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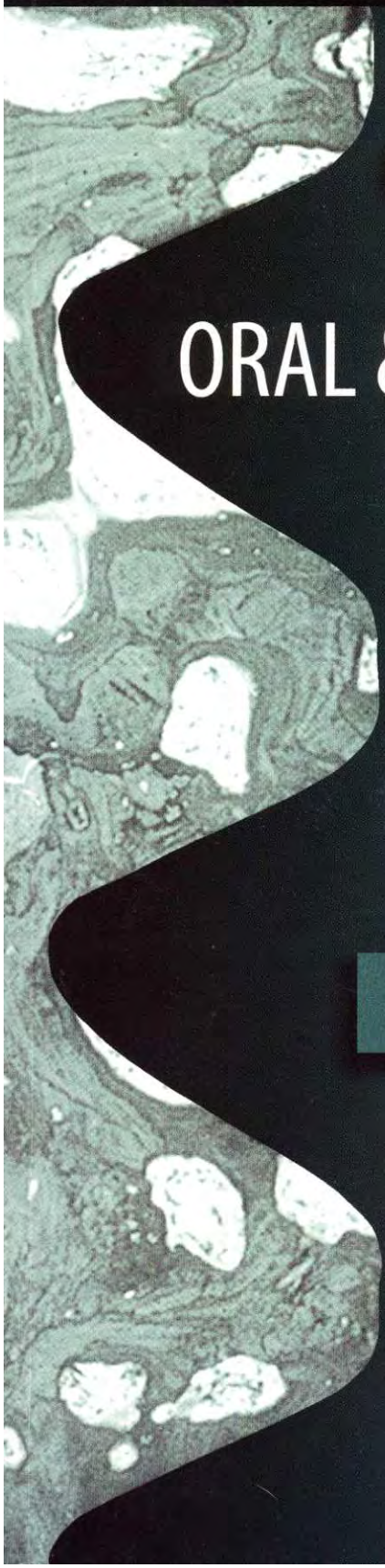

A RESONANCE FREQUENCY ANALYSIS ASSESSMENT OF MAXILLARY AND MANDIBULAR IMMEDIATELY LOADED IMPLANTS

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A Resonance Frequency Analysis Assessment of Maxillary and Mandibular Immediately Loaded Implants

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Purpose: *This study evaluated the stability of implants in 51 patients following a clinical protocol of immediate functional loading. The stability during the first 3 months following implant placement was assessed according to bone type, implant location, and patient gender.* ***Materials and Methods:*** *Twenty-two male and 29 female patients were treated with 344 Brånemark System implants placed in edentulous bone or extraction sites and put into functional loading using the Teeth in a Day protocol. Each implant was tested for primary stability with resonance frequency analysis (RFA) at the time of implant placement, and RFA was performed at examinations 30, 60, and 90 days following surgery.* ***Results:*** *The analysis was based on the 276 implants that were successfully measured using RFA at all postoperative intervals. The clinical implant survival rate was 98.5% for the total population. RFA showed a decrease in bone-implant stability in the first month after implant placement from 70.35 ± 0.5 to 66.38 ± 0.50, followed by increases in stability in the second and third months (68.01 ± 0.50 and 68.82 ± 0.49, respectively), suggesting a process of adaptive bone remodeling around the implant. In general, lower initial stabilities were seen in softer bone types, in the posterior portions of the jaw compared to anterior areas, and in the female population.* ***Discussion and Conclusion:*** *The results of this study suggest an immediate loading protocol should have an undisturbed period of healing for the first 2 months following implant placement. The determination of "predictor" stability levels for different clinical conditions were based on multiple splinted implants, allowing a larger surface area to withstand the distribution of the load. The most significant "predictor" values from a surgical and prosthodontic perspective are those determined in soft bone, in reduced bone, or in areas where lever arms are created as a result of long spans between the implants.* (More than 50 references.)
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Key words: *bone-implant interface, dental implants, immediate loading, implant stability, resonance frequency analysis*

Originally, the protocol described by Brånemark and associates[1,2] for direct bone-to-implant contact used submerged unloaded implants. More recently, many researchers, including Brånemark et al,[3] have revealed comparable results for the integration of implants placed under immediate functional load.[3–10] In many clinical situations, it is beneficial to the patient to use the immediate loading protocol rather than the conventional 2-stage protocol, as the former allows the patient to have a functional fixed prosthesis the same day as implant placement.

Implant stability is necessary for long-term success of implant prosthodontic treatment. However, implant stability remains in question when immediate loading is employed. Studies of immediate loading in the literature[3–10] show data for long-term osseointegration comparable to the results of Brånemark and coworkers' classic 2-stage study[1]; however, the stability of the implant over the initial short-term period after implantation has yet to be studied thoroughly.

