Journal of Oral Biology and Craniofacial Research 10 (2020) 629–638

Contents lists available at ScienceDirect

Journal of Oral Biology and Craniofacial Research

journal homepage: www.elsevier.com/locate/jobcr

The clinical significance of implant stability quotient (ISQ) measurements: A literature review

Huang H[a,b], Wu G[a], Hunziker E[b,c,*]

[a] Department of Oral Implantology and Prosthetic Dentistry, Academic Centre for Dentistry Amsterdam (ACTA), University of Amsterdam and Vrije University Amsterdam, Gustav Mahlerlaan, 3004, 1081LA Amsterdam, Nord-Holland, the Netherlands

[b] Department of Osteoporosis, Inselspital Bern University Hospital, Freiburgstrasse 3, CH-3010, Bern, Switzerland

[c] Departments of Osteoporosis and Orthopaedic Surgery, Inselspital Bern University Hospital, Freiburgstrasse 3, CH-3010, Bern, Switzerland

ARTICLE INFO

Keywords:
Resonance frequency analysis
ISQ
Dental implants
Review
Influencing factors

ABSTRACT

Implant stability quotients (ISQ values) are obtained in dental clinical practice on a non-invasive basis by resonance frequency measurement rapidly after surgical placement of implants. The ISQ-values are used as indicator for mechanical implant stability, and are believed to have predictive power for clinical outcome. It is the aim of this review to provide a synopsis of all factors described in the literature that influence ISQ measurements by performing an exhaustive literature review; moreover, this review aims at elucidating the key factors relevant for a rapid clinical predictive assessment. We searched systematically and exhaustively all major databases for publications relating to ISQ measurement methodology and for ISQ-influencing factor analyses. The reports identified were ordered in experimental (preclinical) studies and in clinical publications. We were able to identify 13 basic factors influencing ISQ-measurements. Among these, local bone quality, playing a key role in such measurements, was subdivided in four specific subfactors; thus a total of 17 individual factors was identified and reported to influence ISQ-measurements. A comprehensive list of these factors is provided in Tableform. A critical analysis points out that only 6 of these factors are of a sound predictive power useful for a rapid clinical assessment; and only two of these factors appear to have a well-documented scientific basis.

1. Introduction

In the past decades, dental implantology has become one of the most widely used therapeutic options to treat (partially or completely) edentulous patients. Without the risk of damaging natural teeth, dental implants serve as artificial roots in jaw bones, thereby mechanically supporting various fixed and removable (partial) dentures. Consequently, their well-established mechanical stability forms the biological basis for their successful use in daily life. Immediately after implantation, a sufficient primary stability must be achieved by the mechanical retention of the implant into the surrounding bone, which provides an indispensable mechanical microenvironment for the gradual establishment of bone healing, also known as osseointegration. The primary stability plays a dominant role for implant stability during the first week after implantation, and thereafter decreases significantly to minimal levels at about 2 weeks[1,2] postoperatively. Whereas the primary stability of implant-to-bone contact sites are established by appropriate surgical anchoring techniques of the implants,[3] the secondary stability is based on a biological process — called osseointegration — during which a new structural and physiological bony contact between the implant surfaces and the pre-existing as well as neoformed surrounding bone tissues is formed[4] by inherent osteogenic activities. The degree of secondary stability then increases continuously over time, and more rapidly increases about 2.5 weeks after implantation to achieve a plateau level at about 5 or 6 weeks after implantation. The whole transition process from the initially dominating primary stability phase to the finally dominating secondary stability phase lasts roughly 5–8 weeks.[1]

In clinical practice, implant stability measurements (ISQ) are used as an indirect indicator to determine the time frame for practical implant loading and as a prognostic indicator for possible implant failure.[5] Given the high clinical significance of quantitative implant stability estimations, a number of methods, such as the periotest assay and resonance frequency analysis (RFA), have been developed to estimate quantitatively this parameter.[6–8]

In recent years, RFA has become one of the most widely used techniques to assess implant stability in clinical practice.[9] RFA is performed by measuring the response of an implant-attached piezo-

* Corresponding author. Clinics for Osteoporosis and Orthopaedic Surgery, Inselspital, Freiburgstrasse 3, CH-3010, Bern, Switzerland.
E-mail address: ernst.hunziker@dbmr.unibe.ch (H. E).

https://doi.org/10.1016/j.jobcr.2020.07.004
Received 27 April 2020; Received in revised form 22 June 2020; Accepted 13 July 2020
Available online 14 August 2020
2212-4268/

ceramic element to a vibration stimulus consisting of small sinusoidal signals in the range of 5–15 kHz, in steps of 25 Hz on the other element. The peak amplitude of the response is then encoded into a parameter called the implant stability quotient (ISQ) that ranges from 0 to 100.[10] The ISQ value reflects positively the general mechanical stability of an implant. And a more detailed analysis of recorded ISQ values of a patient is of significant help for the surgeon to estimate the practical loading scheme for an individual patient and to assess, on a quantitative scale, the long-term survival probability of dental implants.[9]

ISQ values are, however, under the influence of a large number of clinical and biological factors, and it is the goal of this review article to provide a comprehensive overview on the factors that have been reported to influence ISQ values, and on their clinical-practical significance. It was previously established that among the various reported ISQ-influencing factors it is only the age of the patient[11,12] that was later on identified as factor not to have an influence on ISQ values. In this review, the possible potential ISQ-influencing factors will be analyzed.

2. Materials and methods

We analyzed systematically and exhaustively all major literature data bases for publications in which ISQ measurements were performed and in which factors were identified influencing the measurement results. The databases analyzed were: PubMed, Ovid Medline, Cochrane Library, Scopus, Web of Science and Compendex. Search terminologies encompassed the following: implant stability quotient measurement (ISQ), dental implant, mechanical stability, predictive power (value), influencing factor, short term, long term, experimental, clinical. The terms were varied systematically in different combinations in order to identify on a comprehensive basis and exhaustively all scientific publications relating to this topic. The search results were systematically screened for the key terminologies like ISQ, influencing factor, in vitro, in vivo, etc (see above); all publications containing minimally one of these terms (beside ISQ) were considered for this review. The articles were then ordered in experimental (preclinical) studies and clinical publications. From a practical-clinical point of view, it was aimed to obtain information on the initial and follow-up mechanical stability conditions of an implant, for the loading protocol to be recommended to the patient, and to obtain information about the prospective outcome; from a research point of view we aimed to acquire information respecting which implant-related factors need improvement. Moreover, we aimed at assessing the possible role of the individual influencing factor on the ISQ measuring data in order to provide a broadly useful tool both for practitioners and researchers to define appropriately the measuring protocols for acquiring the specific information needed on a rational basis for mechanical stability evaluation of implants, and also for the better understanding of the practical, clinical and/or theoretical significance of ISQ measurements.

The number of influencing factors identified by the authors were selected and listed in Table 1. The statistical methods most frequently used in these publications are summarized in Table 2. The influencing factors found were ordered and presented in these two Tables and the findings described and analyzed for each factor in the Results/Discussion section of this review. In order to improve clarity for the reader in this extensive literature review, the Results and Discussion sections are combined in one unit. A short general Discussion is added at the end of this study.

3. Results and Discussion

The influencing factors identified in this literature review to influence ISQ measurements are summarized in Table 1, together with the corresponding references.The presented studies are divided separately in clinical studies and in in-vitro studies. In the following these factors are presented each one and are shortly and critically discussed respecting their potential usefulness and their limitations.

4. Direction of measurement

Respecting spatial (anatomical) directions of measurements in patients, three publications so far revealed that the measurements from different directions do not lead to significant differences in the ISQ measurement results.[13–15] However, they suggest that if two different spatial directions were to be used this may allow clinicians to detect different patterns of ISQ changes that would otherwise not be identified if only one direction of measurement was applied.

However, in two in-vitro studies[16,17] it was found that the measurement direction appears to have indeed an influence on the ISQ measurement results, but only under very specific conditions that relate to the defect characteristics. And the defined six different defect models in which this effect may occur were the following: a 3-wall-2.5 mm one, a 3-wall-5 mm one, a 1-wall-2.5 mm model, 1-wall-5 mm model, a circumferential-2.5 mm one and a circumferential-5 mm defect model in the adult bovine rib bone. A possible explanation for this finding is that the spatial directions of measurement may have an influence on ISQ measurement results provided that such extreme types of bone defects are established which, however, clinically are very rarely seen (if at all).

5. Gender

In several publications it was reported that the influence of sex on implant stability (and thus ISQ measurements) was variable and inconsistent. Males were found to have either significantly higher,[11,14,18–22] or significantly lower[12,23] ISQ values in comparison with females, or they yielded similar results.[24,25] For example, Gule et al.[26] showed that the gender-parameter indeed is able to influence the ISQ values significantly, but only if a second measurement was performed. This inconsistency may be due to a large variation of the experimental conditions established, such as the choice of the measurement time point, the specific implant locations or the inclusion of different types of populations/ethnics that may have played a role in leading to such conflicting findings with respect to the relationship between gender and ISQ values.

