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The Predictive Value of Resonance Frequency Analysis Measurements in the Surgical Placement and Loading of Endosseous Implants

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The Predictive Value of Resonance Frequency Analysis Measurements in the

Surgical Placement and Loading of Endosseous Implants

A thesis submitted in partial satisfaction

of the requirements of the degree Master of Science

in Oral Biology

by

Serge Varoujan Baltayan

2012

ABSTRACT OF THESIS

The Predictive Value of Resonance Frequency Analysis Measurements in the

Surgical Placement and Loading of Endosseous Implants

By

Serge Varoujan Baltayan

Master of Science in Oral Biology

University of California, Los Angeles 2012

Professor Tara Aghaloo, Chair

Implant stability is an important factor guiding the selection of placement and loading

protocols. An evaluation of the currently available techniques for measuring stability clearly

demonstrates a need for a non-invasive, quantitative, repeatable, and reliable way to measure

implant stability over time. A potential candidate for this purpose is resonance frequency

analysis (RFA).

A retrospective study was performed on implant patient data collected over a five-year

period. Patients were categorized according to their placement protocol (one-stage vs. two-stage)

and loading protocol (early vs. traditional). RFA measurements were recorded during placement

and prior to loading. Survival or failure was determined after a minimum follow-up period of

two years. Receiver operating characteristic (ROC) statistical analysis was used to determine

ISQ cut-off points with respective sensitivity and specificity values for different placement and loading protocols.

In predicting implant failure, sensitivity progressively increased and specificity decreased as ISQ cut-off values increased. All failures occurred at ISQ < 66 for the placement protocol and ISQ < 67 for the loading protocol. When ISQ values were less than 60, higher survival rates were observed when implants were placed utilizing a two-stage rather than a one-stage protocol. The area under the ROC curve for placement was 0.80 ($p < 0.05$) and the area under the ROC curve for loading was 0.89 ($p < 0.05$).

RFA is a non-invasive technique used to measure the stability of implants and help guide placement and loading protocols. This study showed that increasing ISQ values correlated with increased sensitivity in detecting implant failure. Due to the high survival rates of dental implants, additional studies with an increased samples size and more implant failures are necessary to further elucidate the relationship between ISQ values and survival rates.

The thesis of Serge Varoujan Baltayan is approved.

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University of California, Los Angeles
2012

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INTRODUCTION

One of the most influential inventions in the field of dentistry has been the titanium dental implant. Discovered unintentionally by P.I. Brånemark (1), dental implants have offered an excellent alternative to restore function lost due to edentulism.

In his original protocol developed in 1977, Brånemark outlined a 2-staged approach (placement protocol), where implants were placed into the bone, and completely submerged to heal undisturbed. A healing time of 3 to 4 months was recommended for the mandible and 6 to 8 months was recommended for the maxilla before delivering the final restorative prosthesis, also known as the traditional loading protocol (2). As demonstrated in the literature, initial mechanical stability and the absence of any undesired micromovements are two vital elements needed to maximize the survival of implants (3,4).

As implants gained mainstream popularity, researchers and clinicians have been investigating whether implant placement could be performed in a single surgery rather than the two staged surgeries presented by Brånemark. In 1988, Buser outlined a 1-stage approach in order to minimize and reduce a previously required second surgery by allowing for simultaneous healing of bone and soft tissue (5). In future research studies, investigators demonstrated that 1-stage approaches could achieve comparable survival rates as those placed with the original 2-stage approach (6–10).

Similarly, it was also postulated that implants could be loaded with a prostheses at a much earlier time period than traditionally recommended. This more accelerated approach is known as early loading, where the delivery of the final prosthesis is within 3 months after placement. This would minimize the amount of time the patient would spend in the treatment phase and restore function and esthetics as early as possible (11–14).

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Implant stability is a clinical measurement that may assist the clinician in the selection of placement and loading protocols (15–18). Monitoring implant stability during the healing period may provide information to predicting implant failure, an outcome that greatly adds to treatment time, cost, and inconvenience by necessitating further interventions. Stability is divided into primary and secondary components. Primary stability refers to the mechanical bracing of the implant in bone and absence of any micro-movement (15,19–23), while secondary stability refers to successful osseointegration of the implant with the surrounding bone (15,19).

