

# Longitudinal Implant Stability Measurements Based on Resonance Frequency Analysis After Placement in Healed or Regenerated Bone

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Primary stability is an indicator of subsequent osseointegration of dental implants. However, few studies have compared the implant stability among anatomical regions and bone types; thus, not enough data exist regarding the stability of implants placed in regenerated bone (RB). The present study evaluated primary and long-term stability of implants placed in RB and non-regenerated healed bone (HB). A total of 216 screw cylinder implants were placed in 216 patients (98 in HB and 118 in RB, 6 [RB6, N = 68] or 12 [RB12, N = 50] months after tooth extraction). Implant stability was evaluated using resonance frequency analysis (RFA) measured at the time of implant placement (E1), at the time of loading (4 months after placement, E2), and 4 months after loading (E3). Various clinically relevant measurements were obtained, such as implant diameter, length, and location, as well as bone quality. At E1, implant location, bone quality, and experimental group significantly affected implant stability (all at  $P < .05$ ). At E2, implant location, diameter, length, and experimental group significantly affected implant stability (all at  $P < .05$ ). At E3, bone quality, implant diameter, length, and experimental group significantly affected implant stability (all at  $P < .01$ ). Stability for the RB12 group was significantly higher than all other corresponding values; further, the values did not change significantly over time. For the HB and RB6 groups, stability was significantly higher at E2 than at E1 ( $P < .001$ ) and was no different between E2 and E3. Implant location, length, and experimental group were associated with these differences (all at  $P < .05$ ). Compared with HB and RB6, higher implant stability may be achieved in regenerated bone 12 months post-extraction (RB12). This stability was achieved at E1 and maintained for at least 8 months. Variables such as implant length, diameter, and bone quality affected the stability differently over time. Implant stability varied in different anatomic regions and with regard to different healing processes in the bone.

**Key Words:** dental implants, implant stability, resonance frequency analysis/RFA, regenerated bone, guided bone regeneration, socket preservation, ridge preservation, extraction socket

## INTRODUCTION

Dental implants are a safe, reliable, and effective technique of replacing missing teeth.<sup>1-4</sup> And, advances in the field of tissue regeneration have led to new treatments in the field of implantology.<sup>5-7</sup> Implant success and long-term survival are influenced by several factors: (1) the

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patient's oral hygiene and participation in a periodontal maintenance program,<sup>4</sup> (2) factors related to the surgical procedure, (3) quality of the alveolar bone plus occlusal/prosthetic factors.<sup>3,8,9</sup>

Meredith<sup>10</sup> stated that primary implant stability (PISt) is a function of local bone quality and quantity, geometry of an implant, and the placement technique. Primary implant stability is commonly understood as the lack of implant movement immediately after placement. Implant stability (ISt) is thought to be influenced by several factors, including implant design, diameter, length, and available bone support. ISt, both at the time of placement and during function, is an important criterion for the success of implant treatment.<sup>11–14,16–19</sup> However, differences in PISt in different regions of the jawbone have not been studied extensively. Although regenerative bone procedures have created new options in oral implantology, the primary and long-term stability of implants placed in regenerated bone have not been determined.

Resonance frequency analysis (RFA) is a method of determining ISt. It measures the vibration frequency of the implant after a predetermined lateral force has been applied to the implant.<sup>20–22</sup> Established as a simple and noninvasive way to monitor osseointegration, RFA has been used extensively in clinical and experimental studies throughout the past decade. RFA requires the placement of an electronic transducer onto the implant head or prosthetic abutment with a retaining screw and the passage of a low-voltage current, undetectable by the patient, through the transducer. The surrounding bone's resistance to the vibration of the transducer—measured in hertz (Hz)—is registered in a small computer device. Hertz measurements have been calibrated for each transducer and are converted to implant stability quotient (ISQ) numeric values by the computer. ISQ values are favorably related to the bone-implant interface.<sup>18,23–25</sup> However, normal ISQ levels do not appear to have been established.

The aim of the present study was to compare the long-term stability of implants with identical geometry placed in either healed or regenerated bone in different anatomical regions using an identical surgical technique and RFA.

