RESONANCE FREQUENCY ANALYSIS FOR IMPLANT STABILITY MEASUREMENTS. A review

Lars Sennerby, DDS, PhD

Private practice, Clinica Feltre, Feltre, Italy

Professor, Dept of Oral & Maxillofacial Surgery, Sahlgrenska Academy, University of Gothenburg, Sweden

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ABSTRACT: The resonance frequency analysis (RFA) technique for implant stability measurements was developed by Meredith and co-workers more than 20 years ago. RFA makes use of a transducer (peg), which is attached to the implant and excited over a range of frequencies by electro-magnetic waves to measure the resonance frequency (RF) of the transducer. The underlying RF measurements in Hz are translated to Implant Stability Quotients (ISQ) units from 1 (lowest stability) to 100 ISQ units (highest stability). A new generation of RFA technology has been developed consisting of a small pen-like battery-driven instrument (Penguin^{RFA}) used together with reusable transducers (MulTiPeg™). These are made from biocompatible titanium and can be autoclaved and used numerous times. The instrument can be packed in a sterile pouch and kept on the surgical tray and used by the surgeon without jeopardizing sterility. RFA measures implant stability in bending as a function of interface stiffness and correlates with implant displacement, i.e. micro-mobility, under lateral loading. The ISQ value is determined by the local bone density and is influenced by implant placement technique, implant design, healing time and exposed implant height above the alveolar crest. It seems like implants with low and/or falling ISQ values pose an increased risk for failure compared with implants with high and/or increasing values. The RFA technique can be used at any stage during treatment as one additional parameter to support decision-making during implant treatment and follow-up. For instance, authors have proposed that certain levels of stability should be achieved/reached in order to commence immediate and early loading.

INTRODUCTION

Replacement of missing teeth with dental implants represents one of the most successful treatment modalities in modern medicine. However, failures do occur and literature reviews have shown failure rates in the range from 5 to 8 % for routine procedures [1,2] and up to 20% in major grafting cases [3] during at least 5 years of function. The majority of implant losses may be explained as biomechanically induced failures, since low primary implant stability, low bone density, short implants and overload have been identified as risk factors [1,4]. Hence, achievement and maintenance of firm implant stability are regarded as preconditions for a successful clinical outcome with dental implants.

The main determinants of implant stability are the mechanical properties of the bone tissue at the implant site and how well the implant is engaged with that bone tissue [5]. Thus, the bone density, the surgical technique and the implant design determine primary implant stability at the time of surgery. The implant is initially stabilized by compression of bone (Figure 1). Secondary stability is achieved with time as a result of bone healing, i.e. newly formed bone will bridge and fill the voids of the interface zone and grow into surface irregularities and macroscopic undercuts, which results in interlocking and further stabilization of the implant. The

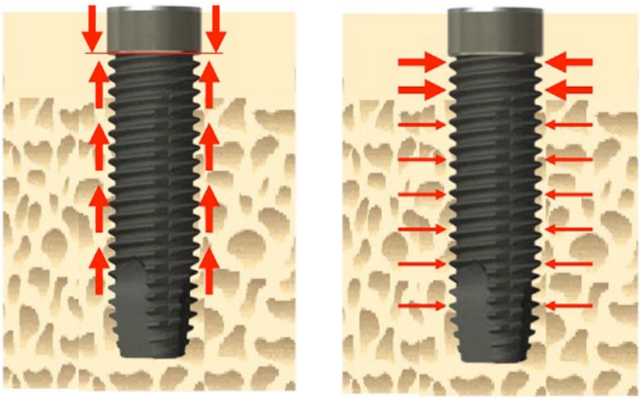

Figure 1. *Illustrations of primary implant stability achieved by axial and lateral compression of bone during insertion*

