-diameter (4.1-mm) implants in the posterior maxilla or mandible were accepted. The only implant lengths accepted in the study were 10 mm and 12 mm. Clinical and radiographic screening was used to limit the study to patients with sufficient bone quantity to completely encase the implant.

Clinical Protocol

All implants were placed using a nonsubmerged technique, according to a strict surgical protocol

1. Patient inclusion criteria
   a. Age 18 years or older
   b. Ability to understand and sign the informed consent prior to starting the study
   c. Ability and willingness to comply with all study requirements
   d. Adequate oral hygiene (defined as an average Modified Sulcus Bleeding Index of 1 or less and an average Modified Plaque index of 1 or less
   e. Adequate bone volume to accommodate the planned endosseous dental implants (eg, sufficient height such that the implant would not encroach on vital structures such as sinuses and sufficient width that the implant could be placed within the confines of the existing bone
   f. One or more missing teeth in either the maxilla or mandible, existing teeth that were healthy and adequately restored, and desired a fixed restoration on implants
   g. If the patient was of childbearing potential, a negative pregnancy test within 1 week prior to surgery
2. Patient exclusion criteria
   a. Moderate or heavy smoking (more than 10 cigarettes per day) or tobacco chewing
   b. History of alcoholism or drug abuse within the past 5 years
   c. Severe bruxing or clenching habits
   d. Untreated periodontitis
   e. At risk for a surgical procedure
   f. Presence of residual roots at the implant site
   g. Presence of local inflammation or mucosal diseases such as lichen planus
   h. High risk for subacute bacterial endocarditis
   i. Uncontrolled diabetes
   j. Current hematologic disorder or coumadin (or similar) therapy
   k. History of leukocyte dysfunction and deficiencies
   l. Metabolic bone disorders
   m. History of renal failure
   n. History of liver disease
   o. Immunocompromised status, including HIV and herpes virus
   p. Current steroid treatment, ie, any person who within the last 2 years had received for 2 weeks a dose equivalent to 20 mg hydrocortisone
   q. Current chemotherapy
   r. History of radiation treatment to the head or neck
   s. Physical limitations that would have interfered with patient's ability to exercise good oral hygiene on a regular basis
   t. A need for grafting of bone or soft tissue at the time of implant placement
   u. Use of any investigational drug or device within the 30-day period immediately prior to implant surgery
   v. A need for submersion of implants for esthetic reasons
   w. Placement of implant in an extraction site that had been healing for less than 6 months

Fig 1 Inclusion and exclusion criteria for the present study.

following the manufacturer's instructions. Bone quality was categorized as Type 1, 2, 3, or 4 at the time of surgery following the anatomic criteria proposed by Lekholm and Zarb.[18] This determination was based upon the drilling resistance to site preparation during implant placement.

Immediately after the implant was placed, the RF analyzer was used for direct measurement of implant stability. This methodology uses changes in a small transducer designed as a simple offset cantilever beam that is screwed onto an implant (Fig 2). The transducer has 2 piezoceramic elements attached.[5] The transducer is vibrated by exciting one of the elements with a sinusoidal signal of increasing frequency. The second piezoceramic element measures the response of the beam, and the signal generated is amplified and compared to the original signal frequency by the frequency response analyzer. The captured data are displayed as a RF versus amplitude graph. The RF values, calculated from the peak amplitude, are represented in a quantitative unit called Implant Stability Quotient (ISQ) on a scale from 1 to 100. ISQ values are derived from the stiffness (N/μm) of the transducer/implant/bone system and the calibration parameters of the transducer. An increased ISQ value indicates increased stability, whereas decreased values indicate a decrease in implant stability. Displacement of the cantilever beam is less than 1 μm and lasts less than 1 second.

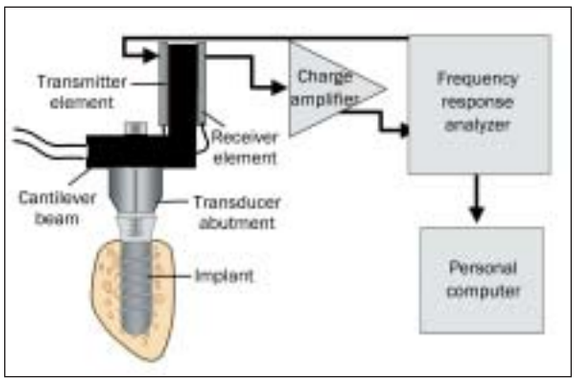

Fig 2 Diagram of instrumentation used.