## MATERIALS AND METHODS

### Study population

In the present controlled, double-blind, randomized, prospective clinical study, a total of 216 cylindrical screw-type implants were placed in 216 patients (Table 1). The implants were placed in areas of both non-regenerated healed bone (HB group, N = 98) and regenerated bone (RB groups, N = 118). In RB, implants were placed 6 (RB6 group, N = 68) or 12 (RB12 group, N = 50) months after tooth extraction. The study was performed according to the Helsinki Declaration of 1975 as revised in 1983, and was approved by the institution's ethics commission. All subjects were informed about the treatment procedures and were given at least 2 weeks to consider the information before signing an informed consent form.

### Patient selection and randomization

All patients were treated at the Division of Periodontology, Dental School, Catholic University, Rome, Italy, and were selected according to the following criteria: (1) history of chronic periodontitis, (2) periodontal treatment was performed 4–6 months before beginning the present study, (3) patients demonstrated good oral hygiene and compliance at the beginning of the present study, (4) teeth adjacent to the implant area were free of overhangs or insufficient restoration margins or caries, (5) only one implant scheduled for a single crown restoration was selected for each patient; if more than one implant per patient fit the above-mentioned criteria, one of the implants was randomly assigned to the study.

Individuals were excluded from the study in the case of (1) presence of a systemic disease, pregnancy, or the regular use of prescription medication or of recreational drugs, (2) smoking more than 10 cigarettes per day, (3) implant placement in areas of teeth with periapical radiolucencies or in areas of third molars.

A commercial random-number software program (MakroBer, Unisol, Braunschweig, Germany) was used to assign each patient to one of three implant groups: HB, RB6, and RB12.

Envelopes numbered from 1 to 200 were prepared for the HB group and from 1 to 300 for the combined regenerated bone groups. A card with either "1" (study participation) or "2" (non-

TABLE 1  
Composition of experimental groups

Variable	Total (N = 216)	RB6 (n = 68)	RB12 (n = 50)	HB (n = 98)	P
Age, mean (SD)	54 (10)	56 (8)	50 (11)	55 (10)	.003
Women, n (%)	122 (56)	33 (49)	23 (46)	66 (67)	.01
Nonsmokers, n (%)	171 (79)	59 (87)	39 (78)	73 (75)	.16
Women smokers, n (%)	92 (75)	28 (85)	16 (70)	48 (73)	.32
Implants in maxilla, n (%)	124 (57)	40 (59)	26 (52)	58 (59)	.68
Implants in mandible, n (%)	92 (43)	28 (41)	24 (48)	40 (41)	
Location, n (%)					
Maxilla anteriors	31 (14)	13 (19)	8 (16)	10 (10)	.02
Maxilla premolars	53 (25)	12 (19)	9 (18)	32 (33)	
Maxilla molars	40 (19)	15 (22)	9 (18)	16 (16)	
Mandible anteriors	19 (9)	0 (0)	7 (14)	12 (12)	
Mandible premolars	29 (13)	13 (19)	8 (16)	8 (8)	
Mandible molars	44 (20)	15 (22)	9 (18)	20 (20)	
Bone quality, n (%)*					
2	171 (79)	50 (74)	42 (84)	79 (81)	.34
3	45 (21)	18 (26)	8 (16)	19 (19)	

RB6, implants placed in regenerated bone 6 months after tooth extraction; RB12, implants placed in regenerated bone 12 months after tooth extraction; HB, implants placed in healed bone.

\*Lekholm and Zarb classification.

participation) was placed into each envelope for the HB group according to the randomized list. For the RB groups, a card with "1/6" (participation in RB6 group), "1/12" (participation in RB12 group), or "2" (non-participation) was placed into each envelope according to the randomized list. The envelopes were sealed and placed into two boxes, one for the HB group and one for the RB group.

### Examiners

Clinical examination and patient selection (HB, RB) was performed by Examiner #1. Patients selected for participation in the RB groups were sent to Examiner #2, who performed the extractions and socket preservations. All implants (HB, RB6, RB12) were placed by Examiner #3, and the Ist measurements were taken by Examiner #4. Examiner #5 performed the restorative treatment.