6. Implant location

Implant location in the dental area is considered to be a potential factor able to influence the ISQ values. However, in several studies the locations used for measurements were defined differently by different authors: anterior or posterior[18,26] and mandibular or maxillary[19,20,24,27–30] locations were used, and using different definitions. In relation to location within the dental arch, statistical analyses indicated higher ISQ values for anterior implants than for posterior fixtures.[12] However, in other studies no significant differences were found among ISQ values relating either implants in the anterior mandible, the posterior mandible, or the anterior maxilla.[18,26] It was also reported that the ISQ values of implants are generally higher in the mandible (ISQ ≈ 59.8) compared to those placed in the maxilla (ISQ ≈ 55). An interesting aspect of this finding is that it seems to be dependent on the shape of implants since when implants of a cylindrical form were used then no significant differences[31] among ISQ data were found, ISQ values in such cases thus being independent of a specific location in the jaw. However, in most publications it is reported that ISQ values of implants placed in the mandibular region are significantly higher than those placed in the maxillary regions.[19,20,24,27–30] And this was also the case if implants of an ultrawide shape were used.[32] In addition a recent study of our own group[14] revealed that the maxillary/mandible location clearly has a significant impact on ISQ data at T1 (T1 is the ISQ data obtained at the time point of surgical implantation), but not at T2 (T2 is the ISQ value obtained one week after implant placement).

Table 1
Overview of ISQ-influencing factors and of corresponding references.

Factors Influencing ISQ	Number of Clinical studies			Number of In vitro studies		
	Positive effect	Negative effect	No effect	Positive effect	Negative effect	No effect
1. Spatial (anatomical) direction of measurements			**2** (10,11)	**2** (13,14)		**1** (12)
2. Gender (male)	**9** (8,11,15–19,39,42)	**2** (9,20)	**2** (21,22)			
3. Implant location	**10** (8,11,16,17,21,24–27,32)		**4** (6,23,28,42)	**1** (29)		
4. Immediate/delayed implantation	**3** (7,11,35)		**1** (36)			
5. Implant diameter	**12** (6,8,11,16–18,23-25, 39,40,42)		**7** (9,22,28,37,38, 42,43)	**1** (41)		**2** (12, 44)
6. Implant length	**3** (28,39,48)	**1** (8)	**5** (9,11,23,40, 42)	**4** (41,45–47)		
7. Insertion torque	**9** (11,16,27,36,48,50, 51,53,103)		**5** (9,18,37,43,44)	**3** (12,52,53)	**1** (49)	
8. Macro-design and micro-design	**10** (7,16,23,54,55,57,59,65,69,129)		**8** (37,60,62–64,66 67,130)	**3** (44,56,58)		**1** (61)
9. Bone Quality at implantation site						
9.1. Bone type	**11** (8,28,40,73–78,84,97)		**5** (9,11,22,28,42)	**1** (131)		
9.2. Bone graft	**2** (11,84)		**4** (39,80–83)	**1** (53)		
9.3. Cortical bone thickness	**4** (85,89,90,92)		**1** (93)	**6** (13, 46, 86–88, 91)		
9.4. Bone to implant contact				**3** (98,99)		**4** (44, 99, 100))
9.5. Bone vascularity	**1** (102)					
10. T1-T2 time interval	**4** (11,37,84,132)		**5** (105–109)			
11. I/II stage implantation	**1** (11)		**1** (112)			**1** (111)
12. Implant number			**1** (113)			
13. Surgical design	**9** (114–116, 118–120, 122–124)		**3** (50, 125, 126)	**1** (117)		

7. Immediate versus delayed implantation

The immediate implantation surgical protocol is able to significantly shorten clinical treatment time, and is thus becoming more and more popular. On the basis of this trend the immediate implantation technique has been extensively evaluated during the last two decades, under the precondition that favorable clinical conditions were present in the patients,[33,34] and patients not fulfilling such criteria were strictly excluded; and various authors reported thereafter clinical success rates ranging from 92.7% to 98%.[35,36]

However, in one long-term follow-up study,[37] no significant differences were reported of the success rates, and also the aesthetic outcomes were comparable when immediately- and delayed-placed implants were compared to each other. But even though this study was prospective in nature, protocols did not entirely fulfill all the required prerequisites for such epidemiological analyses; moreover they were not of a multicenter nature either.

Given this background it is of great interest to realize that immediate/delayed implantation can indeed result in significantly different ISQ values when comparing different maxillary locations.[38] Gehrke et al. showed that delayed-placed implants were not associated with significantly higher ISQ values than immediately placed implants.[10] The same results were revealed in a recent study from our group.[14]

Malchiodi et al.[39] reported that immediate implants when compared with delayed implant placement seem to be associated with similar ISQ values at the time of insertion, and also when loading begins (after more than 3 months); this implies that secondary stability rapidly catches up, i.e. to a level of ISQ values of similar magnitude as those obtained during the primary stability time phase.

8. Implant diameter

Diameter and length of implants were identified as other factors that are able to have an influence on implant ISQ results. In a small-scale prospective clinical trial, Lang and his colleagues[40] showed that ISQ values did not correlate with implant diameter values when measured over a 12-week post-operative monitoring time period. However, a number of other studies showed that implant diameters could indeed significantly influence ISQ values; more specifically, it was found that when the implant diameter was increased, then the ISQ values obtained also increased.[19,20,27,41),42-45]

Interestingly a number of other studies on this topic revealed conflicting data: for the final measurement (8th or 12th week postoperatively) there were no significant differences of ISQ data found between 4.8 mm diameter implants and those of 4.1 mm; however, the ISQ data obtained for these two groups were significantly higher than those for a 3.3 mm diameter group ($p < 0.05$).[26] Surprisingly, no statistical differences between ISQ results were found at primary and secondary implant stability time points, measured by RFA for 3.75 mm diameter groups and for 4.25 mm diameter implants of conventional shapes.[46] We are thus confronted with a number of studies providing conflicting results respecting ISQ measuring data and implant diameter, and no clear correlations could be identified. Furthermore, the studies

Table 2
Numbers of ISQ-influencing factors per study and statistical methods used.

The number of ISQ influencing factors involved in each publication	References	Statistical Methods
3	5 (13, 41, 46, 52, 55)	Pearson's correlation, multiple regression analysis
4	4 (12, 24, 84, 85)	Mann-Whitney U tests
5	3 (19, 23, 89)	Tukey, two-way ANOVA
6	3 (15, 16, 97)	Mixed effects model, Pearson's correlation, stepwise multiple regression test, ANOVA method, Kaplan–Meier survival analysis
7	1 (28)	Shapiro–Wilk W-test, *t*-test, ANOVA with post hoc Tukey HSD test
8	2 (9, 39)	A mixed effects model, *t*-test and ANOVA method
9	1 (8)	Pearson correlation, *t*-test, stepwise multiple regression, chi-squared test
10	1 (11)	Kruskal–Wallis test, Multivariate linear analysis

of Alsabeeha et al.,[25] Akkocaoglu et al.[47] and Ohta et al.[15] showed specifically that no clear correlation is indeed identifiable between ISQ values and implant diameter.

9. Implant length

Various clinical studies reported that implant length does not significantly influence primary stability of dental implants (as for example for 8 mm,10 mm,12 mm and 14 mm long implants,[26] for 10 mm and 11.5 mm lengths[43] and for 7.5 mm, 9.5 mm,11.5 mm,13 mm and 14.5 mm lengths[14]).

In contrast to these clinical data, several in-vitro studies reported that longer implants are generally associated with significantly higher ISQ values than shorter ones.[44,48] In some recent publications it was, however, found that this correlative relationship of implant lengths and ISQ values is not of a general validity, but is restricted in correlation to implants of specific diameter groups such as those of diameters of 3.8 mm.[49] And Bataineh et al.[50] showed that such a significant correlation is only present if an implant length of 15 mm is used. Moreover, two clinical studies ([31,42]) reported that an implant length-correlation to ISQ values could only be found in implants placed in a maxillary location, but not in the mandible. In addition, the maximum implant length that Lozano-Carrascal et al.[9] used in their study was only 17 mm which indeed is not commonly used in clinical practice. Only one clinical study was found in the literature in which ISQ values were reported to correlate with the length of implants used (and these related to implants of 8 mm, 9.5 mm, 11 mm, 13 mm, 15 mm and 18 mm in length[51]).

It thus appears from the presently available literature, that longer fixture length can be a factor that is able to influence the implant stability, but only in case that very particular clinical and geometrical implant situations exist.