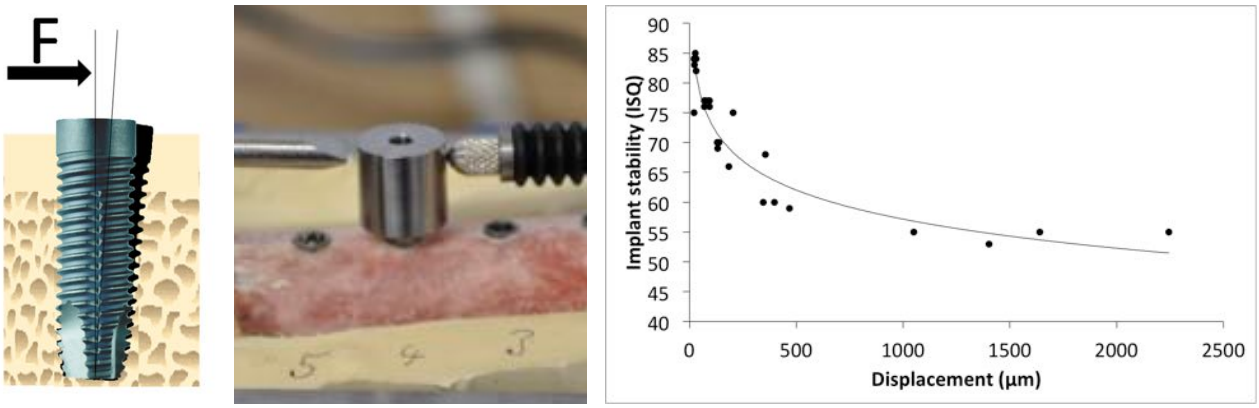

Figure 2. *Lateral loading of a stable implant will result in displacement of the implant in bone. In vitro work has demonstrated a correlation between displacement and RFA measurements in ISQ units* [7].

newly formed bone matures with time, which results in an increased density and stiffness of the implant-bone complex.

A clinically stable implant displays mobility on the micro-scale when loaded. When applying a lateral load to a clinically stable implant, the implant will be displaced in bone (Figures 2) [6-7] . Consequently, a stable implant can exhibit a varying degree of stability (i.e. different degrees of displacement or resistance to load) depending on factors such as bone density, surgical technique, implant design and quality of the bone-implant interface. A failed implant on the other hand shows clinical mobility on the macro-scale as the implant is surrounded by a fibrous scar tissue. The presence of fibrous tissue can be the result of (i) failed osseointegration after initial healing or (ii) gradual "disintegration" of an initially successfully integrated implant due to unfavorable conditions during functional loading. Since failure seems to correlate with biomechanical factors such as bone density, it can be speculated that implants with a high degree of micro-mobility are more prone to failure than more stable implants. Moreover, it is logical to assume that an initially successful but failing implant shows an increasing degree of micro-mobility until clinical failure is obvious. This suggests that techniques to measure and monitor implant micro-motion/stability could give the clinician a possibility to optimize implant treatment, for instance by ensuring sufficient stability at placement and before loading and confirming maintained stability after a period of loading. Some 20 years ago, Meredith and co-workers developed resonance frequency analysis (RFA) for implant stability measurements, a technique which today is commercially available as Osstell (Osstell AB, Gothenburg, Sweden) and more recently as Penguin[RFA] (Integration Diagnostics Sweden AB, Gothenburg , Sweden). As will be described in detail below, the technique measures the resonance frequency of a transducer that is attached to the implants. Recent *in vitro* works have demonstrated the RFA technique to correlate with micro-mobility/displacement, which in turn is mainly determined by the bone density (Figure 2) [6-7]. The purpose of this paper is to summarize the experiences with the technique over 20 years.

RESONANCE FREQUENCY ANALYSIS

After some years of work, Meredith and co-workers first described the RFA method in 1996 [8] . The first generations of RFA utilized a transducer fabricated from stainless steel or titanium and comprised an offset cantilever beam with piezoceramic elements (Figure 3). The beam was vibrated by exciting one of the elements with a sinusoidal signal of varying frequency typically from 5 to 15 kHz, which was synthesised by a frequency response analyser and a