### Extraction and socket preservation

In the HB group, no treatment was performed after tooth extraction except curettage of the socket to induce the necessary secondary healing. In the RB6 and RB12 groups, the extraction socket was debrided and covered with a nonresorbable dPTFE membrane (Cytoplast, Osteogenics Biomedical, Lubbock, Texas) without the use of any soft- or hard-tissue grafts, as previously described.<sup>14,15</sup>

### Implant surgery and loading

In all cases, screw cylinder-type implants with an internal connection (straight line, Dentegris, Duisburg, Germany) were placed using a two-stage surgical approach. The implants used had diameters of 3.3, 3.75, 4.75 or 5.5 mm and lengths of 10, 11.5 or 13 mm. In the HB group, the implants were placed 12 months after tooth extraction. In regenerated bone, the implants were placed 6 or 12 months after extraction (ie, 5 or 11 months after membrane removal) in the RB6 and RB12 groups, respectively. Site preparation was performed at 875 rpm, and the drills were externally cooled using sterile saline solution. The implants were placed manually with a ratchet at a torque of 35 Ncm.

Four months after placement, the implants were uncovered, loaded with metal-fused crowns, and cemented with an acrylic-/urethane-based temporary cement (Implant Provisional, Alvelogro Inc, Snoqualmie, Wash).

### Measurements

At implant placement, bone quality and quantity were recorded according to the classification of Lekholm and Zarb.<sup>16</sup> Ist was evaluated by RFA and reported as ISQ units. ISQ units were defined as the ratio between a measurement on the buccal-palatal axis and a second measurement on the mesial-distal

axis. (ISQs, Osstell Integration Diagnostics, Gothenburg, Sweden). RFA measurements were taken at the time of implant placement (E1), at the time of loading, that is, 4 months after placement (E2), and again at 4 months after loading (E3). Measurements were taken before placement of the abutment and crown at E2, and the abutment and crown were both removed before taking the measurements at E3.

### **Medication and postoperative care**

The patients scheduled for extraction or socket preservation, as well as for implant surgery, were prescribed an analgesic (Voltaren 100 mg, Novartis, Nuernberg, Germany) once daily for 4 days, a systemic antibiotic (amoxicillin 1000 mg, Glaxo-SmithKline, Brentford, UK) once daily for 6 days, and a 0.12% chlorhexidine digluconate solution rinse (Paroex, John O. Butler, Chicago, Ill) twice daily until 1 week after suture or membrane removal. The patients were instructed to start taking the medication 1 day before the procedure.

The sutures were removed 1 week after extraction, socket preservation, or implant surgery, while the membranes were removed after a 4-week healing period. The patients received oral hygiene instructions as well as tooth cleanings and polishings by a dental hygienist once per month. After loading, the patients were enrolled in a maintenance program consisting of semi-annual follow-up appointments. At the follow-up visits, oral hygiene instructions were given, and debridement and tooth polishing were performed.

### **Data analysis**

The characteristics of the groups are expressed as numbers and percentages or as means and standard deviations, as appropriate. Demographic variables were compared between groups with the chi-squared test for categorical variables and analysis of variance (ANOVA) for continuous variables.

ISQs implant stability quotients were normally distributed and analyzed for the three examination time points using linear regression. The mean ISQ of the two measurements for each implant was entered into the regression model. Regression analysis was used to examine the effect of bone type and patient characteristics on the ISQs for each time point and on the changes in values between time points. The joint effect of

the variables was examined in a multivariate analysis using a backward-selection procedure. This analysis examined the differences among the three groups and between pairs of groups using a Bonferroni adjustment for multiple testing. Paired *t*-tests were also used to compare changes in the ISQs between the time points within each group. Alpha was set at .05, and all tests were two-tailed.