Primary stability is a function of peri-implant bone quality, implant preparation site, and properties of the implant itself (3,15,24). The major determinant of stability among these factors is peri-implant bone density (4,15,24–26). A thicker cortical layer braces the implant better than a thinner cortical layer (27–29). Similarly, denser Type I bone offers greater resistance to movement than less dense Type IV bone (30). The preparation of the recipient site for the implant also affects primary stability. An over-prepared site leaves less bone in contact with the implant and the gap associated with it allows for undesired micro-movement (15,20,24), while an underprepared site may lead to implant or bone fractures, or osseous pressure necrosis due to ischemia (31–33). Finally, the design of the implant also greatly affects primary stability (15). Increased implant length, diameter, and taper maximize the surface area of the bone-implant interface. Thread size, angulation, and design also affect the mechanical anchoring of the implant into the surrounding bone and contribute to stability (15,34). Although primary stability determines the initial fit of the implant in alveolar bone at placement, secondary stability via osseointegration is needed for long-term bone to implant contact.

Osseointegration is defined as the direct structural and functional connection between living bone and the surface of a load-bearing artificial implant (3,35). After an implant has been

surgically placed, it undergoes a series of phases designed to eliminate damaged tissue, create new sources for nutrient supply, and ultimately create a mineralized bony matrix to support the new implant. In the inflammatory phase, platelets form a hemostatic plug and allow for the entry of acute inflammatory cells such as neutrophils and macrophages, which begin eradicating damaged tissue via phagocytosis. In the proliferative phase, osseous tissues begin a process known as neovascularization, where microvascular elements are established in order to introduce nutrients and oxygen essential for connective tissue repair and collagen formation. Mesenchymal stem cells differentiate into osteoblasts, which in turn begin to lay down an immature collagenous matrix known as woven bone. In the maturation phase, osteoblasts continue depositing collagen at the bone implant interface, which is then mineralized. Once the implant is loaded, the immature woven bone is transformed into the more mature, organized, and stronger lamellar bone (36).

Secondary stability via osseointegration is largely dependent on the quality and quantity of bone available. It has also has been shown to improve with the use of titanium oxide-layered, hydroxyapatite-coated, and acid-modified implant surfaces (37–40). Moreover, primary stability is crucial in the establishment of secondary stability (19), since any micro-movement of the implant during bone remodeling could prevent bone deposition, and lead to fibrous encapsulation and eventual failure of the implant (19,21,34,35,41,42).

Due to the importance of implant stability in the survival and successful osseointegration of implants, it is essential to monitor it carefully. Steadily declining stability prompts the clinician to take the appropriate countermeasures to prevent implant failure, such as delayed loading and two-staged implant placement (20). Conversely, if the implant shows proper levels of stability, a more accelerated treatment protocol, such as one-stage implant placement or earlier

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loading (loading less than 3 months after placement) may be appropriate (16,43). This is advantageous for both clinicians and patients, as optimizing treatment can yield quicker results and fewer surgeries.

Certain clinical signs portend impending implant failure. These include peri-implant bone loss detectable by periodontal probe, inflammation or purulence of adjacent tissues, and implant mobility. These signs are of little utility in guiding treatment protocols, as they usually occur at a point when the implant can no longer be saved. Useful tests require that implant stability be measurable closer to the time of placement. Current diagnostic tests available to clinicians include histology at the bone-implant interface, radiographs, percussion, insertion torque, reverse torque, and Periotest® (15,20).

The most direct and accurate method of assessing osseointegration is histology and histomorphometry, as it qualitatively and quantitatively assesses the amount of bone present on the implant surface (15). However, this method is time-consuming and expensive, as well as extremely invasive, as bone needs to be biopsied. It is therefore too impractical to be used in a private practice setting.

Radiographs provide the ability to view and gauge bone levels and evaluate the quality and density of trabecular and crestal bone (15,44). They are only partially invasive and can monitor bone levels at any stage of treatment, including presurgery. However, most clinicians use panoramic and periapical films, which provide mesial and distal bone levels, but cannot predict implant stability (15,45). Moreover, radiographs can create distortions due to difficulties in achieving perfect angulations. As a result, the levels of the crestal cortical bone on radiographs are inaccurate. Also, conventional radiographs provide two-dimensional images, which do not disclose any deficiencies in buccal or lingual bone that would be critical for implant stability.

Finally, most radiographs do not show radiolucencies in bone until at least 30-50% of demineralization has occurred (46).

The percussion test is a common test used by clinicians because it is free and easy to perform. Implant stability is inferred from the pitch of the sound produced by tapping the implant with a metal instrument. The highly subjective nature of the test is the major cause of its unreliability and low sensitivity (15,20). In addition, its qualitative nature makes it useless in detecting subtle changes in stability over the course of time (20).

The insertion torque test is commonly used because the insertion torque is easy to determine with a handpiece or hand-held torque driver when placing the implant. High torque correlates with good primary stability (47). This test provides a tactile sensation and direct measurement of primary implant stability at the time of placement. However, it does not allow for stability assessment over time, and is also dependent on the state of the preparation site. Underprepared sites may have high insertion torque values, but this may cause fractures of the implant or bone (31), or osseous pressure necrosis, which negatively correlate with implant survival (33). Furthermore, insertion torque can be misleading as increased values are usually due to the resistance provided by the cortical layer encountered at the neck of the implant (20).