An RFA measurement was taken at weeks 0, 1, 2, 3, 4, 5, 6, 8, and 10 by a single observer. Each visit involved questioning the patient with regard to pain level, removal of the cover screw, and placement of the transducer via hand tightening. In addition, readings were obtained 3 times to ensure repeatability of the instrument. The cover screws were then replaced. To reduce observer bias, the previous recordings on the implant were not accessed prior to RFA measurement. Following the tenth week of healing, a computerized dental radiograph (Schick Technologies, Version 2.5, Long Island City, NY) was taken to examine the area in preparation for the restorative phase of treatment.

Although the length of the study period for RFA measurement was up to 10 weeks for all implants, 7 implants were also evaluated during the 11- to 20-week period and 9 implants were evaluated during the 21- to 25-week period. The average time point for RFA measurement in the 11- to 20-week period was 15 weeks, and the average time point was 23 weeks for the 21- to 25-week period.

Data Analysis

The sample size of 20 subjects was selected to provide data for preliminary assessments of the range of RF values over early time periods following implant placement. Statistical analysis was performed using only alphanumeric identifiers. Descriptive statistics were used to determine the distribution of implants according to bone type and gender and to characterize the ISQ levels over the 10-week healing period. Data analysis was accomplished relative to the implant ISQ values over time grouped by bone quality and arch location.

Three sets of 2-factor mixed-model analyses of variance (ANOVAs) (SAS Software; SAS Institute, Cary, NC) were performed to assess whether ISQ values changed across time depending on *(1)* bone quality, *(2)* implant arch location (maxilla or mandible), and *(3)* implant length. A post hoc analysis was carried out to examine these 3 variables at 4 time intervals: 0 versus 3 weeks, 3 versus 6 weeks, 6 versus 10 weeks, and 3 versus 10 weeks. A Student *t* test (SAS software; SAS Institute) was performed to compare the ISQ values at 10 weeks to the ISQ values at the 11- to 20-week interval and the 21- to 25-week interval for those implants tested beyond the 10-week study period.

RESULTS

Of the 27 SLA implants placed, 1 implant (3.7%) in Type 1 bone failed in the fourth week as a result of parafunctional load. Statistical analysis was carried out on the 26 remaining implants. The characteristics of the originally placed implants are as follows: 13 (48%) were 12 mm long and 14 (52%) were 10 mm long; 10 were placed in the maxilla and 17 were placed in the mandible; and 16 were in premolar sites and 11 were in molar sites. Implant populations in bone Types 2 and 3 were combined into a single group, because of supportive evidence from a recent study[19] that showed that intermediate bone density is difficult for the surgeon to reliably distinguish with drilling resistance. The distribution of implants according to bone type was 29.6% (n = 7) in Type 1 bone, 37% (n = 1 and n = 9, respectively) in Types 2 and 3 bone, and 33.3% (n = 9) in Type 4 bone. The ISQ values showed a high level of repeatability, with an accuracy of ± 1%. No patients reported discomfort when the transducer was used. In testing the effect of implant length with time using the mixed-model ANOVA, the greatest difference was at 3 weeks, when 12-mm implants had marginally higher stability than 10-mm implants (mean difference = 3.92 ISQ units, $P = .069$).

Implant Stability According to Bone Type

An analysis of stability patterns of the implants in each bone type group using descriptive statistics revealed that the lowest mean stability measurement was at 3 weeks for all bone types. Type 4 bone demonstrated the lowest stability at this time point. These results are shown in Fig 3. The percentage change of mean ISQ values from baseline is demonstrated in Fig 4 and shows that in Type 4 bone, an 8.6% decrease in stability occurred at 3 weeks and a 15.8% increase in stability occurred at 10 weeks. The change from 3 weeks to 10 weeks was a gain of 26.9% (± SE 5.07). Comparatively little change in stability from baseline readings was observed in Type 1 and Types 2 and 3 bone.