## **RESULTS**

A total of 216 screw cylinder implants were placed in 216 patients (98 in healed bone [HB], and 118 in patients with regenerated bone at 6 [RB6, N = 68] or 12 [RB12, N = 50] months after extraction). Implant survival rate was 100%, and no adverse tissue reactions or inflammation were observed. A total of 57% of the implants were placed in the maxilla (Table 1), 79% of implants were placed in areas with bone quality 2, and the remainder were placed in areas with bone quality 3 (Table 1).

The three implant groups differed significantly in the distribution of age, sex, and area (eg, implant position) (Table 1). The HB group contained significantly more females than did the RB6 and RB12 groups ( $P = .01$ ). The mean age was lowest in the RB12 group (50 years) when compared with the mean ages of 55 and 56 years in the HB and RB6 groups, respectively ( $P = .003$ ) (Table 1). A greater proportion of maxillary premolars and a smaller proportion of mandibular premolars were included in the HB group than in the other two groups ( $P = .02$ ) (Table 1). No significant differences in other variables were observed among the groups.

### **Implant stability at the time of implant placement (E1)**

Multivariate analysis indicated that the area of implant placement ( $P = .02$ ), bone quality ( $P = .005$ ), and experimental group ( $P < .001$ ) significantly affected ISQ at E1 (Tables 2 and 3). Implants in the anterior maxilla had the lowest mean ISQs, whereas those in the mandibular premolar area had the highest values (Table 3). Multivariate analyses indicated that lower bone quality was significantly associated with lower ISQs (bone quality 2, [70.3 ± 8.5] vs bone quality 3, [65.0 ± 9.4]). ISQs differed significantly between the RB6 and RB12 groups and

TABLE 2  
Changes in implant stability quotients (ISQs)

Group	Mean (SD) E1	Mean change (95% CI) between time periods			
		E2-E1	P	E3-E1	P
HB Total	68.1 (10.2)	4.6 (2.5, 6.7)	<.001	4.8 (2.7, 6.9)	<.001
Maxilla anteriors	66.3 (7.5)	6.3 (0.9, 11.6)	.03	6.5 (0.9, 12.0)	.03
Maxilla premolars	65.8 (8.3)	6.6 (3.2, 9.2)	<.001	6.7 (3.3, 10.1)	<.001
Maxilla molars	62.8 (12.9)	8.3 (1.3, 15.3)	.02	8.9 (2.1, 15.8)	.01
Mandible anteriors	71.6 (4.3)	1.5 (-1.9, 4.8)	.36	1.1 (-2.9, 5.2)	.55
Mandible premolars	75.3 (15.0)	0.9 (-12.6, 14.5)	.87	0.5 (-12.7, 13.7)	.93
Mandible molars	71.7 (9.6)	1.0 (-3.9, 5.9)	.67	1.4 (-3.3, 6.1)	.53
RB6 Total	66.4 (6.6)	5.4 (3.6, 7.2)	<.001	6.1 (4.3, 7.9)	<.001
Maxilla anteriors	62.2 (7.3)	12.6 (6.1, 19.1)	.001	12.2 (5.4, 19.1)	.002
Maxilla premolars	69.4 (4.0)	2.8 (-0.6, 6.1)	.1	5.1 (1.6, 8.5)	.008
Maxilla molars	63.7 (5.7)	6.5 (3.7, 9.3)	<.001	7.1 (4.1, 10.2)	<.001
Mandible anteriors	—	—	—	—	—
Mandible premolars	70.0 (2.3)	2.9 (0.9, 4.9)	.008	3.0 (1.0, 5.0)	.006
Mandible molars	67.3 (8.2)	2.2 (-1.5, 5.9)	.22	70.5 (5.4)	.08
RB12 Total					
Maxilla anteriors	75.1 (5.8)	0.3 (-1.3, 1.9)	.72	0.2 (-1.4, 1.7)	.83
Maxilla premolars	73.6 (2.7)	1.3 (-0.7, 3.3)	.16	2.0 (0.2, 3.8)	.03
Maxilla molars	77.5 (4.7)	0.8 (-2.3, 3.9)	.58	0.8 (-2.0, 3.5)	.53
Mandible anteriors	77.5 (4.7)	0.1 (-3.1, 3.2)	.97	-1.1 (-5.0, 2.8)	.53
Mandible premolars	72.5 (4.6)	1.5 (-2.4, 5.4)	.38	2.2 (-1.9, 6.4)	.24
Mandible molars	76.9 (4.3)	1.8 (-3.0, 6.5)	.41	0.2 (-4.0, 4.3)	.92
	72.2 (9.6)	-3.1 (-10.8, 4.6)	.38	-2.4 (-9.7, 4.9)	.47