10. Insertion torque

A large number of publications deal with the possible correlation between the insertion torque (IT) and ISQ value. IT measurements had been introduced into oral implantology in the early days in order to provide the clinician with a tool to quantify the degree of primary stability of the implant, and in order to place the surgical technique on a solid quantitative footing. The literature data respecting a correlation between IT and ISQ values are conflicting (see Table 1). The basis for these conflicting data may originate in a possibly much smaller degree of correlation (than generally assumed) between degree of micromotion and insertion torque values than the correlation values obtained between micromotion and ISQ measurements.[52] And indeed in some studies a very weak correlation was found between IT values and ISQ values at the time of implant placement.[51,53–55] On the other hand, in several studies a strong correlation between IT values and ISQ values were described.[15,19,30,39,56] Given this conflicting data situation the clinical usefulness of ISQ measurements as a substitute parameter for IT measurements remains questionable, and data need to be interpreted with great caution.

11. Macro- and micro-design of the dental implant

The design of an implant is one of the most fundamental parameter to influence implant primary and secondary stability.[57] In general, the geometrical design features consist of two major categories: 1) the macro-design, such as the thread design and the body shape[19]; 2) the micro-design, such as the implant surface topography.[57]

Respecting primary implant stability values relating to macro-design, it was reported that under experimental conditions in dense bone blocks, wider diameter implants (4.1 mm) are more stable than narrower implants (3.7 mm); and in soft bone blocks, the tapered TSV implants (Tapered Screw-Vent® Implants (from Zimmer Biomet Dental)) were found to be more stable than the TM implants (Trabecular Metal™ implants (from Zimmer Biomet Dental company).[58]

Gehrke et al.[57] recently indicated that conical implants with a wide pitch (1 mm) are associated with significantly greater primary stability values than semiconical implants with narrow pitch (0.5 mm) bores.

Akkocaoglu et al.[47] compared the ITI (International Team for Implantology) - TE® (Tapered Effect) solid implants (having a macro-designed (increased diameter at the collar region, coupled with more threads)) with the solid screw synOcta® (trade name of an implant system from Straumann company) implants from ITI. The study revealed that the ITI TE® implants had ISQ values of a similar level following immediate placing as have the ITI synOcta® implants; it thus was concluded that the macro-design has also an influence on the ISQ values.

Another study with implants of a reverse-tapered design and of narrow-diameters showed lower initial stabilities than the conventionally tapered implants.[59] On the basis of ISQ measurements, it was concluded that it was the design of the apical area of the implant that influences the implant stability.[60]

Respecting straight and tapered implants, significant correlations and linear relationships were found between ISQ data for both of these groups. In the publication of Howashi et al.,[61] ISQ values of SLActive (sand blasted acid etched and free of any contamination) implants (60.42 ± 6.82) showed significantly higher ISQ results than conventional SLA implants,[62] the difference between the two implant surfaces being only the implant surface chemistry, i.e. the reduced degree of surface contamination by organic compounds of the SLActive surface on a molecular level.[63]

Respecting the influence of implant design on ISQ measurement data only one publication was found in which the design factor did not reveal a significant influence on the implant stability quotient.[64] In this study, a comparison was made between an implant body design without self-tapping blades with an implant type with self-tapping blades. However,it remained unclear, what the basis of the absence of a difference of the ISQ values was.

Respecting the role of the micro-design factor in influencing ISQ measurements, Guler et al.[26] pointed out that when comparing sand-blasted, large-grit, acid-etched (SLA) and SLActive surface implants, there were no significant differences detected for insertion ISQ-measurements. However, subsequent measurements at the 4th week showed that SLActive implants revealed significantly higher ISQ values than SLA implants did. As for the final measurement (8th week), there was no significant difference detectable between the two implant types.[26] Thus, only a short temporary difference was found during the healing phase of the implant. However, implant stabilization data (ISQ values) were similar at all time points measured for the conventional SLA and the chemically modified SLAcive implants in patients with type 2 diabetes with a relatively poor glycemic control,[65] implying that under disease conditions such minor differences in just the surface chemistry, but not the micro topography of the surface geometry, are not measurable on an effective basis.

In another study, in which the same two implant groups (SLA vs. SLActive) were compared with each other, researchers found no differences respecting the ISQ values, at any point in time during the postsurgical healing phases, in patients who were not suffering from any disease.[40] Similarly it was found that dioxide grit-blasted dental implants, with and without chemical fluoride implant surface modification, did not reveal any differences in ISQ values at any point in time[66]: neither did the fluoride-surface treated implants exhibit differences in RFA values when compared with grit-blasted ones,[67] even though such chemical implant surface modifications had been found to positively promote the biological process of osseointegration and to shorten the healing time.[68] In another example, a thin molecular implant coating by bisphosphonate-containing fibrinogen was found to be able to improve and accelerate osseointegration of metal implants in human bone[69]; no differences of ISQ data were, however, measurable compared to the control groups. In addition in such surface-modifyed constructs no observable differences in RFA values were found when using the Nobel Active™ implant system (from Nobel Biocare company) as an implant in comparison with appropriate control implants.[70] Thus on a level of surface modifications of chemical and/or biological nature, and in addition to the presently used microtopographically modified surface geometries, the limits of the ISQ measurement sensitivities may be reached when dealing with smaller extents of differences in the degrees of osseointegration and mechanical stabilities. It appears, thus, that strongly bioactive surface modifications need to be operative locally such as, for example, with strong osteogenic agents (like experimentally investigated by Hunziker et al.[71]), that are able to induce significant additional gains of new bone formation in time over conventional surface-modifications, in order to achieve significantly more rapid and more extensive degrees of osseointegration of implants so that this will be clearly detectable by ISQ measurements (which would be in particular also desirable for patients with diseases such as diabetes, osteoporosis, local osteopenia, etc).

Another example of design-based improvement of implant healing is that for implants with a built-in 'platform switch' and a conical connection with a back-tapered collar design. These implants clearly achieved higher primary stability ISQ values at insertion time[72] and thus represent very promising novel design changes forming a basis for future design-based further developments.

In a recent review[73] it was concluded that rough-surface modified implants are associated with significantly higher success rates than dental implants with smooth surfaces; however, a mechanistic relationship between implant surface roughness (microdesign) and degree of primary stability could not be established.

12. Implant site: bone quality

A number of publications report on a possible relationship between bone quality at the implant site and implant stability/ISQ values obtained for implants at the corresponding sites. However, in the various studies relating to this topic different parameters were used to quantify and describe this aspect, for which reason a basis of comparison is hard to identify. In the following we shortly review now this complex topic in a structured way, taking into account the local bone type, the use of bone graft, the cortical bone thickness, the bone to implant contact (BIC) area and the bone vascularity.

12.1. Bone type

The local bone type was not found in previous reports (and in our own recent study[99]) to be a parameter of significant influence on either T1 or T2 data acquisition. Furthermore, using a similar classification method as had been used in these studies, Zarb & Lekholm[74] reported also that the bone type was found not to be a significant influencing parameter either. The authors point out that the ISQ value was only weakly associated with the bone type, if this was assessed by stereomicroscopy or micro-CT in the maxilla. Caution is thus necessary when interpreting data if RFA is used as a tool to evaluate bone quality at the implant site, especially in the mandible.[75] Moreover, in another study[25], it was concluded that host variables, general and local ones, such as age, gender, bone volume, and bone quality did not influence the primary stability values obtained by ISQ measurements of implants.[25]

In contrast to these findings, there are several studies that are in disagreement with these conclusions. They found that bone density assessment using CBCT is an efficient method and significantly correlated with implant stability parameters as well as with the Lekholm and Zarb index.[43,76,77] Given this basis it is thus possible to predict prior to implant placement an expected initial implant stability to be obtained, thus providing clinicians with a tool for the quantitative assessment of the expected values for immediate or early loading of implants using CBCT scans.[78] Directly after placement, at weeks 4 and 12 of the postoperative healing phase, significant differences were found between two groups of patients with either type 2 or with type 4 bone at the implantation site.[79] In addition a significant difference was also reported in the ISQ values of three implants for the bone types III and IV (Barewal et al.[80] and, Salimov et al., [78] and it was found that ISQ was significantly different at 3 weeks in bone types 1 and 4, but after 5 weeks, no signal differences were encountered any more between these different bone types. On the other hand Herekar et al.[81] found that the bone types indeed correlate with secondary stability results (at 4 weeks), obtained by ISQ measurements, but not with those of primary stability.