The examination of stability resulting from osseointegration can be divided into primary and

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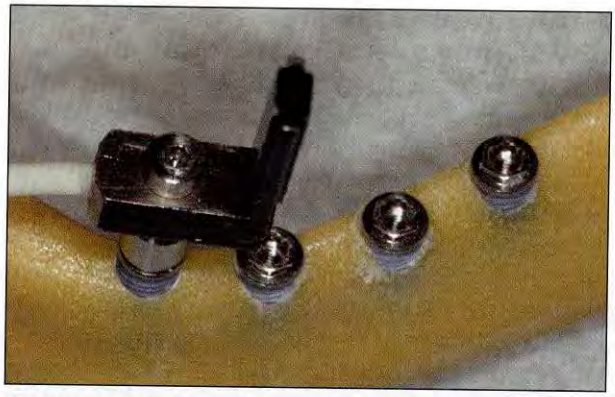

Fig 1a An Osstell transducer attached to a regular-platform (RP) Brånemark System implant parallel to the alveolar ridge of a synthetic bone model.

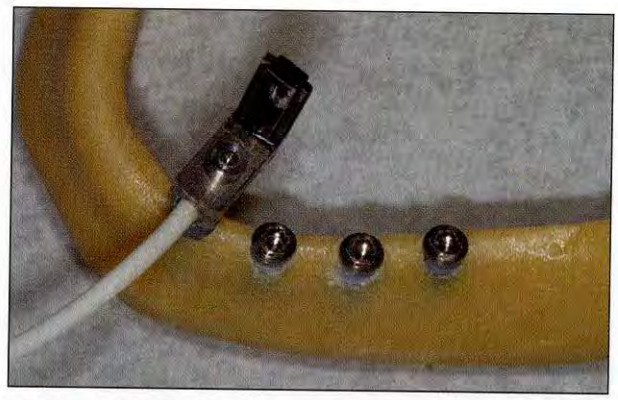

Fig 1b An Osstell transducer attached to an RP Brånemark System implant perpendicular to the alveolar ridge of a synthetic bone model.

secondary phases of stability. Primary stability is attained at implant placement and is determined by numerous factors, including density and mechanical properties of the bone, the implant design,[11] site complications,[12] and the surgical technique. Secondary stability depends on the further reaction of surrounding tissue to the implantation and is influenced by many factors, including patient behavior. These various factors result in different healing periods in various clinical situations. Numerous clinical studies have reported connections between bone characteristics and integration rates.[5–10,13–21] When the appropriate biologic and surgical conditions are present, some implants, including all the implant types and sizes used in this study, can be immediately loaded.

Since immediately loaded implant protocols depend on a certain level of implant stability, it is highly advantageous for the surgeon to measure implant stability in the clinical setting. Quantifying stability allows the clinician to determine whether an implant should be immediately loaded or submerged for a healing period. It has been shown histologically that the bone-implant interface can be stable with immediate loading protocols.[22]

Resonance frequency analysis (RFA) is a steady-state, nondestructive technique in which mechanical vibration is used to measure implant stability.[23,24] The resonance frequency is dependent on the stiffness of the bone-implant interface. It is theorized that changes in resonance frequency are largely the result of differences of the bone-implant interface and density of the adjacent bone.[25] Thus, theoretically, an implant placed in soft bone should yield a relatively low resonance frequency, while the same implant placed in compact bone in the same location should yield a higher resonance frequency. RFA has been used in several studies and with different applications.[21,26–30]

The purpose of this study was to gain insight into the dynamic pattern of implant stability under immediately loaded conditions. Furthermore, it was a goal of this study to develop "predictor" values for RFA measurements that would establish a record of ISQ values in a working range to be used for implant determination according to bone type, implant type, and location in the mouth, all related to the anticipated prosthetic restoration. Currently, only a general "predictor" stability measurement has been identified.[31] A prospective human clinical study was designed for applying the noninvasive RFA technique to quantify the clinical measurement of healing in the first 3 months of immediately loaded Brånemark System implants. It was hypothesized that RFA can be used clinically to monitor changes in implant stability under immediate loading conditions, revealing a dynamic stability pattern dependent on bone type, implant location, and patient gender.

MATERIALS AND METHODS

Resonance Frequency Measurements

All resonance frequency measurements in this study were made using Osstell L-shaped transducers (Integration Diagnostics, Göteborg, Sweden) designed for the Brånemark System. These transducers recorded all information as an implant stability quotient (ISQ), which is a function of bone-implant stiffness (N/μm) and marginal bone height. The ISQ is a dimensionless quantity; larger ISQ values indicate increasing levels of interfacial bone-implant stiffness (and thereby higher integration stability).

Synthetic Bone Model Test

Figures 1a and 1b show the transducer configurations for a synthetic bone study that was completed to show repeatability of measurements and to quan-

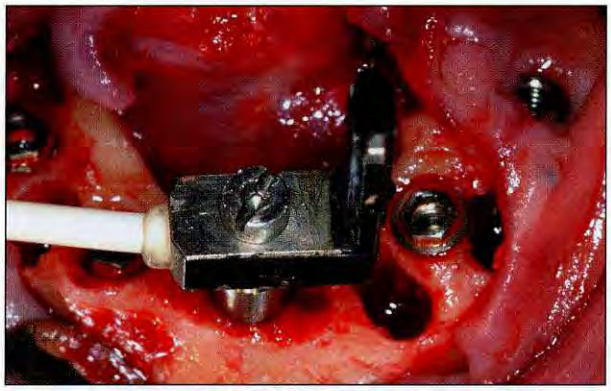

Fig 2 An Osstell transducer attached to an RP Brånemark System implant in the anterior mandible, parallel to the alveolar ridge.