E1, time of implant placement; E2, time of implant loading; E3, 4 months after loading; CI: confidence interval; for further abbreviations, see Table 1.

between the HB and RB12 groups (both at  $P < .001$ ).

**Implant stability at the time of loading (E2)**

At the time of implant loading (E2), the results of the multivariate analysis indicated that at E2, the area of implant placement ( $P = .03$ ), implant length ( $P = .004$ ), implant diameter ( $P = .01$ ), and experimental group ( $P < .001$ ) significantly affected ISt (Table 3). Implants placed in the mandibular molar area yielded the lowest mean ISQs ( $70.9 \pm 6.8$ ), whereas those placed in the mandibular premolar area yielded the highest values ( $75.4 \pm 4.8$ ). Larger implant diameter and length were significantly associated with higher ISQs (Table 3). Multivariate analysis indicated that implants 5.5 mm in diameter were associated with significantly higher ISQs ( $71.7 \pm 9.4$ ) than were implants with a diameter of 3.3 mm ( $69.4 \pm 4.5$ ), whereas implants 13 mm long were associated with higher ISQs ( $75.5 \pm 3.7$ ) than were those 10 mm long ( $71.2 \pm 5.8$ ). ISQs in the RB12 group were significantly higher than those in the RB6 ( $P < .001$ ) and HB ( $P = .03$ ) groups.

**Implant stability 4 months after loading (E3)**

Multivariate analysis indicated that bone quality ( $P = .005$ ), implant diameter ( $P = .007$ ), implant length ( $P < .001$ ), and experimental group ( $P = .009$ ) significantly affected ISt at E3 (Table 3). Implants in bone with a quality rating of 3 had significantly lower mean ISQs ( $70.6 \pm 6.8$ ) than those in bone with a quality rating of 2 ( $74.0 \pm 5.4$ ). ISQs increased with implant diameter; they were significantly higher in implants 5.5 mm in diameter ( $73.0 \pm 7.9$ ) than in implants 3.3 mm in diameter ( $69.2 \pm 4.5$ ). Longer implants were also associated with greater ISt; the greatest difference was observed between the mean ISQs of implants 10 ( $71.5 \pm 5.7$ ) and 13 mm long ( $76.0 \pm 3.6$ ). As in the other two time groups, the ISQs were significantly higher in the RB12 group than in the RB6 ( $P < .001$ ) or HB ( $P = .03$ ) groups.

**Changes in implant stability over time**

Changes in stability between implant and loading and between implant and 4 months after loading were similar (Tables 2 and 4). Paired  $t$ -tests indicated

TABLE 3  
Factors significantly associated with the implant stability quotients (ISQ; multivariate regression analysis)