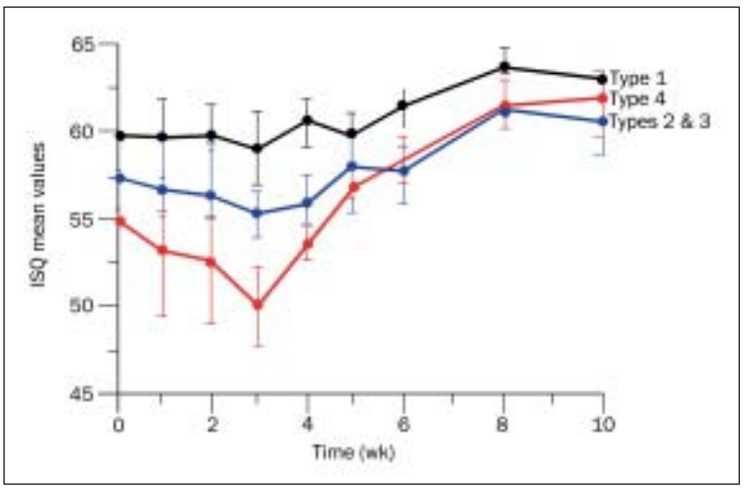

Fig 3 This graph represents the changes in stiffness of the implant in the healing bone relative to bone type. Data represent mean ISQ values ± SE at each time point measured in triplicate for each patient.

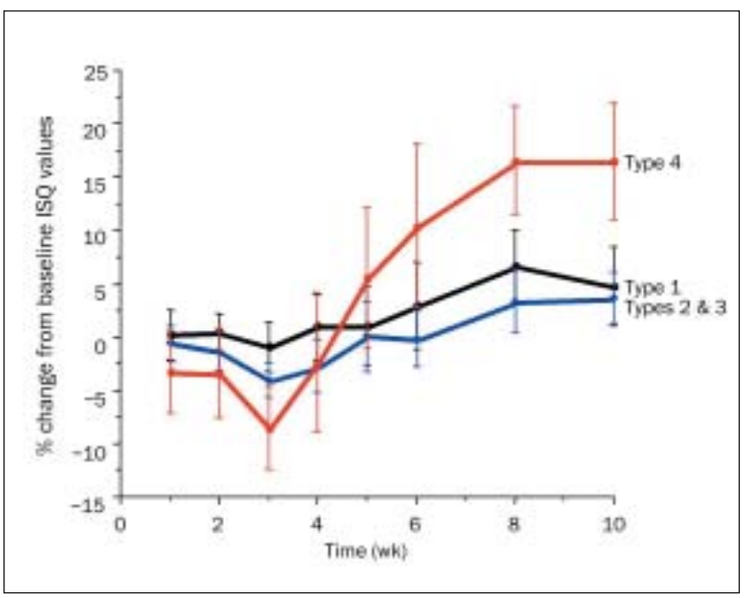

Fig 4 Percentage change in mean ISQ values ± SE as compared to baseline mean values relative to bone type. Data are based on mean ISQ values at each time point measured in triplicate for each patient.

A 2-factor mixed-model ANOVA demonstrated that both the main effect for time ($P < .001$) and time/bone quality interaction ($P < .005$) had a significant effect on ISQ values, but that bone quality alone did not. A Bonferroni adjusted Student *t* test comparison of bone groups at each time point revealed highly significant differences between implant stability in Types 1 and 4 bone ($P = .004$) and moderately significant differences between Types 2 and 3 and Type 4 bone at 3 weeks ($P = .08$). By 5 weeks, no bone groups showed any difference in implant RF measurements ($P = 1.0$). A post hoc analysis was performed to compare significant time points in the healing period (Fig 3). The time points that were included in the analysis were 0, 3, 6, and 10 weeks; 0 weeks was baseline, 3 weeks was the time point for the lowest observed ISQ values, 6 weeks was the time point for loading established in the literature,[6] and 10 weeks was the conclusion of the study.