tify the effect of variable implant length and variable abutment height on ISQ measurements. Once a standardized measurement protocol could be determined, ISQ values could be confidently ascribed to a given implant condition. Two manufactured synthetic jawbones (Nobel Biocare USA, Yorba Linda, CA) with different densities, 1 high and 1 low, were used for this testing. Twelve different Brånemark System implant types (Nobel Biocare USA) were placed in both synthetic bone types. All implants were placed consistently in the manner in which they would be surgically placed in a clinical setting.[20,32,33] Using an implant-level transducer, RF values were recorded 6 times (a triplicate measure parallel to the alveolar ridge, and a triplicate measure perpendicular to the alveolar ridge) on each of the 24 implants. A second implant-level Osstell transducer was used to perform RFA on the same implants to determine the accuracy between different transducers. These transducers were then sterilized and retested to determine accuracy after sterilization.

Following the implant-level measurements, 8 different Brånemark System abutments (3.0, 4.0, and 5.5 mm Standard; 1, 2, and 3 mm Estheticone; and 2 and 3 mm 17° Angulated) were fastened on each implant in sequence, and RFA was again performed 3 times in the parallel orientation on each of the 24 implants using an abutment-level transducer. No perpendicular measurements were taken at the abutment level. All implants and abutments used in the synthetic bone test were chosen for their frequency of usage in the clinical setting.

Clinical Measurements

All implants in this study were surgically placed in healed bone or fresh extraction sites by an experienced implant surgeon. Abutments were connected to the implants, and the implants were immediately loaded with a Teeth in a Day (TIAD) prosthesis made as previously described in the literature.[32,33] At the time of implant placement, the bone quality was determined clinically by the surgeon[34] according to the anatomic and bone density criteria established by Lekholm and Zarb.[35] Parallel RFA measurements were made for each implant before abutment connection (Fig 2). After the abutments were connected, an appropriate abutment transducer was accurately and firmly connected, and parallel RF values were recorded again on each implant. The transducers used in this study were connected using a torque driver set to 10 N/cm, which allowed the surgeon to attach the transducer to each implant and abutment with a uniformly firm clamping force. Patients were asked to return for postoperative visits 30, 60, and 90 days following the date of the surgery.

Three hundred forty-four Brånemark System implants were placed in 51 patients with a mean age of 55.6 ± 17.3 years (range 14 to 87 years); 202 implants were placed in 29 female patients and 142 implants were placed in 22 male patients. Inclusion criteria were based on the patient's current stable medical condition and his or her ability to undergo dental implant surgery. Patients with metabolic bone disease or an unstable systemic condition such as uncontrolled diabetes or untreated hypothyroidism were excluded.

Some patients were noncompliant with the postsurgical data-gathering protocol; therefore, not all 344 implants were tested at each follow-up visit. This reduced the sample size used for data analysis to 276 implants, the number of implants measured at all follow-up intervals. Statistical analysis was performed using analysis of variance (ANOVA) to assess whether ISQ values changed over the first 3 months according to position, bone type, or gender.

RFA "Predictor" Range Assessment

Using the results, it was possible to establish a set of preliminary guidelines for applying an immediate loading protocol based on 3 main characteristics: bone quality, implant location, and patient gender. The "predictor" ISQs formulated incorporated a safety margin based on the statistical averages of implants that remain in function ± 1 standard deviation. The resulting ISQ predictor ranges provide the surgeon with an expected level of implant stability according to RFA in the various clinical scenarios.

RESULTS

Synthetic Bone Test

Proof of RFA reproducibility was achieved from the synthetic bone tests, as shown in Tables 1 to 4 (mean

Table 1 Synthetic Bone Test: Brånemark System Implant-Level Transducer Measurements (ISQ Values) on Various Implant Sizes and Types

	ISQ values*							
	10		13		15		18	
	||	⊥	||	⊥	||	⊥	||	⊥
Hard synthetic jawbone								
Mk III TiU RP 3.75 mm	75	48	60	61	72	57	73	59
	75	48	60	62	68	57	75	59
	75	49	60	62	68	57	75	59
Mk III TiU RP 4.0 mm	71	34	72	46	73	48	74	65
	71	33	71	46	73	48	74	64
	71	34	72	33	72	48	74	65
Mk IV TiU RP 4.0 mm	71	33	76	46	82	66	70	57
	71	33	76	46	83	66	69	56
	71	33	75	46	83	65	69	59
Soft synthetic jawbone								
Mk III TiU RP 3.75 mm	74	71	73	72	76	76	77	79
	74	72	73	72	76	76	77	79
	74	71	73	72	76	76	77	79
Mk III TiU RP 4.0 mm	68	52	61	64	72	71	62	81
	67	52	61	62	73	71	63	82
	67	52	62	62	73	72	63	80
Mk IV TiU RP 4.0 mm	72	68	73	70	74	80	73	80
	72	68	73	70	74	79	73	81
	72	68	73	71	74	79	73	80

ISQ values grouped by implant length (mm).
*|| = parallel; ⊥ = perpendicular.