There are thus controversial views in the literature concerning this aspect of the value of ISQ measurements. A possible reason for this may be that bone type classification is very rough and is a subjective method, lacking a clear-cut quantitative and reproducible basis, and thus the identification of a specific prevailing bone type in studies remains quite variable between different authors.[82]

12.2. Bone graft

In our recent investigation[14] we found that bone grafting during surgery in a patient indeed is negatively correlated to ISQ values. However, other publications[83–85] showed that no significant differences are found for ISQ values between bone grafted and non-bone grafted cases. These results are similar to those of the study by Yang et al.[86] In this study there was no correlation detectable between marginal bone loss and changes of implant stability data.

Several other studies describe clinical cases with the presence of local bone defects, and they found that with the increase of the size of the bone defects, the ISQ measurement values decreased,[56] and implant stability at the time of placement correlated with bone quantity and quality assessments.[87]

12.3. Cortical bone thickness

In clinical studies it was recently reported[49,88] that the thickness of the cortical bone exhibited a positive correlation with local ISQ values, and loss of cortical bone lead to a reduced stability of implants resulting in reduced ISQ values.[16] And in an in-vitro study, ISQ values were found to highly correlate with each other respecting trabecular bone density and cortical bone thickness, and with changes in their densities/thickness (Pearson correlation = 0.90, $p < 0.01$) in [89]). The same type of correlations was found in studies by Bayarchimeg,[90] Hsu,[91] Merheb,[92] Song,[93] Andres-Garcia[94] and Turkyilmaz.[95]

However, a recent 1-year follow-up study with 101 implants[96] concluded that cortical bone thickness changes over time did not significantly influence implant stability values when analyzed using CBCT methods. The reasons for this discrepancy of data remain unclear.

In a previous systematic review[7] it was concluded that a positive association exists between the degree of implant primary stability and bone mineral density. However, the methodological quality and control of bias of the study needs improvement in order to provide convincing evidence.

12.4. Bone to implant contact (BIC)

Primary implant stability is related to the degree of mechanical fixation of an implant with the surrounding native bone tissue after implant insertion.[50] Secondary stability of implants depends on the formation of new bone tissue in the peri-implant space and on the bone remodeling activities at the implant-bone interface, and is under influence of the implant surface itself and a number of biological factors such as vascularity, local bone density, etc., and the wound healing time.[94,95,97] Some researchers hypothesize that the BIC values correlate with the implant stability quotient, and they found a positive correlation between them.[98,99] However, others found that when BIC-values are used as a parameter to assess the degree of osseointegration that these data did not correlate with ISQ-values of the same implants; and neither did they to bone mineral density values or to the Periotest results.[47,100] We wish to point out here that BIC values indeed are referring only to a relative bone-coverage (i.e. a percentage value) of the implant surface area, but they ignore the presence (or absence) and number of anchoring trabeculae that are needed to establish the connections and mechanical anchoring of the implant surface with the parent bone surface. This aspect was recently discussed in more detail by Haegi et al.[101] Moreover, BIC measurements are often restricted by authors to the analysis of only one central histological section through the implant, rather than encompassing 360° around the implant by applying an appropriate systematic random sampling protocol over the entire range; BIC-values presented in the literature thus remain in most cases non-representative of the truly established 3-dimensional quantitative degree of osseointegration.

12.5. Bone vascularity

Vascularity of bone tissue is an important factor in the process of new bone formation and osseointegration. In spite of this importance only one publication was found to deal with this parameter.[102] The authors found a significant correlation between the mean value of bone vascularity (quantified by Laser Doppler Flowmetry) and values obtained by RFA. A positive correlation was indeed detected when the degrees of vascularity changed.

13. T1-T2 time interval

In a number of publications the time intervals chosen between T1 and T2 were arbitrarily chosen, and were often found to be defined at 6 weeks,[103] at 12 weeks,[104] or at 16 weeks[29] intervals for monitoring purposes of implant stability. Lang et al.[40] recommended to monitor implant stability by RFA at earlier time points, i.e. at 3 weeks and 8 weeks post-surgically. In our recent retrospective analysis,[14] it was found that time periods from 4 weeks to more than 9 months had been used, and it was also found that secondary stability is indeed positively correlated to the T1-T2 time interval under these measuring conditions. This result was found to be consistent with Fischer's study[87] in which ISQ measurement values were found to increase with healing time when measured at 3, 6, and 12 months postoperatively.

Some surgeons suggest immediate loading after implant insertion, and the respective studies showed that[105,106] immediate loading did indeed not negatively affect implant stability, neither the marginal bone levels nor the peri-implant health status when compared to conventional postoperative loading schemes of single-tooth implants.

We were able to identify one systematic review[107] and meta-analysis on loading protocols for single-implant crowns; it was concluded[107] that immediately and conventionally loaded single-implant crowns are equally successful regarding implant survival and marginal bone loss. This conclusion was primarily derived from studies evaluating implants inserted with a torque $\geq$20 to 45 Ncm, or an implant stability quotient (ISQ) of $\geq$60 to 65, and with no need for simultaneous bone augmentation; the authors then concluded that the success rate of these two procedures is dependent on a number of specific conditions (and is thus of limited usefulness). Given this, it appears indeed important to consider all possible influencing factors (as illustrated in this literature review article) for ISQ data acquisition when planning clinical studies.

14. I/II stage implantation

A I - stage surgery refers to an implant that is placed in its total i.e. including the abutment, at the time of surgery; in a II-stage operation initially only the implant is placed; the abutment is placed at the time of a secondary surgical intervention. Only a few publications investigate a possible relationship between I/II stage implantation and ISQ values. There were no differences found between 2-stage and 1-stage implant surgical protocols respecting ISQ values obtained in an in-vitro study,[108] and neither in a clinical investigation[109] over the post-operative time course (observed for 6 months). However, in our recent publication,[14] we identified that in stage I surgery cases, higher ISQ values were encountered over the postoperative time interval of 26–302 days.

15. Implant number

We were able to identify one publication that investigated this aspect of the possible role of implant numbers influencing implant stability; the authors found that an increasing number of implants, i.e. from 2 to 4 in mandibular implant overdentures, did not have a significant influence on implant stability values assessed by ISQ measurements.[110]

16. Surgery

From the perspective of the surgical technique used during implant placement, the results presented in the literature are very variable and controversial. In many publications the authors express the belief that the use of a specific surgical technique is able to improve the post-surgical implant stability quotient. For example it was reported that the application of the so-called osteotome expansion technique is associated with a significant improvement in secondary stability results,[111] and the use of the osseous densification technique was reported to increase the degree of primary stability achievement.[112] The technique also influences the resulting bone mineral density as well as the percentage of bone coverage of the implant surface when compared with conventional drilling techniques. The described data showed that the bone expansion technique is able to substantially increase the ISQ values for primary stability and also achieved similar degrees of primary and secondary stabilities compared with the conventional technique. Both groups reached stability plateaus at week 10.[113] When we look at FG (full-guided workflows) implant surgical approaches, they are reported often to be associated with a reduced need of bone volume reduction for osteotomy preparation purposes, and they thus can lead to greater primary stability results (higher ISQ values).[114] Some authors report that the flap design also has a measurable and positive influence on postoperative ISQ values.[115] And the study of Shayesteh[116] illustrates that an osteotome-based technique yielded higher primary stability results than a conventional drilling techniques is able to do. However, after 3 months observation time it was found that this technique did not show superior results respecting ISQ data than the conventional technique. Moreover, it was reported that self-tapping implants achieve significantly higher stability values than non-self-tapping ones.[117] In another technical report it was described that when using thinner drills for implant placement[118] in the maxillary posterior region (where bone quality generally is poor) this procedure may improve the primary implant stability results; and this may help clinicians to obtain higher implant survival rates in their patients. At sites with poor bone density placement of implants by use of an adapted drilling technique[119] was described to be beneficial in enhancing primary implant stability (illustrated be improved ISQ measuring results) and thus may improve the total implant survival rate.

A technique relating to piezoelectric-based surgical approaches, as described by Stacchi et al.,[120] was reported to decrease ISQ values to a smaller degree and in an earlier shifting from a decreasing to an increasing stability pattern, when compared with the traditional drilling technique. Conventional implant placement techniques and those using Summer's Osteotome technique[121] were reported to also influence stability results assessed by ISQ measurements.

However, two different clinical studies report that osteotomy preparation by either standard or soft bone surgical protocols does not lead to significantly different implant survival results nor to any differences in postoperative stability data for the specific implant designs used[53]; in another report no evidence was found of any additional beneficial or adverse effect when using low-level laser surgical approaches (the first irradiation was performed in the immediate postoperative period)[122] on the stability of the implants (measured by RFA). A recently published systematic review on this topic[123] concluded that there is, at best, very weak evidence that surgical techniques used would influence primary and/or secondary postoperative implant stability results.