Bonferroni-adjusted Student *t* test analysis of time within each bone type revealed that in Type 4 bone there was a significant decrease in stability from 0 to 3 weeks ($P = .05$). The mean ISQ values were significantly higher at 6 weeks as compared to 3 weeks ($P < .001$). The improvement in stability from 6 to 10 weeks was not statistically significant ($P = .094$). Implant stability in Types 2 and 3 bone showed significant changes only between 0 and 3 weeks ($P = .03$) and between 3 and 10 weeks ($P = .002$). There was no statistically significant change in implant stability at the 4 time intervals analyzed for Type 1 bone. A graphic representation of the changes in ISQ values for the 3 bone categories at each of the time intervals is shown in Figs 5 to 7; a

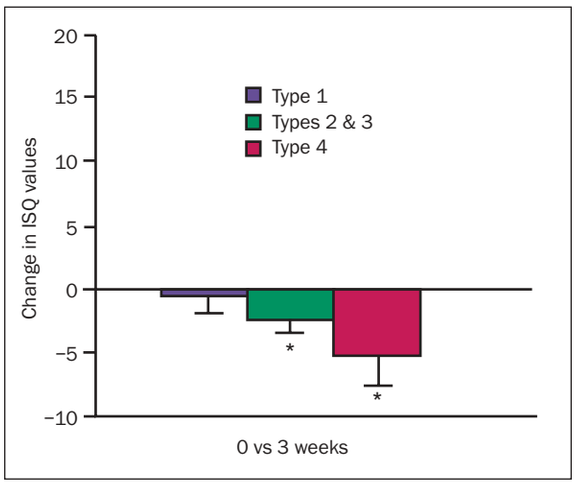

Fig 5 Post hoc analysis of change in mean ISQ values at the day of implant placement and 3 weeks later for all bone types. Statistically significant changes were observed for implants in Types 2 and 3 bone ($P = .034$) and Type 4 bone ($P = .049$).

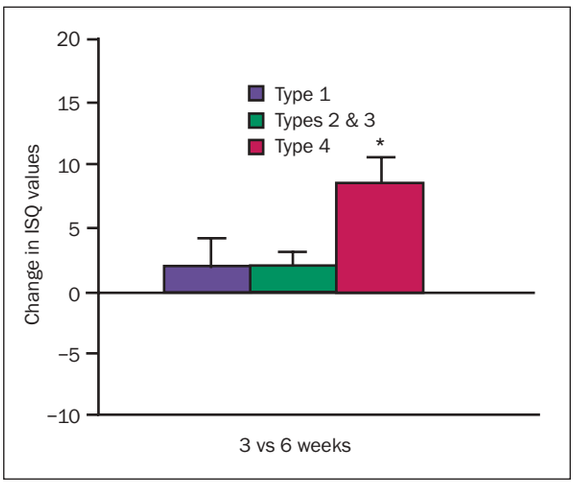

Fig 6 Post hoc analysis of changes in mean ISQ values between 3 and 6 weeks post–implant placement for all bone types. Statistically significant changes were observed for implants in Type 4 bone only ($P = .006$).

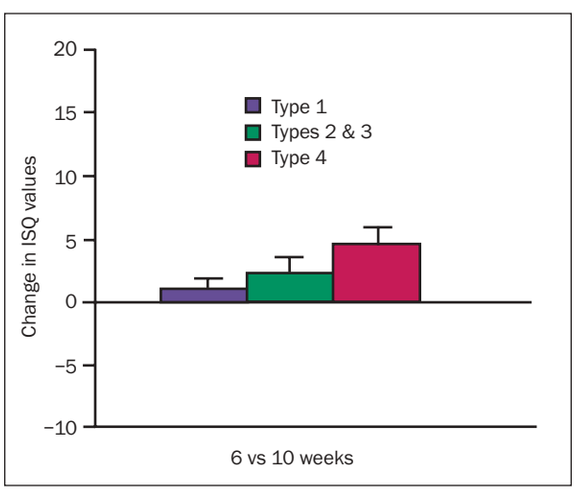

Fig 7 Post hoc analysis of change in mean ISQ values between 6 and 10 weeks post–implant placement for all bone types. No statistically significant changes ($P \leq .05$) were observed for implants in all bone types.