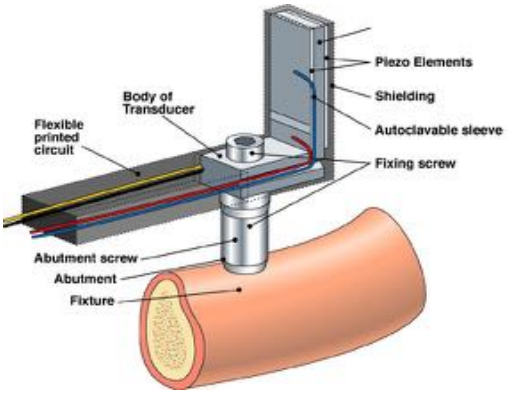

Figure 3. *Schematic of a first generation RFA transducer*

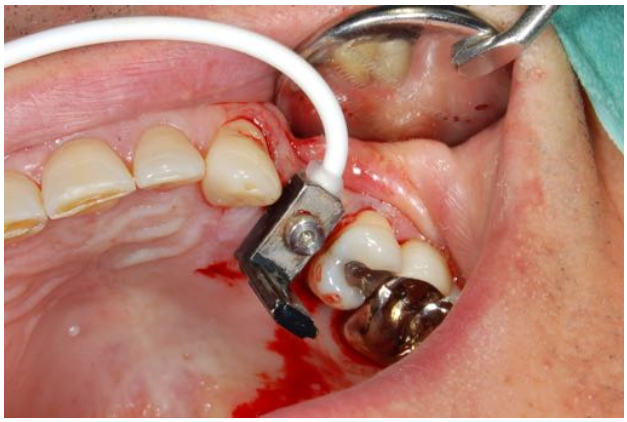

Figure 4. *The first commercial RFA instrument (Osstell) with a wired transducer.*

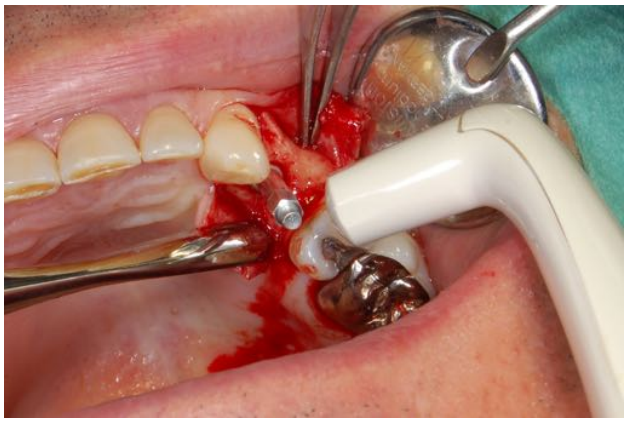

Figure 5. *Showing the use of wireless RFA technique (SmartPeg and Osstell Mentor).*

PC. The second piezoceramic element measured the response of the beam and a charge amplifier amplified the signal generated. At the first flexural resonance frequency of the beam, there was a marked increase in amplitude and change in phase of the received signal. The RF at which the peak appeared was used to describe the stability of the implant in Hertz (Hz). Thanks to a grant from the European Commission for a demonstration project between 1997 and 2000 [9], it became possible to develop a commercially available instrument (Figure 4). The most evident changes compared to the early prototypes were related to the electronics, the design and function of the transducer and a new measurement unit. Thus, a dedicated computer (Osstell, Osstell AB, Gothenburg, Sweden) and autoclavable and calibrated transducers could be fabricated. Moreover, a new unit called Implant Stability Quotient (ISQ) was established. The ISQ scale runs from 1 to 100 units, where the former is the lowest and the latter the highest degree of stability. With the new instrument, the former wired transducer was (SmartPeg™), which allows for non-contact measurements (Figure 5). The RF of the peg is measured by the electronics by using the same principle as with the first dedicated instrument. However, while the transducer was excited with a swept sinusoidal signal through a cable, the magnet attached to the peg is excited with magnetic pulses. After each pulse, an electric coil in the measurement probe picks up the alternating magnetic field that is the result of the self-vibrating peg. A second coil in the same probe generates the magnetic pulses. The aluminum pegs have a simplified mechanical design compared to the transducers, and do not require individual calibration. However, a drawback is that they are disposable and any attempts to clean and sterilize the peg results in corrosion and probably in questionable measurements.

A new generation of RFA technology has been developed by members of the original team behind the commercialisation of RFA (Integration Diagnostics Sweden AB, Gothenburg, Sweden). A small pen-like battery-driven instrument (PenguinRFA) is used together with reusable transducers (MulTiPeg™)(Figure 6). These are made from biocompatible titanium and can consequently be autoclaved and used numerous times. The instrument can be packed in a sterile pouch and kept on the surgical tray and used without the assistance from a second person (Figure 7). The ISQ values are shown in two displays, one each side of the instrument.