Table 2 Synthetic Bone Test: Brånemark System Implant-Level Transducer Comparison

	ISQ values*							
	10		13		15		18	
	||	⊥	||	⊥	||	⊥	||	⊥
Transducer 1	72	68	73	70	74	80	73	80
	72	68	73	70	74	79	73	81
	72	68	73	71	74	79	73	80
Transducer 2	72	68	73	70	74	80	73	80
	72	68	73	70	74	79	73	81
	72	68	73	71	74	79	73	80
Sterilized transducer	71	68	72	70	74	77	73	75
	71	68	72	70	73	77	73	75
	71	67	72	70	73	76	73	74

*Mk IV TiU RP 4.0-mm implants and soft synthetic jawbone used for all measurements.
ISQ values grouped by implant length (mm).
|| = parallel; ⊥ = perpendicular.

SE = 0.008). These tables are representative examples of the clinical data and provided a means for calibrating the measurement system.

Table 1 shows the triplicate measure of ISQ for both orientations (parallel and perpendicular) on each implant type. A high level of repeatability was achieved. The Mk III TiU RP 13 × 4 mm implant in the hard synthetic jawbone had 1 inconsistent reading in the perpendicular orientation.

Table 2 shows the comparison made using Mk IV TiU RP 4.0 mm implants between 2 implant-level transducers and also between transducer 1 before and after sterilization. These results show that the Osstell transducers were interchangeable and that the sterilization process used in this study did not affect the transducer accuracy.

Table 3 shows all the ISQ measurements made with the Brånemark System standard complete 5.5

mm abutments parallel to the alveolar ridge. One implant, Mk III TiU RP 4.0 × 18 mm, was very sensitive to changes in the transducer placement. Slight alterations from the parallel orientation showed dramatic differences in ISQ measurements. For this particular implant, 5 recordings were taken to substantiate the stability level.

Table 4 shows that the ISQs for all 8 abutment types on the Mk IV TiU RP 4.0 × 18-mm implant were comparable. There was no change in ISQ when the angulated abutments were subjected to a variety of rotated positions on the externally hexed implant, suggesting that ISQs can be successfully measured on angulated abutments.

Clinical Population

Patients received various implant designs at various locations determined by the prosthodontist's discretion. Table 5 shows the resultant frequency distribution of implant types used in this study and also details the location and bone type where implant was placed. Of the 276 implants, 2.2% were placed in type 1 bone, 23.2% in type 2 bone, 61.9% in type 3 bone, and 12.7% in type 4 bone. Of the 276 implants, 164 were immediately loaded in the maxilla and 112 in the mandible. The clinical survival rate (CSR) for this immediately-loaded implant population was 98.5% (339 of 344), which is higher than many reported 2-stage loading CSRs.[14,36–41]

Chronologic Composite RFA Measurements

RFA measurements from an accepted sample population were collected by the surgical team at 3 time points separated by 30-day intervals. Figure 3 represents the average ISQ values for the accepted sample population of implants (n = 276) at the 0- (70.35 ± 0.51), 30- (66.38 ± 0.50), 60- (68.01 ± 0.50), and 90- (68.82 ± 0.49) day evaluation times. The ISQ is a measure of the stiffness (and thereby the stability) of the implant-bone interface, and the results show a mean decrease of 3.97 ISQ from the initial placement date to 30 days postsurgery, followed by a mean increase of 2.44 ISQ from 30 to 90 days postsurgery. The ANOVA demonstrated statistical differences in mean ISQ between 0 and 30 days ($P < .01$) and between 30 and 60 days ($P < .02$). There was no statistical difference noted between the mean ISQ at 60 and 90 days ($P = .24$). Statistical significance was noted in mean ISQ between 0 and 60 days ($P = .01$), and between 0 and 90 days ($P = .03$).

Bone Quality

The ISQ values for each of 4 categories of bone quality[35] were analyzed (Fig 4). There was no significant difference between types 1 and 2 bone at any given time point. There was a signficant difference between types 2 and 3 bone and also between types 3 and 4 bone at each time point ($P < .02$). The ISQ of each particular bone type at the different time points was examined. No significant change in ISQ between time points was found for types 1 or 4 bone; however, types 2 and 3 bone showed a significant difference in ISQ between time points ($P < .01$). The ISQ for type 2 bone decreased but returned to its 0-day ISQ value by day 60; the ISQ for type 3 bone also decreased, but it returned to the 0-day ISQ by day 90. Thus, the effective zone of bone-implant interface

Table 3 Synthetic Bone Test: Brånemark System Abutment Level Recordings

Implant type	ISQ values		
Hard synthetic jawbone			
MK III TiU RP 3.75 × 10 mm	75	75	75
MK III TiU RP 3.75 × 13 mm	65	66	66
MK III TiU RP 3.75 × 15 mm	75	76	76
MK III TiU RP 3.75 × 18 mm	66	67	65
MK III TiU RP 4.0 × 10 mm	71	68	68
MK III TiU RP 4.0 × 13 mm	69	69	70
MK III TiU RP 4.0 × 15 mm	73	75	74
MK III TiU RP 4.0 × 18 mm*	75	60	76
MK IV TiU RP 4.0 × 10 mm	72	71	71
MK IV TiU RP 4.0 × 13 mm	73	73	74
MK IV TiU RP 4.0 × 15 mm	62	62	63
MK IV TiU RP 4.0 × 18 mm	70	70	69
Soft synthetic jawbone			
MK III TiU RP 3.75 × 10 mm	74	74	74
MK III TiU RP 3.75 × 13 mm	69	68	70
MK III TiU RP 3.75 × 15 mm	72	72	71
MK III TiU RP 3.75 × 18 mm	80	81	81
MK III TiU RP 4.0 × 10 mm	69	69	68
MK III TiU RP 4.0 × 13 mm	62	61	64
MK III TiU RP 4.0 × 15 mm	67	69	69
MK III TiU RP 4.0 × 18 mm	64	66	66
MK IV TiU RP 4.0 × 10 mm	73	72	72
MK IV TiU RP 4.0 × 13 mm	73	73	73
MK IV TiU RP 4.0 × 15 mm	77	77	77
MK IV TiU RP 4.0 × 18 mm	77	77	77