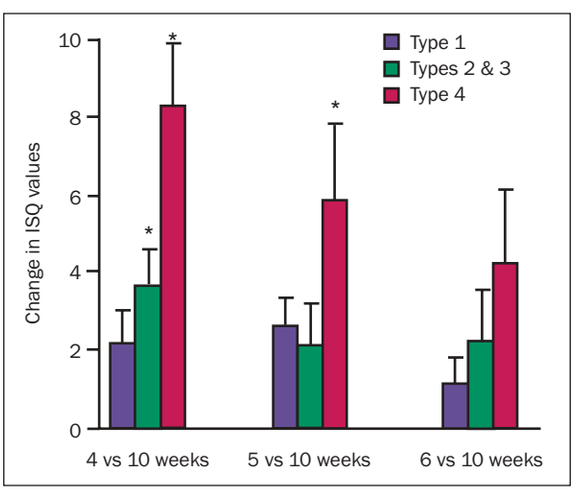

Fig 8 Post hoc analysis of the change in mean ISQ values between the 3 time intervals: 4 versus 10 weeks, 5 versus 10 weeks, and 6 versus 10 weeks for all bone types. A statistically significant change ($P < .05$) was observed for Types 2 and 3 and Type 4 bone between 4 and 10 weeks and for Type 4 bone between 5 and 10 weeks. All bone groups showed no significant change from 6 to 10 weeks.

significant difference in implant stability levels was clearly demonstrated within Type 4 bone at all time intervals except 6 versus 10 weeks. The changes and relative stability in Types 2 and 3 bone were more similar to those seen in Type 1 bone than those seen in Type 4 bone.

Because of the presence of statistically significant changes in implant stability from 3 to 10 weeks for Types 2 and 3 bone and Type 4 bone ($P < .05$) and the lack of significant change for all bone groups between 6 and 10 weeks, a post hoc comparison of 4 and 10 weeks and 5 and 10 weeks was performed to enable a closer examination of these critical time intervals. A statistically significant change in implant stability occurred for Types 2 and 3 bone and for Type 4 bone at the 4-week versus 10-week interval ($P < .05$) and for Type 4 bone at the 5-week versus 10-week interval (Fig 8).

Implant Stability Relative to Arch Location

In a 2-factor mixed-model ANOVA, the main effects of jaw position ($P < .005$) and time ($P < .001$) on ISQ values were significant. The overall jaw position/time interaction was not significant

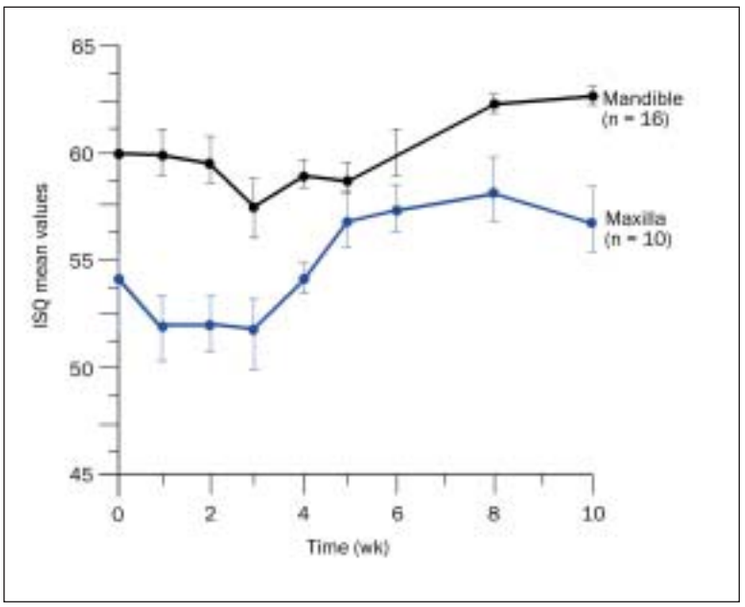

Fig 9 This graph represents the changes in stability of the implant in the healing bone relative to the arch in which the implant was located. Data represent mean ISQ values ± SE at each time point measured in triplicate for each patient.

($P > .30$) (Fig 9). Mean stability levels were higher for implants placed in the mandible compared to those placed in the maxilla at all time points observed. Therefore, there was no interaction between these groups. According to the Fisher exact test, mandibular implants, in general, were placed in better quality bone ($P < .035$).