17. Statistics

The statistical methods used by the different publications are illustrated and summarized in Table 2. The ISQ data very often do not show a normal distribution pattern. Therefore statistical comparisons of ISQ data between experimental groups and control groups are preferrably performed by using nonparametric tests,[14,47,51] an observation that often is not considered in the scientific literature related to this topic. In a large number of studies[14,38,57] linear regression analyses (multivariate linear analysis, stepwise multiple regressions) were applied, which represent the adequate methods for the analysis of such multifactorial data.

18. General discussion

In view of the published literature it appears that the stability of dental implants depends on a number of factors, and results from various authors often are in conflict with each other. We present an overview of the factors that possibly influence ISQ measurements and conclude that at least 17 relevant factors (see Table 1) can be identified in the literature to do so, but as a whole set they have never been taken into account in any single study (see Table 2). So far, researchers only focused on a few subjectively chosen factors in their investigations. For example, Bischof et al.[31] reported that the ISQ values of various implants are generally higher in the mandible than in the maxilla; however, this finding seems to be dependent on the shape of implants since when implants of a cylindrical form were placed in the same area then no significant differences were encountered between ISQ data of implants. There are some researchers that took larger numbers of contributing factors into consideration in their studies, but no one went to the optimal experimental design to consider all those playing a possible role in influencing ISQ measurements, thus yielding a basis for conflicting results.

Another possible reason of the presence of large numbers of conflicting data in the literature may be related to the fact that some of these factors were not clearly quantified such as the bone type when used as a contributing factor. Bone type is difficult to reproducibly quantify and classify, and thus, most authors simply choose a subjective scheme according to the Lekholm and Zarb classification.[74] Another example for this is the bone defect,[16] or the implant location, if not provided in a precise and quantitative way respecting anatomical site and location. Thus there is a great need to develop methods that allow precise and reproducible descriptions of influencing factors on a quantitative basis.

In this study, we tried to identify and list all the potential factors that possibly have an influence on implant stability quotient measurements (see Tables 1 and 2), and if researchers do not consider these factors before the clinical trial designs and/or experimental studies, their studies will easily result in biased information.

Given the above defined aim of this review, we intentionally did not perform a literature analysis in the traditional way such as to classify the publications according to study-classification (such as a retrospective study, or a random controlled study (to assess the degree of reliability of these studies). In a recent systematic review in 2015 by Manzano-Moreno et al.,[124] it was described that from hundreds of publications the number of publications fulfilling strict scientific criteria for a solid and conclusive study was only 39, and in these they were able to identify only 6 factors that potentially contribute to ISQ measurement results. They found that 12 publications relate to dental implant design in relation to dental implant stability, 8 relate to surgical techniques in relationship to dental implant stability and 5 relate to a relationship between cone beam computed tomography (CBCT) and ISQ. This does not necessarily mean that the possible influencing factors are limited to 6 since many factors seem to be associated with the ISQ measurements. It does illustrate, however, that the availability of prospective randomized controlled trial publications is still quite insufficient.

The number of factors modulating ISQ measurement data is useful to know for experimental investigations, experimental designs and clinical trials. However, for the practicing clinician who needs a quick and reliable feedback from such measurements for the clinical assessment of predictability of the outcome of the implant and the assessment of it's stability, but also for the patient information, a simplified and rapid approach that provides this information on the spot is still needed. Clearly for such practical purposes the analysis needs simplification for rapid feasibility. In order to be able to suggest such a rapid approach for the practicing clinician we analyzed in our recent study[125] this situation and found that for example the 'bone graft' factor is a general factor, i.e. is an independent factor of other influences on primary (ISQ1) implant stability measurements. More such analyses will be possible in the future with the availability of more well-planned and well-founded prospective randomized clinical trials. The overview information provided in this literature review may be useful for the planning and design of future ISQ-related experimental studies both for the clinician and the experimental scientist.

Funding

China Scholarship Council (to H H); Foundation of the clinic of osteoporosis, Inselspital Bern (to EBH); Natural National Science Foundation, China (to GW).

Declarations of competing interest

None of the authors has any conflict of interest.

Acknowledgements

This study was financially supported by the Chinese Scholarship Counsel (to Hairong Huang), by the Foundation of the Clinic of Osteoporosis, Inselspital (University Hospital)d (to Ernst B Hunziker), and by the National Natural Science Foundation of China (No. 81470724, to Gang Wu).

References

1. Raghavendra S, Wood MC, Taylor TD. Early wound healing around endosseous implants: a review of the literature. *Int J Oral Maxillofac Implants.* May-Jun 2005;20(3):425–431.
2. Cochran DL, Buser D, ten Bruggenkate CM, et al. The use of reduced healing times on ITI implants with a sandblasted and acid-etched (SLA) surface: early results from clinical trials on ITI SLA implants. *Clin Oral Implants Res.* Apr 2002;13(2):144–153.
3. Albrektsson T, Johansson C. Osteoinduction, osteoconduction and osseointegration. *Eur Spine J.* Oct 2001;10(Suppl 2):S96–S101.
4. Guo CY, Matinlinna JP, Tang AT. Effects of surface charges on dental implants: past, present, and future. *Int J Biomater.* 2012;2012:381535.
5. Dottore AM, Kawakami PY, Bechara K, et al. Stability of implants placed in augmented posterior mandible after alveolar osteotomy using resorbable nonceramic hydroxyapatite or intraoral autogenous bone: 12-month follow-up. *Clin Implant Dent Relat Res.* Jun 2014;16(3):330–336.
6. Meredith N. Assessment of implant stability as a prognostic determinant. *Int J Prosthodont (IJP).* Sep-Oct 1998;11(5):491–501.
7. Marquezan M, Osorio A, Sant'Anna E, Souza MM, Maia L. Does bone mineral density