*Two additional measurements were taken (61, 77).
Brånemark System Complete 5.5-mm abutments used.

Table 4 Synthetic Bone Test: Brånemark System Abutment Level Comparison

Abutment type	ISQ values			Average
3 mm Standard	72	72	71	72
4 mm Standard	72	70	69	70
5.5 mm Standard	70	70	69	70
1 mm Estheticone	74	74	74	74
2 mm Estheticone	74	74	74	74
3 mm Estheticone	70	73	73	72
2 mm 17°Angulated	76	75	73	75
3 mm 17°Angulated	73	75	74	74

Brånemark System Mk IV TiU RP 4.0 × 18-mm implants in hard synthetic jawbone used.

Table 5 Clinical Distribution of Brånemark System Implants by Location and Bone Quality

Implant type/ length (mm)	n	Maxilla bone type								Mandible bone type							
		Posterior				Anterior				Posterior				Anterior			
		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Standard (3.75 mm diameter)																	
13 mm	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Standard (5.0 mm diameter)																	
12 mm	2	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
TiUnite Mk III RP (3.75 mm diameter)																	
8.5 mm	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
10 mm	8	0	0	2	0	0	0	1	0	2	2	0	0	1	0	0	0
13 mm	33	0	1	2	0	1	1	10	0	0	5	1	0	0	7	5	0
15 mm	45	0	0	3	0	1	6	3	0	0	3	2	0	0	24	2	1
18 mm	13	0	0	0	0	0	0	5	0	0	1	2	0	0	0	5	0
TiUnite Mk III RP (4.0 mm diameter)																	
10 mm	2	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0
13 mm	6	0	0	1	2	0	0	3	0	0	0	0	0	0	0	0	0
15 mm	14	0	1	1	3	0	0	2	2	0	0	3	0	0	0	2	0
18 mm	12	0	0	0	0	0	0	0	0	0	0	4	0	0	0	8	0
TiUnite Mk IV RP (4.0 mm diameter)																	
8.5 mm	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
10 mm	34	0	0	12	8	0	0	5	0	0	1	8	0	0	0	0	0
13 mm	39	0	2	9	1	0	0	16	3	0	0	5	0	0	3	0	0
15 mm	42	0	1	14	4	0	0	12	0	0	1	8	0	0	0	1	1
18 mm	15	0	0	6	3	0	0	1	5	0	0	0	0	0	0	0	0
Zygoma																	
35 mm	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
42.5 mm	3	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0
45 mm	2	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
47.5 mm	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
50 mm	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	276	0	7	56	23	2	7	59	10	3	16	33	0	1	34	23	2

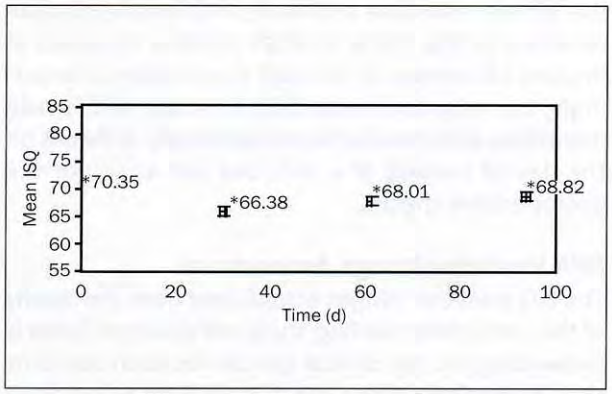

Fig 3 Stiffness of the implant population (n = 276) represented in mean ISQ values ± SE 0, 30 ± SE, 60 ± SE, and 90 ± SE days postsurgery. The SE shown on the x-axis represents the variation in days of the patient postsurgery evaluation time point. Statistical differences were seen between 0 and 30 days, 0 and 60 days, 30 and 60 days, and 0 and 90 days. No statistical significance was noted between 60 and 90 days. The SE values for the ISQ at each time point were 0.511 at surgery, 0.496 at 30 days, 0.497 at 60 days, and 0.488 at 90 days. The SE for the synthetic bone test was 0.008. * Statistically significant difference between time points ($P < .03$).