Extended-term Implant Stability in Bone Categories

Although the length of the study period for RFA measurement was 10 weeks postplacement, measurements were taken up to 6 months later on 16 implants. The mean ISQ values for the 3 bone categories during the 2 time periods (11 to 20 weeks and 21 to 25 weeks) were compared to the values at 10 weeks for each bone type. Figure 10 demonstrates a much greater increase in stability in the 21- to 25-week group for all 3 bone categories in comparison to the 11- to 20-week group. Because the n value was relatively low for each bone group beyond the 10-week examination point, all bone groups were combined to perform a Student *t* test comparison of the 7 implants that were measured at both 10 weeks and at 11 to 20 weeks. Similarly, a *t* test was performed to compare the 9 implants measured at both 10 weeks and 21 to 25 weeks (Table 1). The mean change in ISQ value for the 7 implants from 10 weeks to 11 to 20 weeks was 1.6 (SE 0.70), which was not statistically significant ($P = .07$). However, the change in ISQ for the 9 implants measured at 10 weeks and 21 to 25 weeks was 6.4 (SE 0.63), or a 10.1% change, which was significant ($P < .001$).

DISCUSSION

The overall objective of this study was to quantify the early stability patterns of roughened-surface implants. Specifically, implants in different bone types and in both arches were evaluated and compared. The Osstell device, which is essentially identical to the RFA developed by Meredith,[5] was able to measure the overall stiffness of the transducer/implant/tissue system. The Osstell also served as a sensitive tool for clinically monitoring implant stability in bone of varying density. This finding is in agreement with earlier work.[15,16] However, direct comparison of this study with previous studies could not be established, as all previously published studies tested the machined-surface Brånemark System implant (Nobel Biocare, Göteborg, Sweden). The Brånemark System implant geometry, surface characteristics, stoichiometric composition, and loading protocols all differ from that of the ITI SLA implant. Particularly at early healing periods, the roughened-surface implant has been shown to provide a higher percentage of bone-to-implant contact[20] and increased removal torque values[21,22] as compared to a machined-surface implant. Thus, the improved biomechanical characteristics of the roughened-surface implant could affect the stability patterns during the

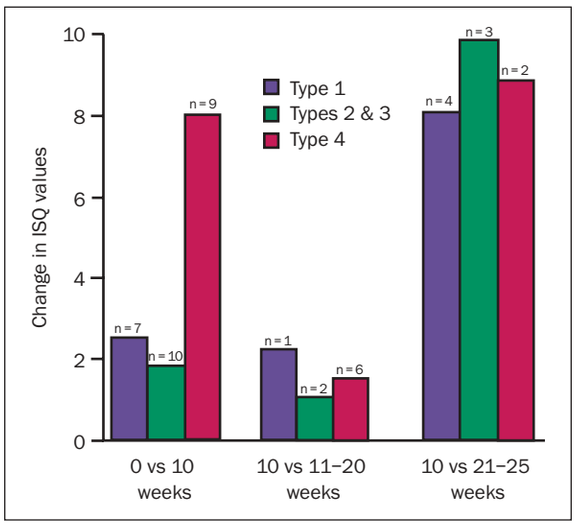

Fig 10 Changes in mean ISQ values from baseline to 10 weeks were compared to later healing periods of 11 to 20 weeks and 21 to 25 weeks. n = no. of implants measured at each time interval.

Table 1 Comparison of ISQ Values from 10 Weeks to 11–20 Weeks and 10 Weeks to 21–25 Weeks

Implant group	Mean ISQ score (%)	SE (%)
Group of 7 implants		
10 weeks	58.7	2.2
11–20 weeks	60.3	2.0
Change*	1.6 (2.8)	0.70 (1.3)
Group of 9 implants		
10 weeks	63.59	0.70
21–25 weeks	69.96	0.34
Change†	6.4 (10.1)	0.63 (1.10)

*$P = .07$; †$P < .001$.

early healing period. It has also been shown that the length of the implant above bone significantly impacts the RF values.[12] The ITI SLA implant is positioned with the smooth collar above the bone level. Therefore, the effective implant length above bone is 3 mm higher than Brånemark System implants, which would be reflected in a lower RF value. Therefore, to compare the results of this study with previous studies using the Brånemark-type implant, a conversion table must be created to account for the differences in implant height above the crestal bone. Furthermore, all previous studies recorded the RF values in Hertz as opposed to ISQ units. Although all ISQ units can be back-calibrated to Hertz units based on the patented algorithm provided by the manufacturer of the Osstell, the current understanding is that ISQ values will become the standard unit of stability reported in future articles.