The reverse torque test assesses secondary stability of the implant by providing a rotational force opposite to the direction of insertion (48–51). However, this test measures rotational stability and not lateral stability, the latter being more representative of actual forces an implant is subjected to during function (20,51). Furthermore this maneuver poses a risk to implant survival, as numerous studies have shown that any micromovement of an implant before proper osseointegration may lead to microfractures, fibrous encapsulation, and eventual failure of the implant (19,21,34,35,41,42). Also, these reverse rotational forces can disrupt contact at the

bone-implant interface, thereby delaying osseointegration and increasing treatment time (15,52).

Many authors have suggested various values of torque to test stability, but those values have not

been corroborated and may differ for different densities of bone or different cortication levels

(15,51).

The importance of accurately measuring implant stability has prompted the development

of highly sensitive electronic devices for this purpose. The Periotest® is an example of such a

device. It uses an electromechanically controlled tapping head that percusses the tooth, while a

sensor inside the unit measures the damping ability of the object (53). The higher the damping

ability, the more stable the object. While studies have shown that Periotest® may be used in

measurement of implant stability (54–56), the device was originally designed to be used on

natural teeth, which are not in direct contact with bone and have a greater natural range of

movement than implants (53,57). In assessing implant stability, the Periotest® would therefore

not be operating within its optimum range. In addition, accurate measurements require the device

to have proper angulation and contact points (58,59). This makes it difficult to use in areas with

limited access, such as posterior dentition. Lastly, the Periotest® is operator dependent, which

further limits its utility and reliability (58,59).

In evaluating the currently available techniques and their shortcomings, there is clearly a

need for a non-invasive, quantitative, repeatable, and reliable way to measure implant stability

over time. A potential candidate for this purpose is the relatively novel technique of resonance

frequency analysis (RFA) (15,20).

RFA subjects the implant to a lateral bending test functioning in a manner similar to an

electronic tuning fork (20). Alternating waves of varying frequencies are sent to the transducer,

which is a mounted fixture screwed directly onto the implant. The transducer begins to vibrate at

a specific resonance frequency. This vibration is then transmitted to the frequency response analyzer of the unit. The sensor inside the unit begins to measure these frequencies and assigns numerical values corresponding to the resonance frequencies at the bone-implant interface. Typical resonance frequency values range from 3.5-8.5 kHz, and the device expresses these frequencies using a unit known as implant stability quotient (ISQ). ISQ values range from 0 to 100 and higher ISQ values correspond to greater mechanical stability (20). Current RFA devices use magnetic waves to induce resonance frequencies.

From a conceptual perspective, a higher resonance frequency implies a higher resistance to lateral bending. Lateral bending, in turn, is affected by the length of exposed implant and the stiffness of the bone-implant interface (57,60,61). Stiffness of the bone-implant interface is determined largely by the thickness of cortical bone (29,62–64).

RFA is non-invasive and does not place the implant at any risk during any part of the treatment. It is also quantifiable, which leads to better case documentation and communication between clinicians, and allows for objective decision-making when selecting treatment protocols. Moreover, it makes it possible to trend implant stability over time, and modify treatment protocols accordingly.

The purpose of this study was to investigate the predictive value of RFA in assessing implant survival. This was accomplished by determining the correlation between ISQ values (obtained both at the time of implant placement and prior to loading) and clinical outcomes following different placement (one-stage vs. two-stage) and loading (early vs. traditional) protocols.

MATERIALS AND METHODS

A retrospective study was performed on implant patient data collected over a five-year period from 2002 – 2007. Patients ranged from 16 – 91 years of age. All implants were placed and all measurements were performed and recorded by a single oral & maxillofacial surgeon in private practice. Multiple parallel-wall and tapered-body implant systems were used including 3i™ (Biomet, Palm Beach Gardens, USA), Straumann ITI® (Institut Straumann AG, Basel, Switzerland), NobelReplace™, Brånemark System® MkIII and MkIV (Nobel Biocare AB, Gothenburg, Sweden). Implant stability was measured by resonance frequency analysis using Osstell™ (Osstell AB, Gothenburg, Sweden) during placement and prior to loading. Implant patients were categorized according to their placement protocol (one-stage vs. two-stage) and loading protocol (early vs. traditional). IRB approval (#12-001669) was obtained for the study.