FACTORS DETERMINING RFA MEASUREMENTS

Factors related to bone properties

Bone density is a major determinant of RFA measurement as shown in numerous studies. A positive correlation between ISQ units and bone density as assessed with the Lekholm & Zarb index [10-15], with insertion torque measurements [16-25] and with quantitative CT [7,17, 19-20, 23, 26-27] has been demonstrated. Implant stability is usually higher in the mandible than in the maxilla [11, 28-30] due to the fact that mandibular bone is often denser than maxillary. It is also possible to find differences when comparing anterior and posterior sites within each jaw [3, 29].

The properties of the marginal bone influences RFA measurements [31-36] .For instance, Myiamoto et al [32] observed a strong, positive correlation between cortical bone thickness, as

Figure 6. *Showing a novel RFA instrument and reusable transducers made from titanium (Penguin[RFA] and MulTipegs).*

judged from computed tomography scans and initial ISQ values for 225 screw-shaped implants placed in the maxilla and the mandible. Similarly, Nkenke et al [33] and Gedrange et al [34] found a positive correlation between the height of the crestal cortical bone and ISQ values in cadaver studies. In an in vitro investigation, Tözum and co-workers [36] demonstrated a decreased ISQ value with decreasing bucco-lingual thickness from 8 to 0 mm.

Implant factors

The influence of implant length and diameter on RFA measurements is not clear and seems to vary between studies. Östman et al [29] and Miyamoto et al [32] found higher stability with increased implant diameter but decreasing stability with increasing implant length, which is explained by the fact that some long implant designs have a reduced diameter (negative tolerance) in the coronal part to minimize friction heat and to facilitate insertion. Other authors reported that the primary stability for the same implant design placed in grafted bone was significant higher for 15 and 18 mm long implants than for 10 and 13 mm implants[3].

Bischof et al [37] found no influence of implant position, implant length, implant diameter and vertical position on the ISQ values of 106 implants placed in the maxilla and the mandible, which is in line with the findings from other researchers [38-39]. Sim & Lang [14] reported a non-significant lower stability for 8 compared with 10 mm implants at placement, but that the 8 mm showed a significant increase up to12 weeks. A clinical study found a higher stability for 12 than for 10 mm implants and for 4.8 mm than for 4.1 mm wide implants [15]. Also Tözum and co-workers found higher ISQ values with increased implant diameter in an *in vitro* study [36].

Surgical technique

The use of technique to create increased lateral compression during insertion seems to result in higher stability. This may be due to undersized preparation before placing the implant [40], wider implants [41] or the use of tapered implant [42-43].

Time dependence

The resonance frequency analysis technique has been used in animals to study implant healing in normal bone [44-45], in grafted bone [46-48] and in membrane-induced bone [49]. In the rabbit tibia model the resonance frequency increases with time as a function of an increased stiffness resulting from new bone formation and remodelling. However, if the primary stability of an implant is very high, as can be achieved in the dog mandible, subtle changes in stiffness may not be evident [50-52].

Friberg and co-wokers [16] reported that all implants placed in the edentulous maxilla, irrespective of initial stability, tended to reach a similar level of stability at the time of abutment connection (6– 8 months later) and after 1 year in function. This is in line with a clinical study by Sennerby et al [50], where implants in soft bone with low primary stability showed a marked increase in stability compared with implants in dense bone . Other researchers [3, 11, 28, 54-56] have reported similar findings. The data indicate that healing and remodelling process of soft trabecular bone seems to result in an increased stiffness of the peri-implant bone.

Studies on one-stage and immediately loaded implants have demonstrated an initial decrease of implant stability, which, however, seems to reverse after 3 months when an increase in implant stability is usually seen [11, 57-60]. The initial decrease in im-