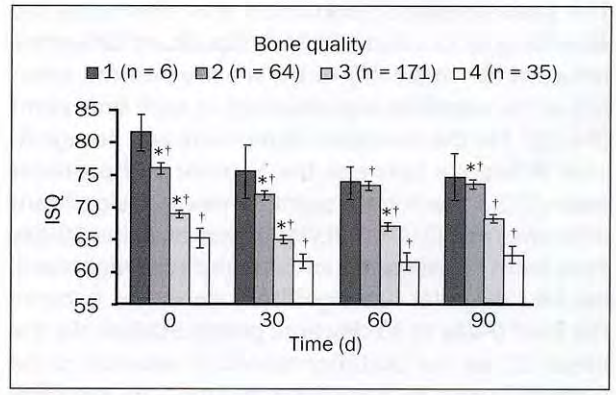

Fig 4 Stiffness of the implant population according to bone type, represented in mean ISQ values ± SE 0, 30, 60, and 90 days postsurgery. Statistically significant changes in ISQ were seen in bone types 2 and 3 between 0 and 30 days ($P < .01$). Bone type 3 also changed significantly in ISQ between 30 and 60 days ($P < .01$). There was no statistical difference between 0 and 90 days for bone types 1, 3, or 4. A statistically significant change was noted between 0 and 90 days for bone type 2 ($P < .03$). *Statistically significant difference within a respective bone type category between time points ($P < .01$). †Statistically significant difference between bone types at a given time point ($P < .02$).

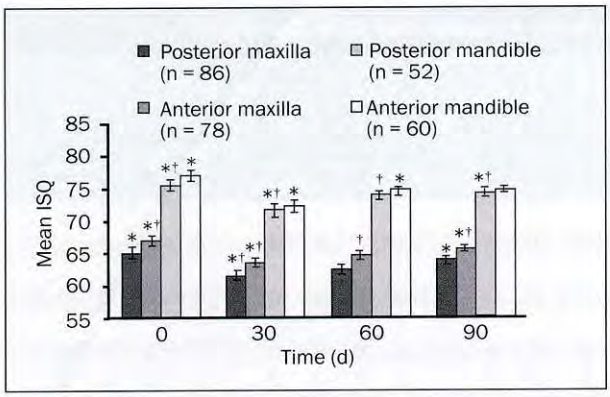

Fig 5 Stiffness of the implant population according to implant location, represented in mean ISQ values ± SE 0, 30, 60, and 90 days postsurgery. Statistically significant changes in ISQ were seen in all regions between 0 and 30 days, in the anterior mandible between 30 and 60 days, and in the anterior and posterior maxilla between 30 and 90 days. Statistically significant differences were seen between the maxilla and mandible at all time points and between the anterior and posterior maxilla at 30 days. * Statistically significant difference within a respective implant location category between time points ($P < .03$). † Statistically significant difference between implant locations at a given time point ($P < .02$).

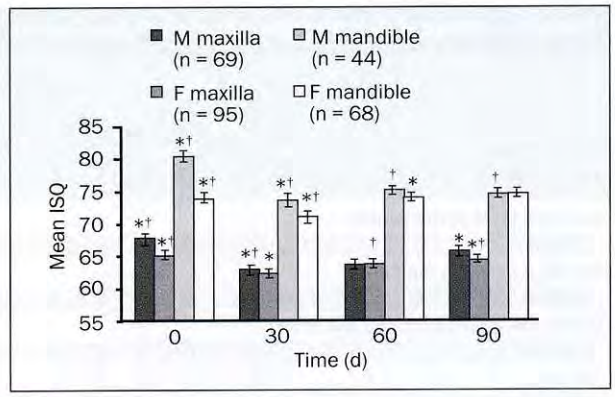

Fig 6 Stiffness of the implant population according to gender and arch, represented in mean ISQ values ± SE 0, 30, 60, and 90 days postsurgery. Statistically significant changes in ISQ were seen in all categories between 0 and 30 days, in the female mandible between 30 and 60 days, and in the female and male maxillae between 30 and 90 days. Statistical differences in mean ISQ were noted between all categories at implant placement, and between the mandible and maxilla at each postoperative interval. * Statistically significant difference within a respective category between time points ($P < .03$). † Statistically significant difference between categories at a given time point ($P < .02$).

remodeling appeared to be confined to bone types 2 and 3 in the first 90 days postsurgery. Successful osseointegration occurred in both type 1 and type 4 bone within 90 days. Successful osseointegration may have been influenced by the thread configuration (implant type), number, size, and distribution of the implants along with the splinting effects of the TIAD prosthesis.

Implant Location

The same implant population was also analyzed according to location (Fig 5). A significant difference between the mean ISQ of the maxilla and the mean ISQ of the mandible was observed at each time point ($P < .02$). For the mandible alone, there was no significant difference between the anterior and posterior mean ISQ at each time point; however, a significant difference in ISQ ($P = .02$) was observed at the 30-day time point between the anterior and posterior maxillae. All categories had significant decreases in mean ISQ from 0-day to 30-day time points. Statistically, the mean ISQ for the posterior mandible returned to the 0-day ISQ value by day 60; the mean ISQ for the anterior and posterior maxillae returned to the 0-day ISQ value by day 90. There remained a statistical significance in mean ISQ for the anterior mandible between 0 and 90 days, suggesting the presence of dense bone at implant placement.