influence the primary stability of dental implants? A systematic review. *Clin Oral Implants Res.* Jul 2012;23(7):767–774.
8. Khalaila W, Nasser M, Ormianer Z. Evaluation of the relationship between Periotest values, marginal bone loss, and stability of single dental implants: a 3-year prospective study. *J Prosthetic Dent.* 2020;124(2):183–188.
9. Lozano-Carrascal N, Salomo-Coll O, Gilabert-Cerda M, Farre-Pages N, Gargallo-Albiol J, Hernandez-Alfaro F. Effect of implant macro-design on primary stability: a prospective clinical study. *Med Oral Patol Oral Cir Bucal.* 2016;21(2):e214–221.
10. Gehrke SA, da Silva Neto Ut, Rossetti PH, Watinaga SE, Giro G, Shibli JA. Stability of implants placed in fresh sockets versus healed alveolar sites: early findings. *Clin Oral Impl Res.* 2016;27(5):577–582.
11. Ostman PO, Hellman M, Wendelhag I, Sennerby L. Resonance frequency analysis measurements of implants at placement surgery. *Int J Prosthodont.* Jan-Feb 2006;19(1):77–83 discussion 84.
12. Boronat Lopez A, Balaguer Martinez J, Lamas Pelayo J, Carrillo Garcia C, Penarrocha Diago M. Resonance frequency analysis of dental implant stability during the healing period. *Med Oral Patol Oral Cir Bucal.* Apr 01 2008;13(4):E244–E247.
13. Park JC, Kim HD, Kim SM, Kim MJ, Lee JH. A comparison of implant stability quotients measured using magnetic resonance frequency analysis from two directions: a prospective clinical study during the initial healing period. *Clin Oral Implants Res.* Jun 2010;21(6):591–597.
14. Huang H, Wismeijer D, Shao X, Wu G. Mathematical evaluation of the influence of multiple factors on implant stability quotient values in clinical practice: a retrospective study. *Therapeut Clin Risk Manag.* 2016;12:1525–1532.
15. Ohta K, Takechi M, Minami M, et al. Influence of factors related to implant stability detected by wireless resonance frequency analysis device. *J Oral Rehabil.* Feb 2010;37(2):131–137.
16. Shin SY, Shin SI, Kye SB, et al. The effects of defect type and depth, and measurement direction on the implant stability quotient value. *J Oral Implantol.* Dec 2015;41(6):652–656.
17. Shin SY, Shin SI, Kye SB, et al. Bone cement grafting increases implant primary stability in circumferential cortical bone defects. *J Periodontal Implant Sci.* Feb 2015;45(1):30–35.
18. Zix J, Kessler-Liechti G, Mericske-Stern R. Stability measurements of 1-stage implants in the maxilla by means of resonance frequency analysis: a pilot study. *Int J Oral Maxillofac Implants.* Sep-Oct 2005;20(5):747–752.
19. Park KJ, Kwon JY, Kim SK, et al. The relationship between implant stability quotient values and implant insertion variables: a clinical study. *J Oral Rehabil.* Feb 2012;39(2):151–159.
20. Kim HJ, Kim YK, Joo JY, Lee JY. A resonance frequency analysis of sandblasted and acid-etched implants with different diameters: a prospective clinical study during the initial healing period. *J Periodontal Implant Sci.* Apr 2017;47(2):106–115.
21. Simunek A, Strnad J, Kopecka D, et al. Changes in stability after healing of immediately loaded dental implants. *Int J Oral Maxillofac Implants.* Nov-Dec 2010;25(6):1085–1092.
22. Aksoy U, Eratalay K, Tozum TF. The possible association among bone density values, resonance frequency measurements, tactile sense, and histomorphometric evaluations of dental implant osteotomy sites: a preliminary study. *Implant Dent.* Aug 2009;18(4):316–325.
23. Brochu JF, Anderson JD, Zarb GA. The influence of early loading on bony crest height and stability: a pilot study. *Int J Prosthodont.* Nov-Dec 2005;18(6):506–512.
24. Shiffler K, Lee D, Rowan M, Aghaloo T, Pi-Anfruns J, Moy PK. Effect of length, diameter, intraoral location on implant stability. *Oral Surg Oral Med Oral Pathol Oral Radiol.* Dec 2016;122(6):e193–e198.
25. Alsabeeha NH, De Silva RK, Thomson WM, Payne AG. Primary stability measurements of single implants in the midline of the edentulous mandible for overdentures. *Clin Oral Implants Res.* May 2010;21(5):563–566.
26. Guler AU, Sumer M, Duran I, Sandikci EO, Telcioglu NT. Resonance frequency analysis of 208 Straumann dental implants during the healing period. *J Oral Implantol.* Apr 2013;39(2):161–167.
27. Liaje A, Ozkan YK, Ozkan Y, Vanlioglu B. Stability and marginal bone loss with three types of early loaded implants during the first year after loading. *Int J Oral Maxillofac Implants.* Jan-Feb 2012;27(1):162–172.
28. Huber S, Rentsch-Kollar A, Grogg F, Katsoulis J, Mericske R. A 1-year controlled clinical trial of immediate implants placed in fresh extraction sockets: stability measurements and crestal bone level changes. *Clin Implant Dent Relat Res.* Aug 2012;14(4):491–500.
29. Monje A, Suarez F, Garaicoa CA, et al. Effect of location on primary stability and healing of dental implants. *Implant Dent.* Feb 2014;23(1):69–73.
30. Suzuki EY, Suzuki B, Aramrattana A, Harnsiriwattanakit K, Kowanich N. Assessment of miniscrew implant stability by resonance frequency analysis: a study in human cadavers. *J Oral Maxillofac Surg.* Nov 2010;68(11):2682–2689.
31. Bischof M, Nedir R, Szmukler-Moncler S, Bernard JP, Samson J. Implant stability measurement of delayed and immediately loaded implants during healing. *Clin Oral Implants Res.* Oct 2004;15(5):529–539.
32. Ku JK, Yi YJ, Yun PY, Kim YK. Retrospective clinical study of ultrawide implants more than 6 mm in diameter. *Maxillofac Plast Reconstr Surg.* Dec 2016;38(1):30.
33. Ebenezer V, Balakrishnan K, Asir RV, Sragunar B. Immediate placement of endosseous implants into the extraction sockets. *J Pharm BioAllied Sci.* Apr 2015;7(Suppl 1):S234–S237.
34. Villa R, Rangert B. Early loading of interforaminal implants immediately installed after extraction of teeth presenting endodontic and periodontal lesions. *Clin Implant Dent Relat Res.* 2005;7(Suppl 1):S28–S35.
35. Penarrocha M, Uribe R, Balaguer J. Immediate implants after extraction. A review of the current situation. *Med Oral.* May-Jul 2004;9(3):234–242.
36. Barone A, Marconcini S, Giammarinaro E, Mijiritsky E, Gelpi F, Covani U. Clinical outcomes of implants placed in extraction sockets and immediately restored: a 7-year single-cohort prospective study. *Clin Implant Dent Rel Res.* 2016;18(6):1103–1112.
37. Mangano FG, Mangano C, Ricci M, Sammons RL, Shibli JA, Piattelli A. Esthetic evaluation of single-tooth Morse taper connection implants placed in fresh extraction sockets or healed sites. *J Oral Implantol.* Apr 2013;39(2):172–181.
38. Granic M, Katanec D, Vucicevic Boras V, Susic M, Juric IB, Gabric D. Implant stability comparison of immediate and delayed maxillary implant placement by use of resonance frequency analysis–a clinical study. *Acta Clin Croat.* Mar 2015;54(1):3–8.
39. Malchiodi L, Balzani L, Cucchi A, Ghensi P, Nocini PF. Primary and secondary stability of implants in postextraction and healed sites: a randomized controlled clinical trial. *Int J Oral Maxillofac Implants.* Nov/Dec 2016;31(6):1435–1443.
40. Han J, Lulic M, Lang NP. Factors influencing resonance frequency analysis assessed by Osstell mentor during implant tissue integration: II. Implant surface modifications and implant diameter. *Clin Oral Implants Res.* Jun 2010;21(6):605–611.
41. Gehrke SA, Neto UTD. Does the time of osseointegration in the maxilla and mandible differ? *J Craniofac Surg.* Nov 2014;25(6):2117–2120.
42. Kim YH, Choi NR, Kim YD. The factors that influence postoperative stability of the dental implants in posterior edentulous maxilla. *Maxillofac Plast Reconstr Surg.* Dec 2017;39(1):2.
43. Gomez-Polo M, Ortega R, Gomez-Polo C, Martin C, Celemin A, Del Rio J. Does length, diameter, or bone quality affect primary and secondary stability in self-tapping dental implants? *J Oral Maxillofac Surg.* Jul 2016;74(7):1344–1353.
44. Barikani H, Rashtak S, Akbari S, Badri S, Daneshparvar N, Rokn A. The effect of implant length and diameter on the primary stability in different bone types. *J Dent.* Sep 2013;10(5):449–455.
45. Zix J, Hug S, Kessler-Liechti G, Mericske-Stern R. Measurement of dental implant stability by resonance frequency analysis and damping capacity assessment: comparison of both techniques in a clinical trial. *Int J Oral Maxillofac Implants.* May-Jun 2008;23(3):525–530.
46. Gonzalez-Garcia R, Monje F, Moreno-Garcia C. Predictability of the resonance frequency analysis in the survival of dental implants placed in the anterior non-atrophied edentulous mandible. *Med Oral Patol Oral Cir Bucal.* Aug 01 2011;16(5):e664–669.
47. Akkocaoglu M, Uysal S, Tekdemir I, Akca K, Cehreli MC. Implant design and intraosseous stability of immediately placed implants: a human cadaver study. *Clin Oral Implants Res.* Apr 2005;16(2):202–209.
48. Tsolaki IN, Najafi B, Tonsekar PP, Drew HJ, Sullivan AJ, Petrov SD. Comparison of osteotome and conventional drilling techniques for primary implant stability: an in vitro study. *J Oral Implantol.* 2016;3 Mar.
49. Wada M, Tsuiki Y, Suganami T, et al. The relationship between the bone characters obtained by CBCT and primary stability of the implants. *Int J Implant Dent.* Dec 2015;1(1):3.
50. Bataineh AB, Al-Dakes AM. The influence of length of implant on primary stability: an in vitro study using resonance frequency analysis. *J Clin Exp Dent.* Jan 2017;9(1):e1–e6.
51. Degidi M, Daprile G, Piattelli A. Primary stability determination by means of insertion torque and RFA in a sample of 4,135 implants. *Clin Implant Dent Relat Res.* Aug 2012;14(4):501–507.
52. Brizuela-Velasco A, Alvarez-Arenal A, Gil-Mur FJ, et al. Relationship between insertion torque and resonance frequency measurements, performed by resonance frequency analysis, in micromobility of dental implants: an in vitro study. *Implant Dent.* Oct 2015;24(5):607–611.
53. Simmons DE, Maney P, Teitelbaum AG, Billiot S, Popat LJ, Palaiologou AA. Comparative evaluation of the stability of two different dental implant designs and surgical protocols-a pilot study. *Int J Implant Dent.* Dec 2017;3(1):16.
54. Zita Gomes R, de Vasconcelos MR, Lopes Guerra IM, de Almeida RAB, de Campos Felino AC. Implant stability in the posterior maxilla: a controlled clinical trial. *BioMed Res Int.* 2017;2017:6825213.
55. Kwon TK, Kim HY, Yang JH, et al. First-order mathematical correlation between damping and resonance frequency evaluating the bone-implant interface. *Int J Oral Maxillofac Implants.* Sep-Oct 2016;31(5):1008–1015.
56. Tozum TF, Turkyilmaz I, McGlumphy EA. Relationship between dental implant stability determined by resonance frequency analysis measurements and peri-implant vertical defects: an in vitro study. *J Oral Rehabil.* Oct 2008;35(10):739–744.
57. Gehrke SA, Neto UTD, Del Fabbro M. Does implant design affect implant primary stability? A resonance frequency analysis-based randomized split-mouth clinical trial. *J Oral Implantol.* Dec 2015;41(6):E281–E286.
58. Romanos GE, Delgado-Ruiz RA, Sacks D, Calvo-Guirado JL. Influence of the implant diameter and bone quality on the primary stability of porous tantalum trabecular metal dental implants: an in vitro biomechanical study. *Clin Oral Implants Res.* 2018;29(6):649–655.
59. Chang YY, Kim SH, Park KO, Yun JH. Evaluation of a reverse-tapered design on the osseointegration of narrow-diameter implants in beagle dogs: a pilot study. *Int J Oral Maxillofac Implants.* May-Jun 2016;31(3):611–620.
60. Gehrke SA, Perez-Albacete Martinez C, Piattelli A, Shibli JA, Markovic A, Calvo Guirado JL. The influence of three different apical implant designs at stability and osseointegration process: experimental study in rabbits. *Clin Oral Implants Res.* Mar 2017;28(3):355–361.
61. Howashi M, Tsukiyama Y, Ayukawa Y, et al. Relationship between the CT value and cortical bone thickness at implant recipient sites and primary implant stability with comparison of different implant types. *Clin Implant Dent Relat Res.* Feb 2016;18(1):107–116.
62. Karabuda ZC, Abdel-Haq J, Arisan V. Stability, marginal bone loss and survival of standard and modified sand-blasted, acid-etched implants in bilateral edentulous