Pre-operative radiographs were used to assess the quantity and relative quality of bone available. Implants were placed strictly adhering to manufacturer's guidelines and specifications. Appropriate post-operative radiographs were taken to verify positioning when implants were placed in close approximation to vital anatomic structures. During implant insertion, stability was assessed using a hand-held torque driver to gauge the insertion torque in addition to the percussion test, where the clinician listens to the pitch of the sound acquired after the implant is tapped with the blunt end of a metal instrument (i.e. mirror handle). Based on these initial assessments of stability, the clinician decided between a one-stage placement and a two-stage placement protocol. After selecting a placement protocol, the clinician proceeded to record RFA measurements. The transducer was screwed onto the placed implant and was tightened to the manufacturer recommended torque specification of 10 N-cm. The ISQ values representing the

resonance frequencies were obtained. Four measurements were performed and corresponding values were averaged and recorded.

Prior to loading, clinical evaluation was performed during a follow-up period of 4 – 12 weeks after placement. Appropriate radiographs were taken to monitor the status of the bone-implant interface. The stability of the implant was assessed by the percussion test and by evaluating for any mobility of the implant. Based on these assessments, additional follow-ups were performed if the stability of the implant was questionable and further time was given for the implant to osseointegrate. If the implant was deemed stable by the clinician and was ready for loading less than 3 months after placement of the implant, this would be considered an early loading protocol. If the implant was deemed stable and was ready for loading greater than 3 months after placement, the clinician would be following a traditional loading protocol. After the appropriate loading protocol was determined by the clinician, RFA measurements were taken during the final follow-up appointment prior to the start of the restorative reconstruction. The transducer was attached to the placed implant and tightened to the manufacturer's recommended torque specification of 10 N-cm. The ISQ values representing the resonance frequencies were obtained. Four measurements were taken and corresponding values were averaged and recorded.

An implant's survival (remained in position) or failure (removal), along with its respective ISQ value, was recorded for each patient. This data was further stratified according to placement (one-stage vs. two-stage) and loading (early vs. traditional) protocols. In this study, 703 implants were analyzed during placement. Of these, 417 were placed in the maxilla, and 286 were placed in the mandible. In addition, 1254 implants were analyzed prior to loading. Of these, 714 were located in the maxilla, and 540 were located in the mandible. Patients were followed for a minimum of 2 years after implant loading.

Receiver operating characteristic (ROC) statistical analysis was used to calculate ISQ cut-off points with respective sensitivity and specificity values for different placement and loading protocols. The cut-off values were then used to determine the survival rates for all implants with ISQ values above and below the respective cut-off points. Differences in survival for implants with different placement and loading protocols and with ISQ values below pre-determined cut-offs were then analyzed with chi-square tests. Significance was set to $p < 0.05$.

RESULTS

Evaluation of Implant Placement Protocol: One-Stage vs. Two-Stage

To begin to determine whether RFA can predict implant survival utilizing a one-stage or two-stage protocol, 703 implants were evaluated. Of these, 439 were placed using a one-stage protocol and 264 using a two-stage protocol. Overall 17 implants failed, yielding a 97.6% survival rate (Table 1). When failures were further stratified, 11 had been placed using a one-stage protocol, and 7 were placed using a two-stage protocol with survival rates of 97.5% and 97.7%, respectively (Table 1). The area under the ROC curve, demonstrating the accuracy of RFA measurements at placement to predict implant survival, was 0.80 (80%; $p < 0.05$) (Figure 1).

ISQ measurements of 45, 50, 55, and 60 were selected for evaluation of sensitivity and specificity to detect implant failures since most implants fell within this range. These measurements or cut-off values were used to demonstrate implant survival rates above or below these values. ISQ measurement of 66 was selected as an additional cut-off value because all failures were below 66 (Table 2). Sensitivity, the ability of RFA at placement to correctly predict implant failure, progressively increased, and specificity, the ability of RFA at placement to correctly predict when an implant will not fail, correspondingly decreased with increasing ISQ cut-off values (Table 2). Since all implant failures occurred below an ISQ of 66, the corresponding sensitivity was 100% (Table 2).

When we evaluated all implants placed with a one-stage protocol, implant survival rates with ISQ values above all selected cut-offs were consistently higher than implants with ISQ values below the cut-off (Table 3, Figure 2). Furthermore, there was a progressive decrease in the differences between implant survival rates with ISQ values above the cut-off and implants

with ISQ values below the cut-off; this trend occurred for all cut-off values except at 50 (Table 3, Figure 2). When we evaluated all implants placed with a two-stage protocol, implant survival rates with ISQ values above all selected cut-offs were also consistently higher than implants with ISQ values below the cut-off (Table 3, Figure 3). There was no obvious trend in the differences between implant survival rates with ISQ values above the cut-off and implants with ISQ values below the cut-off as ISQ cut-off values increased (Table 3, Figure 3).

Implants placed with a two-stage protocol with ISQ values less than 60 had significantly higher survival rates than those placed using a one-staged protocol ($p < 0.05$). However, at all other ISQ cut-off values, there was no significant difference observed.