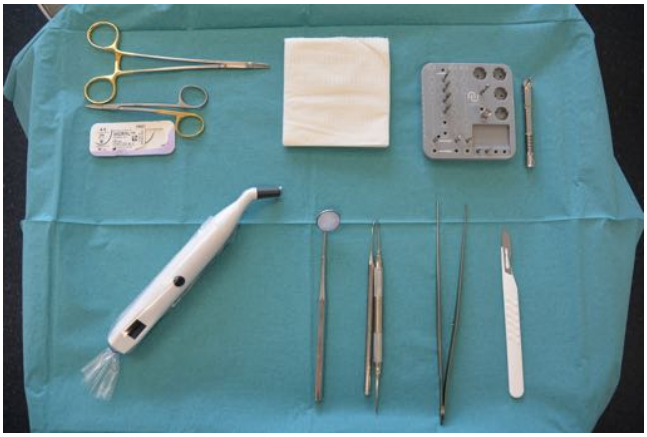

Figure 7. *Showing the Penguin[RFA] in a sterile pouch on a surgical tray for implant placement.*

plant stability is probably reflects the healing and remodelling process and thereby a temporary weakening of the bone. It can be speculated that loading of the implants during this period may accentuate this initial decrease of ISQ value [57]. However, studies have also shown no initial dip [61-63], which may be explained by that different implant surface has been used.

Marginal bone resorption and presence of defects

The relationship between the length of an implant abutment and resonance frequency analysis data has been examined in various model systems. In vitro work has demonstrated a correlation between ISQ readings and the size of 0.5 mm deep peri-implant defects [24]. Turkyilmaz et al [64] demonstrated a negative correlation between exposed implant height and ISQ values for implants placed in fresh extraction sockets in human jaws. The authors proposed using the resonance frequency analysis technique to monitor the healing of implants in extraction sockets. Other researchers [65-66] reported similar results.

Sennerby et al demonstrated a negative correlation between radiographic bone loss and ISQ measurements in a dog model [51]. Turkyilmaz and co-workers [67] found a negative correlation between increased marginal bone loss around mandibular implants and decreased implant stability over the first 6 months following implant placement. No such correlation was observed between the 6-month and the 12-month study period. The authors suggested that the effect of bone loss was compensated for by an increased interfacial stiffness resulting from bone formation and remodelling from 6 to 12 months. In a clinical study on mandibular implants, Tözum et al [68] noted a negative correlation between ISQ and marginal bone resorption. However, Fischer et al [61] found no correlation between marginal bone loss and resonance frequency analysis measurements during a 1-year period. The ongoing healing process may have counteracted and masked the effect of marginal bone loss. However, after 3 and 5 years, when healing must be regarded as being complete, the same research group found a strong correlation between marginal bone loss and ISQ values. This is in line with Meredith et al [69], who suggested that variations in implant stability after 5 years in function could be explained by differences in marginal bone height.

Implant surface

Most researchers have not found implant surfaces to impact on ISQ measurements [51, 70-72]. However, in dogs, Rompen et al [50] showed that surfaced-modified implants maintained stability, whilst machined implants experienced a decrease in stability during the early healing period. This has been confirmed in two clinical studies. Glauser et al [73] compared machined and oxidized implants using an immediate loading protocol and found more decrease in stability for machined implants during the first 3 months post-loading. A clinical study on immediate loading in the posterior mandible found no difference in primary stability between machined and oxidized titanium implants [74]. However, the machined implants showed a significant loss of stability, while the oxidized implants remained their stability after 4 months of loading.

RFA MEASUREMENTS AND IMPLANT FAILURE

In a study by Friberg at al [74], 75 one-stage implants in the edentulous mandible was evaluated with RFA. One implant showed a decreasing stability from week 2 to week 15, when the implant was found to be clinically mobile. In a second patient, three of five implants showed a marked decrease in stability from week 2 to week 6, which corresponded to the period of implant loading with a relined denture. After a period of unloading, the implant stability increased for two implants and was maintained at the same level for one implant. The same research group showed an increase in implant stability from the time of placement to abutment connection for 56 maxillary implants except for two failing implants [16]. In an immediate loading study, Glauser et al [58] monitored the stability of 81 implants from placement to 1 year in function. A total of nine implants failures were experienced. All implants showed a high degree of initial stability, around ISQ 70, but the group of future failures showed a continuous decrease in implant stability. After 1 month, the mean ISQ value of 52 was statistically lower for the group of future failures than for the successful implants, which showed an ISQ of 68. Also, ISQ values of 49–58 were associated with an 18.2% risk of failure. Evidently, the lower the ISQ value after 1 month of immediate loading, the higher the risk for future failure.