spaces: a prospective 15-month evaluation. *Clin Oral Implants Res.* Aug 2011;22(8):840–849.
63. Oates TW, Valderrama P, Bischof M, et al. Enhanced implant stability with a chemically modified SLA surface: a randomized pilot study. *Int J Oral Maxillofac Implants.* Sep-Oct 2007;22(5):755–760.
64. Kim YS, Lim YJ. Primary stability and self-tapping blades: biomechanical assessment of dental implants in medium-density bone. *Clin Oral Implants Res.* Oct 2011;22(10):1179–1184.
65. Khandelwal N, Oates TW, Vargas A, Alexander PP, Schoolfield JD, Alex McMahan C. Conventional SLA and chemically modified SLA implants in patients with poorly controlled type 2 diabetes mellitus–a randomized controlled trial. *Clin Oral Implants Res.* Jan 2013;24(1):13–19.
66. Geckili O, Bilhan H, Mumcu E, Bilgin T. Three-year radiologic follow-up of marginal bone loss around titanium dioxide grit-blasted dental implants with and without fluoride treatment. *Int J Oral Maxillofac Implants.* Mar-Apr 2011;26(2):319–324.
67. Geckili O, Bilhan H, Bilgin T. A 24-week prospective study comparing the stability of titanium dioxide grit-blasted dental implants with and without fluoride treatment. *Int J Oral Maxillofac Implants.* Jul-Aug 2009;24(4):684–688.
68. Schatzle M, Mannchen R, Balbach U, Hammerle CH, Toutenburg H, Jung RE. Stability change of chemically modified sandblasted/acid-etched titanium palatal implants. A randomized-controlled clinical trial. *Clin Oral Implants Res.* May 2009;20(5):489–495.
69. Abtahi J, Tengvall P, Aspenberg P. A bisphosphonate-coating improves the fixation of metal implants in human bone. A randomized trial of dental implants. *Bone.* May 2012;50(5):1148–1151.
70. Ho DS, Yeung SC, Zee KY, Curtis B, Hell P, Tumuluri V. Clinical and radiographic evaluation of NobelActive(TM) dental implants. *Clin Oral Implants Res.* Mar 2013;24(3):297–304.
71. Hunziker EB, Jovanovic J, Horner A, Keel MJ, Lippuner K, Shintani N. Optimisation of BMP-2 dosage for the osseointegration of porous titanium implants in an ovine model. *Eur Cell Mater.* 2016;32:241–256 Nov 18.
72. Gultekin BA, Gultekin P, Leblebicioglu B, Basegmez C, Yalcin S. Clinical evaluation of marginal bone loss and stability in two types of submerged dental implants. *Int J Oral Maxillofac Implants.* May-Jun 2013;28(3):815–823.
73. Javed F, Almas K, Crespi R, Romanos GE. *Implant Surface Morphology and Primary Stability: Is There a Connection? Implant Dent.* Feb 2011; Feb 2011:40–46 1.
74. Lekholm U, Zarb GA. Patient selection and preparation. In: Bra˚nemark P-I, Zarb GA, Albrektsson T, eds. *Tissue Integrated Prostheses: Osseointegration in Clinical Dentistry.* Chicago: Quintessence; 1985:199–209.
75. Fu MW, Shen EC, Fu E, Lin FG, Wang TY, Chiu HC. Assessing bone type of implant recipient sites by stereomicroscopic observation of bone core specimens: a comparison with the assessment using dental radiography. *J Periodontol.* Mar 10 2017:1–13.
76. Fuster-Torres MA, Penarrocha-Diago M, Penarrocha-Oltra D. Relationships between bone density values from cone beam computed tomography, maximum insertion torque, and resonance frequency analysis at implant placement: a pilot study. *Int J Oral Maxillofac Implants.* Sep-Oct 2011;26(5):1051–1056.
77. Oh JS, Kim SG. Clinical study of the relationship between implant stability measurements using Periotest and Osstell mentor and bone quality assessment. *Oral Surg Oral Med Oral Pathol Oral Radiol.* Mar 2012;113(3):e35–40.
78. Salimov F, Tatli U, Kurkcu M, Akoglan M, Oztunc H, Kurtoglu C. Evaluation of relationship between preoperative bone density values derived from cone beam computed tomography and implant stability parameters: a clinical study. *Clin Oral Implants Res.* Sep 2014;25(9):1016–1021.
79. Hieu PD, Baek DH, Park DS, Park JT, Hong KS. Evaluation of stability changes in magnesium-incorporated titanium implants in the early healing period. *J Craniofac Surg.* Sep 2013;24(5):1552–1557.
80. Barewal RM, Oates TW, Meredith N, Cochran DL. Resonance frequency measurement of implant stability in vivo on implants with a sandblasted and acid-etched surface. *Int J Oral Maxillofac Implants.* Sep-Oct 2003;18(5):641–651.
81. Herekar M, Sethi M, Ahmad T, Fernandes AS, Patil V, Kulkarni H. A correlation between bone (B), insertion torque (IT), and implant stability (S): BITS score. *J Prosthet Dent.* Oct 2014;112(4):805–810.
82. Valiyaparambil JV, Yamany I, Ortiz D, et al. Bone quality evaluation: comparison of cone beam computed tomography and subjective surgical assessment. *Int J Oral Maxillofac Implants.* Sep-Oct 2012;27(5):1271–1277.
83. Al-Khaldi N, Sleeman D, Allen F. Stability of dental implants in grafted bone in the anterior maxilla: longitudinal study. *Br J Oral Maxillofac Surg.* Jun 2011;49(4):319–323.
84. Rasmusson L, Thor A, Sennerby L. Stability evaluation of implants integrated in grafted and nongrafted maxillary bone: a clinical study from implant placement to abutment connection. *Clin Implant Dent Relat Res.* Mar 2012;14(1):61–66.
85. Ozkan Y, Ozcan M, Varol A, Akoglu B, Ucankale M, Basa S. Resonance frequency analysis assessment of implant stability in labial onlay grafted posterior mandibles: a pilot clinical study. *Int J Oral Maxillofac Implants.* Mar-Apr 2007;22(2):235–242.
86. Yang SM, Shin SY, Kye SB. Relationship between implant stability measured by resonance frequency analysis (RFA) and bone loss during early healing period. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod.* Feb 2008;105(2):e12–19.
87. Fischer K, Backstrom M, Sennerby L. Immediate and early loading of oxidized tapered implants in the partially edentulous maxilla: a 1-year prospective clinical, radiographic, and resonance frequency analysis study. *Clin Implant Dent Relat Res.* Jun 2009;11(2):69–80.
88. Mierzwinski J, Konopka W, Drela M, et al. Evaluation of bone conduction implant stability and soft tissue status in children in relation to age, bone thickness, and sound processor loading time. *Otol Neurotol.* Aug 2015;36(7):1209–1215.
89. Kim DS, Lee WJ, Choi SC, et al. Comparison of dental implant stabilities by impact response and resonance frequencies using artificial bone. *Med Eng Phys.* Jun 2014;36(6):715–720.
90. Bayarchimeg D, Namgoong H, Kim BK, et al. Evaluation of the correlation between insertion torque and primary stability of dental implants using a block bone test. *J Periodontal Implant Sci.* Feb 2013;43(1):30–36.
91. Hsu JT, Fuh LJ, Tu MG, Li YF, Chen KT, Huang HL. The effects of cortical bone thickness and trabecular bone strength on noninvasive measures of the implant primary stability using synthetic bone models. *Clin Implant Dent Relat Res.* Apr 2013;15(2):251–261.
92. Merheb J, Van Assche N, Coucke W, Jacobs R, Naert I, Quirynen M. Relationship between cortical bone thickness or computerized tomography-derived bone density values and implant stability. *Clin Oral Implants Res.* Jun 2010;21(6):612–617.
93. Song YD, Jun SH, Kwon JJ. Correlation between bone quality evaluated by cone-beam computerized tomography and implant primary stability. *Int J Oral Maxillofac Implants.* Jan-Feb 2009;24(1):59–64.
94. Andres-Garcia R, Vives NG, Climent FH, et al. In vitro evaluation of the influence of the cortical bone on the primary stability of two implant systems. *Med Oral Patol Oral Cir Bucal.* Feb 01 2009;14(2):E93–E97.
95. Turkyilmaz I, Tumer C, Ozbek EN, Tozum TF. Relations between the bone density values from computerized tomography, and implant stability parameters: a clinical study of 230 regular platform implants. *J Clin Periodontol.* Aug 2007;34(8):716–722.
96. Dias DR, Leles CR, Lindh C, Ribeiro-Rotta RF. Marginal bone level changes and implant stability after loading are not influenced by baseline microstructural bone characteristics: 1-year follow-up. *Clin Oral Implants Res.* 2016;27(10):1212–1220.
97. Atsumi M, Park SH, Wang HL. Methods used to assess implant stability: current status. *Int J Oral Maxillofac Implants.* Sep-Oct 2007;22(5):743–754.
98. Park IP, Kim SK, Lee SJ, Lee JH. The relationship between initial implant stability quotient values and bone-to-implant contact ratio in the rabbit tibia. *J Adv Prosthodont.* Jun 2011;3(2):76–80.
99. Huang HL, Tsai MT, Su KC, et al. Relation between initial implant stability quotient and bone-implant contact percentage: an in vitro model study. *Oral Surg Oral Med Oral Pathol Oral Radiol.* Nov 2013;116(5):e356–361.
100. Nkenke E, Hahn M, Weinzierl K, Radespiel-Troger M, Neukam FW, Engelke K. Implant stability and histomorphometry: a correlation study in human cadavers using stepped cylinder implants. *Clin Oral Implants Res.* Oct 2003;14(5):601–609.
101. Hagi TT, Enggist L, Michel D, Ferguson SJ, Liu Y, Hunziker EB. Mechanical insertion properties of calcium-phosphate implant coatings. *Clin Oral Implants Res.* Nov 2010;21(11):1214–1222.
102. Kokovic V, Krsljak E, Andric M, et al. Correlation of bone vascularity in the posterior mandible and subsequent implant stability: a preliminary study. *Implant Dent.* Apr 2014;23(2):200–205.
103. Makary C, Rebaudi A, Sammartino G, Naaman N. Implant primary stability determined by resonance frequency analysis: correlation with insertion torque, histologic bone volume, and torsional stability at 6 weeks. *Implant Dent.* Dec 2012;21(6):474–480.
104. Crismani AG, Bernhart T, Schwarz K, Celar AG, Bantleon HP, Watzek G. Ninety percent success in palatal implants loaded 1 week after placement: a clinical evaluation by resonance frequency analysis. *Clin Oral Implants Res.* Aug 2006;17(4):445–450.
105. Guncu MB, Aslan Y, Tumer C, Guncu GN, Uysal S. In-patient comparison of immediate and conventional loaded implants in mandibular molar sites within 12 months. *Clin Oral Implants Res.* Apr 2008;19(4):335–341.
106. Cannizzaro G, Leone M, Esposito M. Immediate versus early loading of two implants placed with a flapless technique supporting mandibular bar-retained overdentures: a single-blinded, randomised controlled clinical trial. *Eur J Oral Implantol. Spring.* 2008;1(1):33–43.
107. Benic GI, Mir-Mari J, Hammerle CH. Loading protocols for single-implant crowns: a systematic review and meta-analysis. *Int J Oral Maxillofac Implants.* 2014;29(Suppl):222–238.
108. Gulay G, Asar NV, Tulunoglu I, Turkyilmaz I, Wang HL, Tozum TF. Primary stability/mobility of 1-stage and 2-stage dental implants: a comparative in vitro study. *Implant Dent.* Dec 2012;21(6):461–466.
109. Degidi M, Daprile G, Piattelli A. Primary stability determination of implants inserted in sinus augmented sites: 1-step versus 2-step procedure. *Implant Dent.* Oct 2013;22(5):530–533.
110. Al-Magaleh WR, Swelem AA, Radi IA. The effect of 2 versus 4 implants on implant stability in mandibular overdentures: a randomized controlled trial. *J Prosthet Dent.* 2017;118(6):725–731.
111. Lin YT, Hong A, Peng YC, Hong HH. Developing stability of posterior mandibular implants placed with osteotome expansion technique compared with conventional drilling techniques. *J Oral Implantol.* Apr 2017;43(2):131–138.
112. Huwais S, Meyer EG. A novel osseous densification approach in implant osteotomy preparation to increase biomechanical primary stability, bone mineral density, and bone-to-implant contact. *Int J Oral Maxillofac Implants.* Jan/Feb 2017;32(1):27–36.
113. Hong HH, Hong A, Yang LY, Chang WY, Huang YF, Lin YT. Implant stability quotients of osteotome bone expansion and conventional drilling technique for 4.1 mm diameter implant at posterior mandible. *Clin Implant Dent Relat Res.* Apr 2017;19(2):253–260.
114. Mohlhenrich SC, Heussen N, Loberg C, Goloborodko E, Holzle F, Modabber A. Three-dimensional evaluation of implant bed preparation and the influence on primary implant stability after using 2 different surgical techniques. *J Oral Maxillofac Surg.* Sep 2015;73(9):1723–1732.
115. Katsoulis J, Avrampou M, Spycher C, Stipic M, Enkling N, Mericske-Stern R. Comparison of implant stability by means of resonance frequency analysis for flapless and conventionally inserted implants. *Clin Implant Dent Relat Res.* Dec 2012;14(6):915–923.