Evaluation of Implant Loading Protocol: Early vs. Traditional

To determine whether RFA can predict implant survival utilizing an early or traditional loading protocol, 1254 implants were evaluated. Of these, 408 were loaded using an early protocol and 846 using a traditional protocol. Overall 21 implants failed, yielding a 98.3% survival rate (Table 4). When failures were further stratified, 4 had been loaded using an early protocol, and 17 were loaded using a traditional protocol with survival rates of 99.0% and 98.0%, respectively (Table 4). The area under the ROC curve, demonstrating the accuracy of RFA measurements at loading to predict implant survival, was 0.89 ($p < 0.05$) (Figure 4).

ISQ measurements of 45, 50, 55, and 60 were selected for evaluation of sensitivity and specificity to detect implant failures since most implants fell within this range. These measurements or cut-off values were used to demonstrate implant survival rates above or below these values. ISQ measurement of 67 was selected as an additional cut-off value because all failures were below 67 (Table 5). Sensitivity, the ability of RFA at loading to correctly predict

implant failure, progressively increased, and specificity, the ability of RFA at loading to correctly predict when an implant will not fail, correspondingly decreased with increasing ISQ cut-off values (Table 5). Since all implant failures occurred below an ISQ of 67, the corresponding sensitivity was 100% (Table 5).

When we evaluated all implants loaded with an early protocol, implant survival rates with ISQ values above all selected cut-offs were consistently higher than implants with ISQ values below the cut-off (Table 6, Figure 5). Furthermore, there was a progressive decrease in the differences between implant survival rates with ISQ values above the cut-off and implants with ISQ values below the cut-off; this trend occurred for all cut-off values except at 50 (Table 6, Figure 5). When we evaluated all implants loaded with a traditional protocol, implant survival rates with ISQ values above all selected cut-offs were also consistently higher than implants with ISQ values below the cut-off (Table 6, Figure 6). Moreover, there was a progressive decrease in the differences between implant survival rates with ISQ values above the cut-off and implants with ISQ values below the cut-off; this trend occurred for all cut-off values (Table 6, Figure 6). There were no significant differences in survival rates between early loading and traditional loading for all respective ISQ cut-off values.

DISCUSSION

Implant stability is an important determining factor to achieve successful osseointegration. Initial mechanical stability at placement, known as primary stability, eventually leads to biologic, or secondary stability (15,19,20). Biologic stability occurs through bone remodeling at the bone-implant interface after placement, and is ultimately responsible for implant survival (19). Monitoring the transition from mechanical to biologic stability will allow us to predict the process of osseointegration, and ultimately, implant survival.

Multiple diagnostic tools are utilized to gauge the stability and health of an implant. However, most of them have considerable limitations. Histologic analysis is too invasive for the patient, and impractical clinically (15). Radiographs are two-dimensional, are heavily angulation dependent, and bone density changes are not seen until significant bone has been lost (15,45,46). Periodontal probes can detect bone loss around implants, and clinical examination can determine implant mobility (65). However, by the time of diagnosis, implant prognosis is often poor or hopeless. The percussion test, used by the majority of clinicians, is very subjective and non-quantifiable (15,20). Insertion torque can only be measured at placement, and changes based on the implant geometry and drilling protocol. The reverse torque test measures rotational, but not lateral forces, and may lead to damage at the bone-implant interface (20,52). The Periotest®, which uses an electromechanical device that measures stability, was designed for natural teeth and not implants and is heavily operator dependent (53,58,59).

Since RFA was developed, it has shown great potential to predict implant stability, while being non-invasive and reproducible. It assesses stability by measuring the implant's resonance frequency within the implant site. Higher resonance frequencies imply a stiffer bone-implant interface, and therefore higher stability (15,20). The goal of the current research is correlate ISQ

values with implant survival rates to determine optimal placement and loading protocols. Survival rates increased steadily with increasing ISQ cut-off values in one-stage vs. two-stage placement protocols (Figure 2, Figure 3). Survival rates also increased steadily with increasing ISQ cut-off values in early vs. traditional loading protocols (Figure 5, Figure 6). Although this increase in sensitivity was coupled with a decrease in specificity, accuracy of the test as reflected by the area under the ROC curves, were statistically significant ($p < 0.05$). All implant failures occurred at ISQ < 66 at the time of placement, and at ISQ < 67 regardless of loading protocol.