In a follow-up study on implants placed in extraction sockets and subjected to immediate/early loading, Vanden Boagerde and co-workers [76] demonstrated rescue of one implant based on resonance frequency analysis measurements. This implant showed a significant drop from 67 ISQ to 53 ISQ during the first six weeks. The implant was unloaded and recovered to an ISQ value of 72 after 6 months.

Sjöström et al [3] found lower primary stability for 17 implants (ISQ 54.6) that failed during the first year of function compared with 195 implants (ISQ 62.0) that were successful installed in grafted maxillae.

Nedir and co-workers [54] compared immediately loaded

implants with implants loaded after 3 months of healing and concluded that the resonance frequency analysis technique did not reliably identify mobile implants. However, implant stability could be reliably determined for implants with an ISQ of more than 47. One explanation for not detecting some mobile implants may be a result of the nature of the resonance frequency analysis technique, which measures stability as a function of stiffness. Clinically mobile implants display an exceptionally low stiffness, which prevents the resonance frequency analysis system from identifying the first resonance frequency, and which therefore records a falsely high ISQ value corresponding to the second resonance frequency [89].

Huwiler et al [78] followed 17 implants with repeated resonance frequency analysis measurements for up to 12 weeks after implant surgery (24). One implant failed and its ISQ value decreased from 68 to 45. As implant mobility occurred at low ISQ values, the authors concluded that the resonance frequency analysis system couldn't be used to predict implant failure.

Fischer et al [61] studied the stability of 53 implants during a period of 1 year (15). The implants supported single crowns (n = 16) or partial bridges (n = 16) in the maxilla placed at the time of, or within 16 days of, implant surgery. The average primary stability of all implants after surgery was 63.3 ISQ, and one failed implant showed a value of 56 ISQ, which was the fifth lowest value of the 53 implants. In an other study, the same group performed resonance frequency analysis measurements in 24 patients with 139 maxillary implants at 3 and 5 years following implant surgery [79]. Four implants were lost during the third to the fifth year. At year 3, the failing implants showed lower ISQ values than the average implant (i.e. 44 ISQ, 53 ISQ, 54 ISQ and 54 ISQ vs. an average of 57.7 ISQ for all other implants in the study). An assessment of the risk for implant failure showed that ISQ values below 44, 53 and 54 were associated with failure rates of 100%, 6.7% and 9.5%, respectively. None of 97 implants with ISQ values higher than 54 failed from study year 3 to study year 5.

In a retrospective study on 300 implants of which 20 were lost after three years, Turkyilmaz and McGlumphy [20] found a significant difference between the failed and the successful implants with regard to primary stability and bone density. Thus, the failed implants showed lower ISQ values than the successful ones, 46.5 $\pm$ 4 vs 67.1 $\pm$ 7 ISQ. Similar significant differences were found for HUs and insertion torque.

In a clinical study comprising ISQ measurements of 542 implants, Rodrigo et al [80] experienced loss of 37 implants over a three-year period. They found no correlation between ISQ measurements of primary stability and implant failure but a significant association between measurements after a mean period of 2.8 months and implant failure

THE USE OF RFA TO DECIDE WHEN TO LOAD

In a series of clinical studies, Östman and co-workers used RFA and insertion torque measurements at implant placement as inclusion criteria for immediate/early loading [74,81-82]. An ISQ of at least 60 and and an insertion torque of at least 30 Ncm were utilized as inclusion criteria in a study on partial mandibular restorations [6-7]. A total of 96 patients were evaluated and 77 met with the inclusion criteria. The authors reported a survival rate of 98.4% for 257 implants after 1 to 4 years of follow-up. The same group used a slightly modified protocol for immediate loading in the maxilla [81]. Here, an ISQ value above 60 was required for the posterior implants and a sum of 200 for the four anterior implants together with an insertion torque of 30 Ncm. One of 123 immediately loaded implants in 20 patients was lost after one year of follow-up. In a study on consecutive patients with different needs of implant treatment, Östman et al used an ISQ value of 55 and a minimal insertion torque of 25 Ncm in order to apply immediate loading [82]. Thirty-five of 38 patients met with the criteria and their 102 implants were subjected to immediate loading. One failure was experienced after one year of follow-up.