Variable	ISQ, mean (SD)		
	E1	E2	E3
Sex			
Women	68.6 (9.8)	72.9 (6.5)	73.1 (6.4)
Men	70.0 (7.6)	73.1 (5.6)	73.5 (5.2)
Smoker			
No	69.2 (9.2)	73.0 (6.1)	73.3 (6.0)
Yes	69.2 (7.8)	73.0 (6.2)	73.5 (5.7)
Area			
Maxilla anterios	66.5 (7.8)	74.1 (4.3)	74.2 (4.7)
Maxilla premolars	68.6 (8.1)	73.3 (5.4)	73.9 (5.4)
Maxilla molars	66.4 (10.8)	72.2 (8.4)	72.5 (7.7)
Mandible anterios	71.9 (4.3)	73.4 (2.6)	73.4 (3.3)
Mandible premolars	73.4 (8.5)	75.4 (4.8)	74.9 (4.3)
Mandible molars	70.3 (9.2)	70.9 (6.8)	71.5 (6.7)
<i>P</i> (statistical significance)	.02	.03	
Bone quality*			
2	70.3 (8.5)	73.7 (5.6)	74.0 (5.4)
3	65.0 (9.4)	70.3 (7.3)	70.6 (6.8)
<i>P</i> (statistical significance)	.005		.005
Diameter, mm			
3.3	67.3 (7.5)	69.4 (4.5)	69.2 (4.5)
3.75	70.3 (7.6)	73.7 (5.0)	73.7 (5.2)
4.5	67.7 (10.7)	73.0 (6.8)	73.6 (6.4)
5.5	68.5 (10.4)	71.7 (9.4)	73.0 (7.9)
<i>P</i> (statistical significance)		.01	.007
Length, mm			
10	68.5 (8.2)	71.2 (5.8)	71.5 (5.7)
11.5	70.9 (9.6)	73.8 (6.7)	73.9 (6.3)
13	66.2 (7.8)	75.5 (3.7)	76.0 (3.6)
<i>P</i> (statistical significance)		.004	<.001
Group			
HB	68.1 (10.2)	72.6 (6.5)	72.8 (6.3)
RB6	66.4 (6.6)	71.8 (4.7)	72.5 (4.7)
RB12	75.1 (5.8)	75.4 (6.6)	75.3 (6.1)
<i>P</i> (statistical significance)	<.001	<.001	.009

E1, time of implant placement; E2, time of implant loading; E3, 4 months after loading; CI: confidence interval.

\*Lekholm and Zarb classification; for further abbreviations, see Table 1.

that mean ISQs were significantly higher at E2 and E3 than at E1 in the HB and RB6 groups ( $P < .001$  for all comparisons), but not in the RB12 group (Table 2). Multivariate analysis showed that the area of implant placement, implant length, and experimental group were significantly associated with these differences (all at  $P < .05$ ) (Table 4). Mandibular implants showed a significantly smaller increase in ISQs than did maxillary implants, with the smallest increase in the anterior mandible and the greatest increase in the anterior maxilla (Table 4). The mean increase in ISQ was greater with implants 13 mm long than it was with implants 10 mm long (Table 4).

The degree of change in ISQs over time differed

significantly between the RB12 group and both the RB6 and HB groups (all at  $P < .05$ ) (Table 4), but not between the HB and RB6 groups.

At all time points, ISQs for implants placed in the mandibular premolar area were highest in the RB12 group and lowest in the RB6 group. At E1, ISQs for implants placed in the mandibular molar area were highest in the RB12 group and lowest in the RB6 group; this pattern was completely different at E2 and E3, when ISQs were highest in the HB group and lowest in the RB12 group. For implants placed in the anterior maxilla, ISQs were highest in the RB12 group at all time points; however, these values were nearly identical to those of the other groups (RB6, HB) at E2 and E3. At all time points, the

TABLE 4

Factors significantly associated with changes in implant stability quotients (multiple regression analysis)

Variable	Change in ISQ, mean (SD)	
	E1 vs E2	E1 vs E3
Implant area		
Maxilla anteriors	7.6 (9.3)	7.7 (9.4)
Maxilla premolars	4.7 (8.1)	5.3 (8.1)
Maxilla molars	5.8 (8.1)	6.0 (9.7)
Mandible anteriors	1.5 (4.8)	1.5 (5.6)
Mandible premolars	2.1 (8.6)	1.6 (8.7)
Mandible molars	0.6 (9.2)	1.2 (8.9)
P (statistical significance)	.007	.009
Length (mm)		
10	2.7 (7.4)	3.1 (7.6)
11.5	2.9 (9.4)	3.0 (9.2)
13	9.2 (9.4)	9.8 (9.4)
P (statistical significance)	.002	.001
Group		
HB	4.6 (10.6)	4.8 (10.6)
RB6	5.4 (7.6)	6.1 (7.5)
RB12	0.3 (5.7)	0.2 (5.5)
P (statistical significance)	.02	.006

E1, time of implant placement; E2, time of implant loading; E3, 4 months after loading;

CI: confidence interval; for further abbreviations, see Table 1.

implants placed in the maxillary premolar area demonstrated ISQs that were highest in the RB12 group, followed by the RB6 group. In the HB group, ISQs for maxillary premolar implants were lowest at E1 but had increased by E2 and remained stable at E3. The implants placed in the maxillary molar area exhibited ISQs that were highest in the RB12 group and similar to those in the other two groups (HB, RB6) at all time points. For implants placed in the anterior mandible, ISQs were nearly equal in the HB and RB12 groups.