In all previous studies, the stability of the implant was affected by healing time.[13,15,16] The comparison of time with bone type in the present study also indicates that the main effect for time was significant ($P < .0001$). This study shows that from baseline to 6 weeks of healing, the stability patterns in Type 1 and Type 4 bone were noticeably different, especially at the third week of healing (mean ISQ difference = 10.2; $P = .004$). No difference was found in mean ISQ values between bone groups at each time point after 4 weeks ($P = 1.0$). Although no occlusal forces were applied to the implants, the plateau effect in stability after 6 weeks agrees with the concept of enhanced bone formation around the SLA surface and the possibility of reduced clinical healing times prior to restoration.[6]

A close examination of the third week of healing revealed that in all 3 bone categories a decrease in ISQ values was observed. An examination of the stability change in each bone group between baseline and 3 weeks revealed only a 1% decrease in stability for Type 1 bone ($P > .60$). Implants in Types 2 and 3 bone experienced a stability change of 4.1% ($P = .04$). Type 4 bone showed the most change from baseline to 3 weeks (8.6%) ($P = .06$). Therefore, it appears that the amount and location of cortical and cancellous bone around the implant may be an important factor in providing resistance to lateral mobility, particularly at 3 weeks. When the stability of the implant in bone tissue is measured quantitatively, the stiffness of the tissue adjacent to and surrounding the implant will affect the stability measurement.[5] With Type 4 bone, for example, the overall stiffness of the bone will be less because of the thin cortical layer and large trabecular core of low density. Therefore, the majority of the implant surface will be occupied by bone with a low stiffness; hence the lower stability values. It is not surprising, then, that Type 1 bone showed the least fluctuation at this stage, as the greater bone density would contribute to higher levels of stiffness in the transducer/implant/tissue system during the resorptive phase.

The greatest change in stability occurred between 3 and 10 weeks in all 3 bone groups. This change in

stability might coincide with the physiologic changes reported by Roberts,[23] who extrapolated from the rabbit model that humans would begin to develop a bridging callus of bone from the endosteum and periosteum to the surface of a coated implant during the early modeling phase (0 to 6 weeks). The later stage of lamellar compaction within the loose stroma of the woven bone begins at 6 weeks and progresses to 18 weeks. Roberts[23] believed that the lamellar compaction would provide sufficient strength for loading. Of interest is the dramatic 27% increase in stability ($P < .0001$) for Type 4 bone from 3 to 10 weeks. After 8 weeks of healing, the RF values were similar between all groups. Thus, bone density/quality is not static but dynamic, as it seems to change in relation to an implant surface with time.[24]

This dynamic nature of bone during healing results in a change around the implant over time. Stability is required in this healing period and later during function to allow regeneration of bone to occur around the implant, rather than fibrous repair. Initially, primary stability occurs at the time of implant placement. This may be largely the result of the press-fit of the slightly larger diameter of the implant (in the case of the ITI implant) against the cut native bone surface, referred to as *primary bone contact*.[4] One of the factors thought to affect primary stability is the length of the implant.[25] In this study only 2 implant lengths were tested: 10 mm and 12 mm. The implant length had no significant effect over time ($P = .35$). In a multicenter study evaluating the long-term success of 2,359 nonsubmerged ITI titanium plasma-sprayed implants, Buser and coworkers[26] found no significant difference in the cumulative success rate between 10- and 12-mm implants over a period of 8 years.