Gender

Mean ISQ values according to gender and arch are presented in Fig 6. As with implant location, there was statistical significance at all time points between the mandible and maxilla ($P < .02$). During the first 30 days, the decreases in mean ISQ in each category were found to be statistically significant. From 30 to 90 days, there was a mean increase in ISQ for each category. Only the male mandible did not show a statistically significant difference from 30 to 90 days. At 90 days, the only statistical significance seen in reference to implant placement in primary stability was a decrease in the male mandible ($P < .01$). Statistically, the female mandible and male and female maxillae returned to the initial level of stability recorded at implant placement at 90 days postsurgery. Interestingly, the recorded mean ISQs for male and female mandibles and maxillae were statistically different on the day of surgery ($P < .02$), but not at any of the postoperative checks.

RFA Predictor Range Assessment

The ISQ predictor ranges established from the results of this immediate loading study are shown in Table 6. Depending on the clinical gender-location scenario, the ISQ predictor range can deviate from as low as 57 (female, posterior maxilla, type 4 bone) to as high as 88 (male, anterior mandible, type 1 bone). Table 6 shows a generalized lower ISQ prediction for the maxilla than the previous general predictor reported in the literature.[31] Because of a lack of clinical data for certain gender-location scenarios, ISQ predictor ranges were not established for all scenarios. Although these clinical scenarios may exist, they are least likely to be seen because of the bone quality

Table 6 Clinical Predictors for Successful Osseointegration Under Immediate Loading Conditions

	Mandible				Maxilla			
	Anterior		Posterior		Anterior		Posterior	
Bone type	M	F	M	F	M	F	M	F
1	86 ± 2	–	85 ± 2	–	–	73 ± 6	–	–
2	81 ± 5	75 ± 5	81 ± 4	73 ± 6*	75 ± 6	69 ± 5	72 ± 6	69 ± 6
3	79 ± 4	74 ± 6	76 ± 6	74 ± 6	69 ± 6	66 ± 6†	67 ± 6	64 ± 7‡
4	–	74 ± 5	–	–	69 ± 4	64 ± 7	64 ± 6	64 ± 7§,‖

–No data recorded in the clinical scenario.
*Implant failure with day 0 ISQ 73; reason: facial trauma.
†Implant failure with day 0 ISQ 61; reason: fibrous encapsulation.
‡Implant failure with day 0 ISQ 67; reason: sinus infection around zygoma implant.
§Implant failure with day 0 ISQ 73; reason: sinus infection around zygoma implant.
‖Implant failure with day 0 ISQ 58; reason: fibrous encapsulation.

normally associated with these locations. The determination of predictor stability levels for different clinical scenarios in Table 6 was based on the splinting of multiple implants, which allows a larger surface area to withstand the distribution of the load.

DISCUSSION

RFA is emerging as a valuable tool for the implant surgeon to determine the viability of a particular implant by providing a relatively unobtrusive method for assessing the stability of the newly placed implant. The current tendency in reconstructive medicine, and especially in implant prosthodontics, is to increase patient acceptance of special treatment protocols by decreasing treatment time and the number of surgical episodes. Immediate loading protocols, when appropriate, can provide patients with expedited care while delivering them a predictable and successful prosthetic restoration.

The findings of the present study show that: *(1)* RFA measurements may be applied as a predictor of implant success for immediately loaded implants, *(2)* the bone-implant interface transitions through an adaptive phase of lowered stability and back to a more stable configuration in a 60-day period, and *(3)* the adaptive process is modulated by specifics of the bone type, implant location, and patient gender. Based on these findings and previous efforts by Meredith and Sennerby,[23–25] among others,[21,26–30] a table of RFA ISQ ranges was developed based on bone type, implant location, and patient gender that can be used as a guideline for determining the specifics of immediate loading under the TIAD protocol.[33] However, these guidelines should be used with caution. An ISQ value below the predictor range may indicate the implant does not have sufficient primary stability to undergo immediate functional loading. An ISQ value above the predictor range may represent either an inaccurate identification of bone quality at the implant site or an incorrect resonance frequency measurement technique.

The RF measurements in this study were not used as criteria for loading an implant. This clinical study consisted of a completely random sample of patients. All 276 implants in the clinical sample were immediately loaded within an hour of implant placement. Each implant was placed and loaded according to the surgeon's clinical experience, with load distribution and implant position related to the opposing dentition.

To avoid measurement inconsistencies, it was determined that all of the clinical RFA measurements should be conducted using the parallel orientation of the transducer. In the preliminary stages leading up to this study, it was observed that the ISQ level was often influenced by orientation of the transducer to the axis of the alveolar ridge. An RF value was taken with the transducer oriented perpendicular to the alveolar ridge of the jaw. On the same implant, the transducer was adjusted so its orientation was parallel to the alveolar ridge of the jaw and a second RF value was taken. Some of the perpendicular measurements had ISQs equal to or higher than their parallel counterparts, which prompted the need to maintain a consistent protocol.

Based on the preliminary data of Glauser and colleagues, immediate loading should be possible where the ISQ is greater than 60 at implant placement.[31] However, depending on the implant location and bone type, ISQ values lower than 60 were successful under this immediate loading protocol. Ninety-seven percent (32 of 33) of the implants in this study that had a primary stability less than 60 ISQ (range 47 to 59) achieved osseointegration.