## DISCUSSION

To our knowledge, this article is the first publication to report the direct comparison of ISt in healed (nonregenerated) and regenerated bone using RFA. Although 45% of our subjects were smokers, smoking status did not influence ISt, which contradicts current clinical evidence that smoking impairs periodontal and/or implant surgical outcomes.<sup>17</sup> This finding may be due to the limited cigarette consumption of smokers enrolled in this study.

All implants in the RB groups were placed into extraction sockets after preservation using non-resorbable dPTFE membranes without grafts. Our study was limited only in comparison with studies that employ a two-stage surgical protocol and a similar method for socket preservation (eg, non-resorbable barrier alone without use of grafts). These membranes allow significant socket volume regeneration and normal healing, with newly formed tissue consisting mainly of regular trabecular bone with areas of bone marrow and typical cells,<sup>14</sup> similar to bone found in healed (nonregenerated) extraction sites.<sup>18,19</sup> The observed survival rate of 100% was similar to those reported previously in extraction sockets regenerated exclusively with nonresorbable barriers and in implants placed at the time of extraction or after regeneration.<sup>15,19–22</sup>

The present study found no significant difference in RFA measurements taken from two different directions. These findings are in agreement with those of Park et al,<sup>23</sup> who used the same method to measure ISt during surgery, and 4 and 10 weeks postoperatively.

Implant diameter and length significantly affected ISt at E2 and E3 but not at E1, indicating that they were associated with secondary ISt; these findings are in agreement with previously reported results.<sup>24,25</sup> In contrast, Han et al<sup>26</sup> found no implant diameter–related difference in ISt during a 12-week healing period, and Balleri et al<sup>27</sup> found no correlation between length and stability at 1 year after loading in healed bone. The absence of any implant diameter- or length-related differences in ISQs at E1 may be because implants with identical geometry were placed using an identical surgical technique. Differences in ISt at E2 and E3 may explain the previously reported tendency for higher failure rates of short and small-diameter implants.<sup>28–30</sup>

Our results do not allow for a definitive conclusion about the effect of bone quality on ISt based on ISQs; these factors were not correlated at any time point and did not differ among experimental groups. This finding is in disagreement with data reported in other clinical studies.<sup>27,31–34</sup> Bischof et al<sup>34</sup> found that PISt was affected only by jaw and bone quality; ISQs were higher in the mandible than in the maxilla, and higher in type 1 than in type 3 bone. After 3 months, ISt increased more in the mandible than in the maxilla, but the influence of bone quality had leveled

off and was no longer significant. However, bone quality should be important both at placement and after loading, because lower bone quality was associated with lower ISQs at E1 and E3. Previous studies have demonstrated a radiographic correlation between bone type and ISt.<sup>35–37</sup> Based on these findings, new tools that could quantify the structural or mechanical quality of peri-implant bone may help to improve clinical outcomes with respect to screw fixation.<sup>35</sup>

Human and animal studies have described extraction socket healing with and without membrane use.<sup>14,38–40</sup> During healing, blood coagulum forms and matures and is subsequently replaced by a provisional matrix and woven bone. When a cortical ridge was established in the socket entrance during healing, the immature woven bone was remodeled and replaced by lamellar bone and bone marrow.<sup>38–40</sup> Trombelli et al<sup>40</sup> described much variability in hard-tissue formation within extraction sockets; tissue modeling appears to be rapid, whereas remodeling is slow. Large amounts of mineralized tissue are formed in sockets during the first 6 months, whereas new bone is formed in lesser amounts between 6 and 12 months, when woven bone is replaced by lamellar bone and bone marrow.<sup>40</sup> This new bone could provide additional stability for dental implants. The present study showed three phenomena related to socket healing and regeneration: (1) healing was rapid and stability was present during the first 6 months, (2) bone remodeling started at 6–12 months, and (3) the cortical layer provided additional stability for the dental implants. Corticalization could also have a major influence on ISt because no initial wound collapse appears and the healing bone shows better organization. However, one limitation of the present study was the absence of histological examination.