Secondary stability is the result of bony modeling and remodeling on the osteoconductive titanium surface. During this healing process, woven bone becomes lamellar bone, and secondary bone contact increases while primary bone contact decreases.[4] The present study examined the transition in levels of stability from the time of primary bone contact to the development of early secondary bone contact during the first 10 weeks of healing. In each of the 3 bone groups, the 10-week ISQ values were higher than the baseline values, but the change from baseline to 10 weeks in each bone type group did not achieve statistical significance. During the early transition period between primary stability and secondary stability, Type 1 bone had no detectable difference at any time point up to 10 weeks. With the larger cortical bone volume around these implants, the lateral bending forces of the RFA would most likely be better resisted than in the case of implants in poorer quality bone.

Studies of gap healing have indicated that if stable fixation exists between the bone and implant, that fixation would avoid even minute interfragmentary movement and dynamic load bearing could be withstood.[27] In those implants showing high primary stability with limited change over time, an immediate loading protocol may be indicated. Early loading of Types 1 and 2 bone has been advocated in the literature, especially with roughened-surface implants.[20,28] With regard to Types 2 and 3 bone, the present study demonstrated statistically significant changes in implant stability between 0 and 3 weeks and 3 and 10 weeks. Although these changes were closer to the changes seen in Type 1 bone, it is difficult to advocate possible immediate loading protocols when stability levels were fluctuating in the first 10 weeks of healing. Perhaps a future study that incorporates a larger pool of implants placed in Type 2 bone would allow 4 separate bone groups to be examined. If similar results were found in Type 2 and Type 1 bone, it would provide more supportive evidence for early loading of implants in Type 2 bone.

A comparison of the stability patterns of mandibular and maxillary implants showed that the overall stability level was higher in the mandible. These results were consistent with reported higher survival rates of implants in mandibular than in maxillary bone.[29,30] The major difference in these regions is bone density.[31–33] Denser bone exists in the mandible, with 25% to 50% greater integrative success in the anterior mandible compared to the maxillary posterior area.[31,32] The present findings were also consistent in this regard, with no Type 1 bone found in the maxilla. In addition, 40% of the maxillary implants were in Type 4 bone, as compared to 31% of mandibular implants.

Although the study protocol did not extend out beyond 10 weeks, stability readings were obtained on 10 of the 20 patients at arbitrary time points between 11 and 25 weeks. A *t* test showed a minor increase in stability between 10 weeks and 20 weeks and a 10% increase between 10 weeks and 21 to 25 weeks. The positive changes in stability at 11 to 20 weeks are in contrast to the decrease seen at 15 weeks in studies of machined-surface implants.[15,16] It has been postulated that this decrease is related to marginal bone loss.[16] Another possibility is that roughened-surface implants offer a more osteoconductive surface than smooth-surface implants.[34] This would be important for earlier osseous healing and the development of secondary bone contact during the modeling and remodeling phases.[4]

In summary, this study permitted an evaluation of bone stability during healing around roughened-surface implants during the critical period of early

healing. The weekly visits allowed for a better view of the changes in bone following implant placement. The lowest values for interfacial stiffness between the bone and the implant were found at 3 weeks. This effect was most pronounced in Type 4 bone, and although it was observed in Type 1 bone, the change was not statistically significant. Healing responses of Types 2 and 3 bone were more similar to Type 1 than to Type 4 bone. The RF values at 6 weeks did not differ from those at 10 weeks in all bone types; this supports the idea of a 6-week healing period for ITI implants in Types 1, 2, and 3 bone.[6] The lack of significant change in stability from 5 to 10 weeks for Types 1, 2, and 3 bone supports further testing of an even shorter healing protocol. With regards to Type 4 bone, the current 12-week healing period could be evaluated and potentially shortened. Although these results show that the implants in Type 4 bone seemed to "catch up" to the implants in denser bone by the sixth week, the effect of occlusal loads during this early modeling period might influence the stability patterns and timing of stability.

Future directions for research in this area could involve comparisons of early healing patterns between smooth-surface and roughened-surface implants in humans. With recent interest in immediate loading of single-unit restorations, a study involving monitoring of the stability patterns of single-unit, immediately loaded, roughened-surface implants in Types 1 and 2 bone would offer insight into this relatively new field of study. The effect of splinting versus nonsplinting could be compared in an RFA study involving immediate hybrids and immediate single-unit restorations. It would be beneficial in these studies to also examine occlusal factors as possible variables in the healing process.

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