Bornstein et al [62] used ISQ 65 as a threshold value for loading. Fifty-four of 56 implants could be loaded after 3 weeks of healing, while two implants needed an additional 3 and 4 weeks of healing to reach an ISQ above 65.

Vanden Bogaerde et al [60] reported on the use RFA for inclusion and follow-up in a study on early loading of fixed partial prostheses in both jaws of 21 patients. An ISQ value of 50 was used for inclusion. ISQ values were measured after 1, 2 and 6 month when the bridges were removed. A small average decrease was seen from baseline to 1 month and then an increase to 6 months. One of 69 implants failed during a follow-up of 18 months. Although these authors, as well as Östman et al, have used very low threshold values for immediate loading, the statistics presented in their paper showed high average primary stabilities, i.e. ISQ 68.1 and 73.4, respectively.

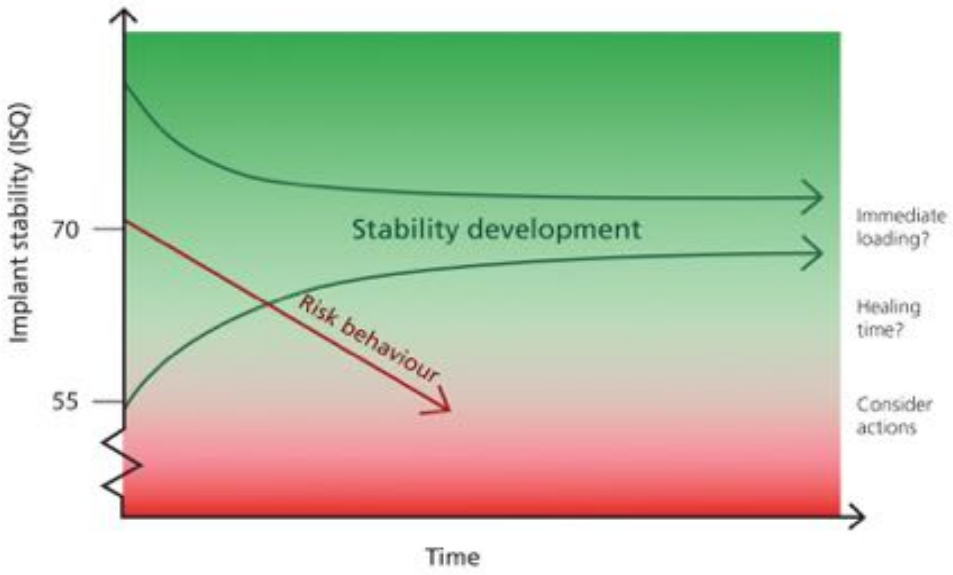

Figure 8. *The author´s interpretation of the use of RFA measurements for clinical decision-making.*

PROPOSED INTERPRETATIONS OF RFA MEASUREMENTS

Research has shown that ISQ measurements can provide the clinician with valuable information about the present state of bone-implant interface. Together with clinical/radiographic findings it seems like as the technique can be used to support decision-making during implant treatment and follow-up with regard to healing times, loading protocol and identification of implants at risk for failure (Figure 8). Figure 11 exemplifies how ISQ values may be used in clinical routine based on the present understanding of the technique. Here, implants are assigned into one of three zones based on measurement at the time of placement. With follow-up measurements the development/changes of stability can be tracked in the graph and measures can be taken in case of low or falling values, i.e. prolonged healing, unloading. In this example, the threshold values are the present author's own somewhat conservative suggestions based on own experience and other values may be relevant for other clinicians and implant designs [60, 81-82]. The green zone contains "safe" implants showing primary ISQ values from, for instance 70 and above. The red zone contains "questionable" implants with an ISQ value below for instance 55. The yellow zone represents implants with an ISQ from 55 to 70. The implants in the green zone may be suitable for immediate loading protocols, while a healing period is used for implants in the yellow and red zone. In the latter groups, a second measurement after healing will confirm that an increased stability (towards the green zone) has been achieved. If low ISQ values are still obtained after an initial healing period, the implant may be left for further healing. For implants with very low ISQ values (<55)(red zone), measures to improve stability should be considered, i.e. by immediately replacing the implant with a longer, wider and/or tapered implant as well as a prolonged healing period should be used and stability checked. Falling ISQ values after some time of loading, particularly in immediate/early loading, may be an unfavourable reaction to loading. Check of occlusion or unloading with a period of healing until the ISQ value has caught up should be considered. Moreover, since the ISQ technique is sensitive to crestal bone loss and reduces the ISQ level with 2-3 units/mm, this should be controlled with an intraoral radiograph.