Without regard to the area of implant placement, we found (1) significantly higher ISt at E2 and E3 than at E1 in the HB and RB6 groups, but not in the RB12 group; and (2) significantly higher ISt in the RB12 group than in the HB and RB6 groups at all time points. ISt increased similarly over time in all groups, suggesting that socket healing type was associated with differences in stability among groups over time.

Our findings may have been the result of initial coagulum stabilization achieved by membrane use

for 4 weeks after extraction. Furthermore, the higher stability in the RB12 group could be the result of more effective corticalization, perhaps due to the early apposition of more compact bone-by-bone marrow from the time of tooth extraction. Also, the membrane's protection of the socket may have prevented minor infectious and inflammatory healing processes, making bone apposition more effective. The exclusion of the periosteum from the healing process reduced remodeling phenomena and subsequent osteolysis within the alveolus, resulting in the deposition of more compact bone.<sup>41</sup>

Our findings suggest that the area of implant placement may affect stability most at E1, with a possible influence at E2 and E3. Longitudinally, ISQs increased less for mandibular than maxillary implants; the smallest increase was observed in the anterior mandible and the greatest in the anterior maxilla. ISt in the HB group was higher in the mandibular premolar area than in the maxilla. This finding corresponds to published results<sup>27,42</sup> and would explain the different degrees of ISQ increase (ie, mandibular implants had higher initial stability due to the anatomical and physical properties of the native bone, such as the greater amount of cortical bone). However, ISt in the RB group was higher in the maxillary premolar and molar areas than in the mandible. Cortical bone is generally thicker and less spongy bone is present in the mandibular premolar and molar areas than in the maxilla. These observed changes in ISQs may be the result of initial stability related to mechanical factors directly influenced by the physical properties of the bone. After healing, other factors—such as the degree of osseointegration—may be of greater importance.

ISt is aided largely by cortical bone. One limitation of the present study was the lack of cortical bone thickness measurements. Recent research has suggested that the mean thickness of cortical bone, which is greater in the edentulous mandible than in the maxilla, played a greater role in ISt than did implant length; thus, adequate cortical engagement is necessary when placing implants.<sup>43,44</sup> The regenerative potential of the greater amount of spongy bone in the posterior area in the maxilla than in the mandible could be explained by the high implant stability measured in the posterior maxilla as compared to the posterior mandible.



In contrast to our results, Balleri et al<sup>27</sup> and Zix et al<sup>45</sup> found no significant difference in ISQs between anterior and posterior implants. However, limited data prevented us from performing further statistical comparisons of ISt according to placement region.

Our results support the hypothesis that post-extraction socket treatment type and differences in post-extraction healing methods are significantly associated with measured differences in ISt.

### CONCLUSIONS

The area of implant placement appears to be an important factor that influences both primary and secondary ISt. Furthermore, the type of bone healing in the area of the extraction socket (i.e., bone regeneration vs non-regeneration) may also be an influencing factor that, in addition to implant location, may complicate the interpretation of RFA measurements and the estimation of long-term implant outcomes. Implant length and diameter appear to affect stability at the time of loading and at least 4 months thereafter. The effects of bone quality on ISt are less clear, although this factor may be important at the time of placement and after loading. Further clinical studies are necessary with larger groups of implants in different jawbone regions, measurements of cortical bone thickness, and a controlled comparison of bone regeneration with and without the additional use of grafts.

### ABBREVIATIONS

HB: healed bone  
 ISQ: implant stability quotient  
 ISt: implant stability  
 PISt: primary implant stability  
 RB: regenerated bone  
 RFA: resonance frequency analysis

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