Regarding placement, two-staged implants had higher survival rates than one-staged implants at ISQ < 60 ($p < 0.05$). This suggests that while a two-staged placement protocol is justifiable with ISQ values below 60, a one-stage placement is also viable when ISQ is greater than 60. At all other ISQ cut-offs, however, there was no significant difference between one-staged and two-stage placement survival rates. An unusual finding was that although survival rate was higher in the two-stage group at ISQ < 60, there was no difference at lower cut-off values. Implants with lower ISQ values should theoretically be less stable and show higher survival rates with two-stage placement. This is likely due to sampling error, as there were very few implant failures in these lower ISQ groups. This may also explain why there was no difference in survival between early and traditional loading protocols for any of the ISQ cut-off values.

Our findings are consistent with other studies investigating the relationship between ISQ values and implant stability. Bornstein et al recommended additional healing prior to loading when the ISQ was less than 65 (66). Rodrigo et al reported no implant failures at ISQ > 60, while those < 60 had a failure rate of 19% (67). It is reasonable then for clinicians to consider implants with ISQ < 60 of questionable stability and > 70 as very stable, with the 60-70 range serving as

the cut-off region. This distinction, however, is arbitrary, and depends largely on the clinician's preferred balance of sensitivity and specificity. In general, it may be better to err on the side of caution and maximize sensitivity in selecting cut-off values, which will decrease the likelihood of implant failure. While this may result in longer healing times or "overtreatment" for a small group of patients near the cut-off (i.e. two-stage placement and traditional loading protocols), the time and financial resources saved from fewer implant failures will more than off-set these costs.

The areas under the ROC curves for placement and loading protocols were 0.80 and 0.89, respectively. This may imply that RFA is a more accurate test when performed some time after placement. This observation can be explained by what is known about osseointegration. After implant placement, the surrounding bone undergoes remodeling, which continues for several weeks. Because the extent of bone remodeling cannot be predicted at the time of implant placement, initial RFA measurements will only reflect primary stability. When taken at loading however, the RFA measurement will reflect the amount of bone remodeling that has occurred, and thus, serves as a better predictor of implant survival. Future studies that compare the relative accuracy of RFA at placement and loading should be conducted to corroborate these findings.

This study helped elucidate the correlation between ISQ values and implant survival by using a large sample size. Additionally, it utilized a single, experienced operator following the same predetermined protocol, which removed a potential source of confounding variables. A limitation of this study is that although the data did allow calculations of sensitivity and specificity of various ISQ values serving as cut-off points (e.g. ISQ = 45, 50, 55, 60, etc.), it did not allow for meaningful calculations for successive ISQ ranges (e.g. ISQ = 45-50, 50-55, 55-60, etc.). Again, the low numbers of implant failures in this study may have contributed to our inability to detect significant differences in survival rates at various ISQ ranges. In this study, the

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follow-up period was at least 2 years. Although the majority of implant failures occur within 1 year (68,69), following patients for a longer time periods may have yielded more failures and made the survival rate differences statistically significant.

Dental implants have very high survival rates, ranging from 95-97% as reported in 5-year systematic reviews (70,71). The survival rate in this study was nearly 98%. However, certain patient populations and compromised sites do not have such high survival rates, such as long-term uncontrolled diabetes (72) or where optimal bone is lacking or osseous defects exist (73). A future study that focuses on these non-ideal situations would likely further demonstrate the utility of RFA in guiding placement and loading protocols. In the future, we would also like to adapt a prospective design to allow for additional follow up periods to monitor the transition from mechanical to biologic stability, and utilize a single implant design to minimize variability. Moreover, the study could expand to a multi-centered design to maximize implant numbers, as an increase in sample size could reveal better representation of cut-offs and their associated survival rates. Finally, having operators of varying expertise who follow the same placement and loading protocols may yield diverse survival outcomes, which would allow us to better understand survival rates in different ISQ ranges.

CONCLUSION

Resonance frequency analysis is a non-invasive method to measure the stability of implants and help guide placement and loading protocols. This study showed that increasing ISQ values correlated with increased sensitivity in detecting implant failure. All implant failures occurred at ISQ < 66 at the time of placement and ISQ < 67 at the time of loading. When ISQ values were less than 60, higher survival rates were observed when implants were placed utilizing a two-stage rather than a one-stage protocol. Since the implant survival rate is generally high, additional studies with an increased samples size and more implant failures are necessary to further elucidate the relationship between ISQ values and survival rates.

Placement Protocol	Total Implants	Survived	Failed	Survival Rate
One-stage Placement	439	428	11	97.5 %
Two-stage Placement	264	258	6	97.7 %
Combined	703	686	17	97.6 %

Table 1: Placement protocol outcomes and survival rates.

Placement Protocol		
ISQ Cut-off	Sensitivity	Specificity
45	11.76 %	95.92 %
50	23.53 %	92.86 %
55	47.06 %	86.30 %
60	76.47 %	70.70 %
66	100 %	50.15 %

Table 2: Placement protocol ISQ cut-off values with sensitivity and specificity.