CONCLUSIONS

The RFA technique provides with clinically relevant information about the state of the implant–bone interface at any stage after implant placement. The ISQ value reflects the micromobility of an implant when loaded, which in turn is determined by the biomechanical properties of the surrounding bone tissue and the quality of the bone-implant interface. It seems like implants with low and/or falling ISQ values pose an increased risk for failure compared with implants with high and/or increasing values. It is likely that ISQ measurements can be used as one additional parameter for diagnosis of implant stability and decision-making during implant treatment and follow-up.

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ISMBio3 CLINICAL ORAL IMPLANTS RESEARCH

Effects of multiple reuse, remounting and consecutive autoclave sterilization on Osstell SmartPegs

D. Duddeck,[1] F. Faber[2]

[1]*University of Cologne, Interdisciplinary Policlinic for Oral Surgery and Implantology, Dep. for Craniomaxillofacial and Plastic Surgery, Cologne, Germany,* [2]*University of Cologne, Center of Dental Medicine, Dental Materials, Cologne, Germany*

Background: The resonance frequency analysis (RFA) is an objective and non-invasive method to measure implant stability. To achieve the data a commercially manufactured attachment (Osstell, Sweden) made of aluminum with a magnetic part on the top (SmartPeg) has to be mounted on the inner threads of the implant after insertion and/or after uncovery. A higher frequency correlates to less micro-mobility of an implant or in other words indicates a higher implant stability. The resonance frequency is shown on a monitor as a numerical figure, the Implant Stability Quotient (ISQ). These measurements are highly reliable regarding reproducibility. The SmartPeg is made of aluminum because it is not supposed to jeopardize or damage the threads of the implant even if incorrectly attached/inserted. Despite the recommendation of the manufacturer that these parts are designed for single session use only, many practitioners reuse the device after autoclave sterilization. This leads to unintended effects like unequal ISQ values compared to single used SmartPegs and sooner rather than later to a manipulation of the aluminum made threads of the SmartPeg.

Aim/Hypothesis: The aim of this study was to find physical effects on the SmartPeg device like the heat from consecutive autoclave processes on the magnetic part and the multiple mechanical load for the aluminum made threads of the device.

Material and methods: Five SmartPegs underwent 20 consecutive autoclave and remounting processes. Between the autoclave processes the SmartPegs were mounted on a Camlog Implant (4.3 × 13) with the recommended torque of 4–6 Ncm, ISQ measurements were performed and recorded. After that the Smartpegs were again unscrewed for the next autoclave process. SEM images of these 'reused' SmartPegs and new control samples were taken. Region of interest were the screw threads to detect friction traces on the soft aluminum from the titanium made implant threads. All samples were loaded in a Zwick servo-hydraulic testing machine for fatigue fracture testing. Fracture dynamic was recorded and fracture-lines were analyzed with SEM.

Results: The fatigue fracture testing showed no significant differences between the reused, consecutive autoclave sterilized samples and the control group. Unequal ISQ data occurred that can possible originate from the heat sensitive magnet or the less precise fit of the SmartPeg after multiple remounting processes. However, the effects of the multiple remounting processes were significant. While one or two remounting processes of the SmartPeg had no influence on the threads, friction traces increased dramatically after five and more remounting processes on the aluminum threads and could be seen even in lower magnification in the SEM images. Aluminum particles may detach after five or more reuses and remain in the inner part of the implant. This may lead to an early loosening of the abutment screw which in turn leads to all well known subsequent complications to the patient and the practitioner. The consequences of multiple autoclave processes and reuse of the SmartPegs counteract the benefits of the ISQ measurement.

Conclusions and clinical implications: The multiple reuse of Osstell's SmartPegs, numerous remounting processes and consecutive autoclave sterilization have significant effects on the device and should be avoided. Only minor savings on the economic side have to pay for less precise and reliable ISQ data and for serious prosthetic complications due to detached aluminum particles that could finally prevent or make it almost impossible to realize a precise fit and stability of the abutment.