The idea that ISQ values of 60 to 65 could be safe for immediate loading is based on the observation

that most implants eventually achieve a secondary stability within this range in the period after the initial healing phase.[31] However, since loading conditions are not the same in all patients and all regions of the mouth, the impact of loading will differ and can alter secondary stability. Axial bite forces can range from 500 N in the canine region to 800 N in the molar region.[42] Thus, categorized RF predictor ranges that consider these variable biomechanical factors can be valuable for determining a safe ISQ value in an immediate loading protocol.

In this general population sample, a statistically significant decrease was seen in mean ISQ between the implant placement date and 30 days postsurgery, which signifies that this is a vulnerable time in the bone remodeling process. However, after 60 days, much of the bone remodeling had already taken place, and the vulnerable period appeared to be over, since there was no decrease in ISQ after the 60-day interval.

The present findings suggest that initial bone quality at implantation can affect the rate of bone remodeling and thus secondary stability. It has been clearly demonstrated that bone quality around the implant influences primary stability.[43] As expected because of the amount and location of cortical and trabecular bone, type 1 bone had the highest primary stability but showed the highest decrease in mean ISQ in the first 30 days. These results are contrary to results of Calandriello and associates,[29] who found that implant stability remained high for implants placed in the molar region over a longer period of 6 months. In the present study, bone types 2 and 3 showed a more consistent return of primary stability while bone types 1 and 4 did not. Ideally, bone types 2 and 3 would be advocated for an immediate loading protocol,[44] because of their combined innate stability and regenerative capabilities. However, osseointegration was achieved with all 4 bone types, despite the fact that not all ISQ values returned to original levels.

In this immediate loading study, an evaluation of the stability patterns of mandibular and maxillary implants showed that survival rates were 99.1% in the mandible and 97.5% in the maxilla. These survival rates are consistent with those reported in previous studies.[13,29,45] A limited number of studies have reported success with immediate loading protocols in the maxilla.[5,46–48] This current work supports those reports with an implant success rate of 98.0% for 164 immediately loaded maxillary implants. An analysis of the stability curves during the early healing period showed that even type 4 bone is capable of achieving osseointegration in this specific immediate loading procedure.

Mandibular flexion, which has been demonstrated and measured clinically in patients with osseointegrated implants,[49] did not contribute to implant failure in this report. Only 1 implant placed in the mandible failed to osseointegrate (99.1% survival) because of reported accidental trauma applied to the area of the face where the implant was placed between the surgery date and the 30 day follow-up visit. All other mandibular implants in this study remained functional.

The results of this study suggest the implant modulation of a bone-implant stability "set point" depending on bone quality, implant location, thread design, and surgical technique. The statistically significant difference in primary stability between the mandible and the maxilla within each gender was expected because of the results seen in Fig 5. What is notable here are the comparisons between the male and female mandibles and male and female maxillae. At implant placement, the primary stability of the male and female mandibles had a statistically different mean ISQ ($P < .02$). At 90 days postsurgery, the mean ISQs of the male and female mandibles were statistically identical (Fig 6). A similar finding was evident in the maxilla. The results from this study and 1 from Olsson and colleagues[21] suggest that implants placed with high levels of primary stability do not return to the initial level of stability but that implants in bone with lower levels of primary stability can return to or exceed the initial level of stability. These data show that although bone levels and stability levels may be different between sexes, gender does not matter in terms of successful long-term osseointegration. Even in patients where osteoporosis is most likely to exist (elderly females),[50,51] functional loading promotes bone formation and maturation around the implants, making the bone stronger. The use of an immediate loading protocol, which applies functional load directly to the implants immediately after implant placement surgery, may promote better bone growth in patients with severe bone loss when compared to a 2-stage protocol. This is of course contingent on maintaining a reasonable level of stability during the critical healing period following implant placement.

In the current report, effective bone remodeling and osseointegration occurred even where implants were placed in type 4 bone with an ISQ as low as 47. However, the predictor ranges for each clinical scenario enumerated in Table 6 should be used with caution. Implants that have a primary stability within the ISQ predictor range for a particular clinical scenario still can fail to osseointegrate because of micromotion created by overload during the initial healing process. This often can be the case with single-tooth

or short-span replacements that are in hyperocclusion from the onset. These ISQ predictor ranges are based on clinical situations in which multiple implants were splinted, allowing a greater joined surface area to withstand the distribution of the load. The most significant predictor values from a surgical and prosthodontic perspective are those determined in soft bone, in less bone, or in areas where lever arms are created because of long spans between the implants.

CONCLUSIONS

RFA was used in this study to assess the stability of the bone-implant interface during the first 3 months of healing for Brånemark System implants under immediate loading conditions. It was observed that stability varied according to bone type, implant location, and patient gender. A common occurrence seen throughout this study was a significant decrease in stability from the time of implant placement to 30 days postsurgery, followed by an increase in stability approaching the original stability level. This finding identified a 60-day critical healing period prevalent after implant placement for the immediate loading protocol, indicating the need for a postsurgical, 2-month healing phase. The stability analysis also demonstrated that immediate loading protocols can be suitable for soft bone implantation, including implantation in the posterior maxilla, which presented the largest percentage of soft bone encountered in this study. Finally, the development of ISQ predictor ranges provides the clinician with a record of viable stability measurements as a reference for effective immediately loaded implantation given different clinical scenarios. This helps the practitioner in assessing the suitable conditions for implantation and is advantageous to the patient by expediting the process for final impressions and delivery of definitive restorations.

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