	One-Stage Placement		Two-Stage Placement	
ISQ Cut-off	Survival Rate < Cut-off	Survival Rate > Cut-off	Survival Rate < Cut-off	Survival Rate > Cut-off
45	85.7 %	97.7 %	95.7 %	97.9 %
50	82.4 %	98.1 %	97.2 %	97.8 %
55	86.0 %	98.7 %	96.6 %	98.0 %
60	90.8 %	99.7 %	97.1 %	98.1 %
66	94.4 %	100 %	96.3 %	100 %

Table 3: Placement protocol ISQ cut-off values with associated survival rates.

Loading Protocol	Total Implants	Survived	Failed	Survival Rate
Early Loading	408	404	4	99.0 %
Traditional Loading	846	829	17	98.0 %
Combined	1254	1233	21	98.3 %

Table 4: Loading protocol outcomes and survival rates.

Loading Protocol		
ISQ Cut-off	Sensitivity	Specificity
45	38.10 %	99.27 %
50	47.62 %	98.86 %
55	57.14 %	93.76 %
60	71.43 %	80.37 %
67	100 %	50.93 %

Table 5: Loading protocol ISQ cut-off values with sensitivity and specificity.

	Early Loading		Traditional Loading	
ISQ Cut-off	Survival Rate < Cut-off	Survival Rate > Cut-off	Survival Rate < Cut-off	Survival Rate > Cut-off
45	83.3 %	99.3 %	36.4 %	98.8 %
50	81.8 %	99.5 %	61.9 %	98.9 %
55	92.3 %	99.5 %	84.1 %	99.1 %
60	96.1 %	99.7 %	93.3 %	99.2 %
67	97.9 %	100 %	96.1 %	100 %

Table 6: Loading protocol ISQ cut-off values with associated survival rates.

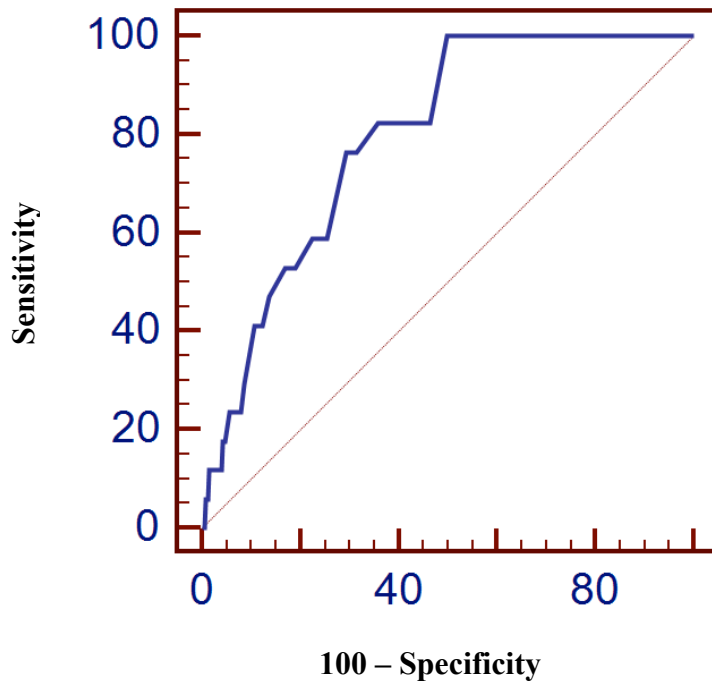**Figure 1:** Receiver operating characteristic curve for placement protocol.

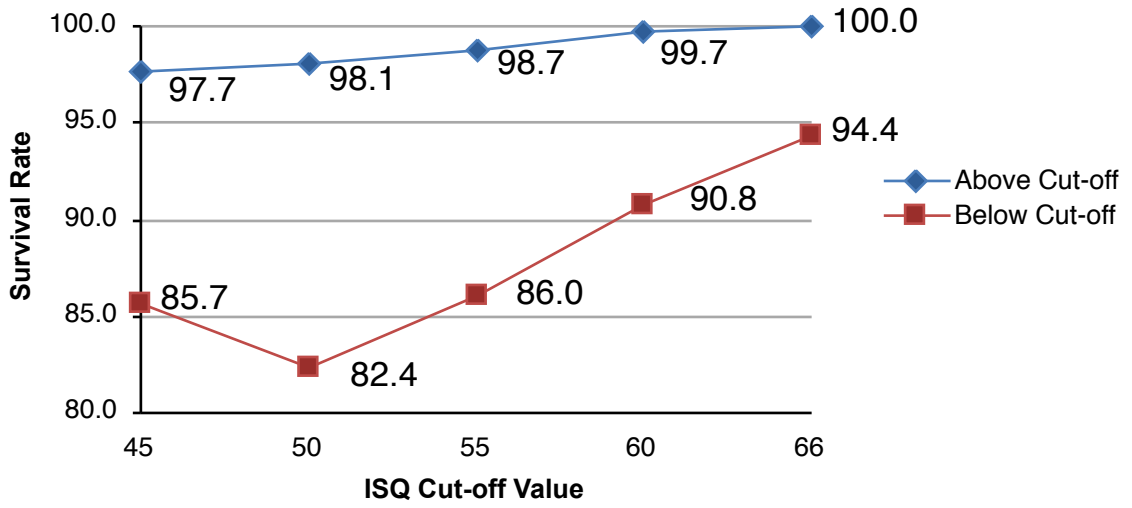**Figure 2:** One-stage placement ISQ cut-off values vs. survival rates.