116. Shayesteh YS, Khojasteh A, Siadat H, et al. A comparative study of crestal bone loss and implant stability between osteotome and conventional implant insertion techniques: a randomized controlled clinical trial study. *Clin Implant Dent Relat Res.* Jun 2013;15(3):350–357.
117. Markovic A, Calvo-Guirado JL, Lazic Z, et al. Evaluation of primary stability of self-tapping and non-self-tapping dental implants. A 12-week clinical study. *Clin Implant Dent Relat Res.* Jun 2013;15(3):341–349.
118. Turkyilmaz I, Aksoy U, McGlumphy EA. Two alternative surgical techniques for enhancing primary implant stability in the posterior maxilla: a clinical study including bone density, insertion torque, and resonance frequency analysis data. *Clin Implant Dent Relat Res.* Dec 2008;10(4):231–237.
119. Alghamdi H, Anand PS, Anil S. Undersized implant site preparation to enhance primary implant stability in poor bone density: a prospective clinical study. *J Oral Maxillofac Surg.* Dec 2011;69(12):e506–512.
120. Stacchi C, Vercellotti T, Torelli L, Furlan F, Di Lenarda R. Changes in implant stability using different site preparation techniques: twist drills versus piezosurgery. A single-blinded, randomized, controlled clinical trial. *Clin Implant Dent Relat Res.* Apr 2013;15(2):188–197.
121. Padmanabhan TV, Gupta RK. Comparison of crestal bone loss and implant stability among the implants placed with conventional procedure and using osteotome technique: a clinical study. *J Oral Implantol.* 2010;36(6):475–483.
122. Garcia-Morales JM, Tortamano-Neto P, Todescan FF, de Andrade Jr JC, Marotti J, Zezell DM. Stability of dental implants after irradiation with an 830-nm low-level laser: a double-blind randomized clinical study. *Laser Med Sci.* Jul 2012;27(4):703–711.
123. Shadid RM, Sadaqah NR, Othman SA. Does the implant surgical technique affect the primary and/or secondary stability of dental implants? A systematic review. *Int J Dent.* 2014;2014:204838.
124. Manzano-Moreno FJ, Herrera-Briones FJ, Bassam T, Vallecillo-Capilla MF, Reyes-Botella C. Factors affecting dental implant stability measured using the ostell mentor device: a systematic review. *Implant Dent.* Oct 2015;24(5):565–577.
125. Huang H, Shao X, Wismeijera D, Sun P, Wang J, Wu G. Multivariate linear regression analysis to identify general factors for quantitative predictions of implant stability quotient values. *PloS One.* 2017;12(10):e0187010.