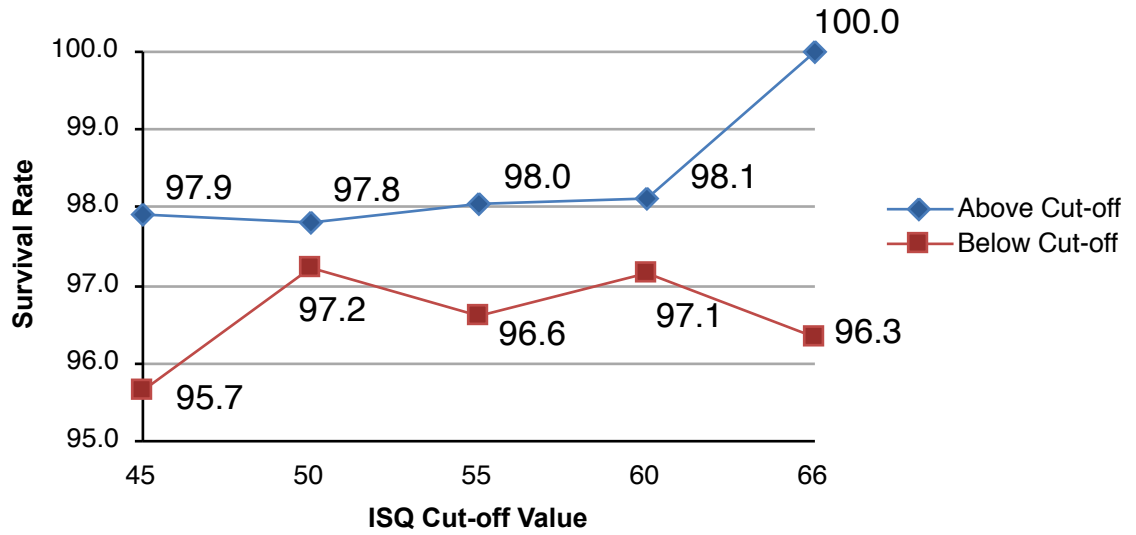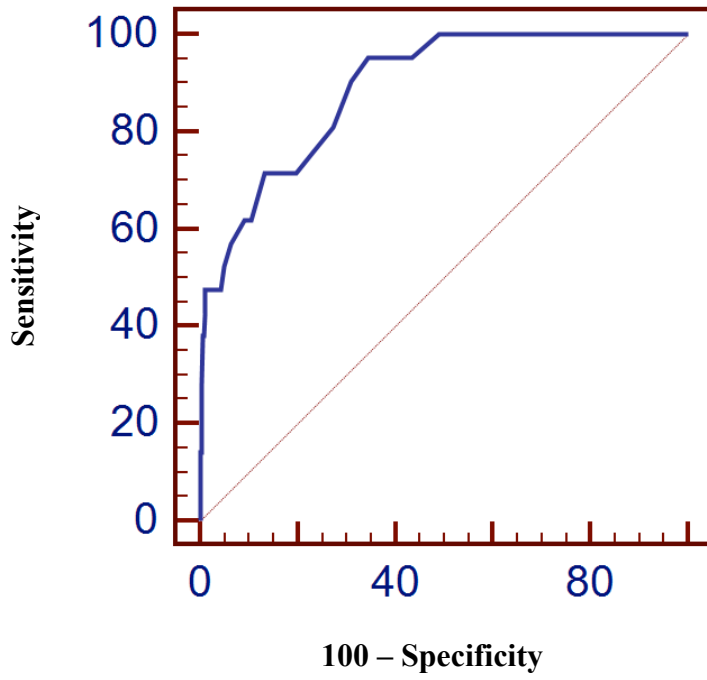**Figure 3:** Two-stage placement ISQ cut-off values vs. survival rates.

Figure 4: Receiver operating characteristic curve for loading protocol.

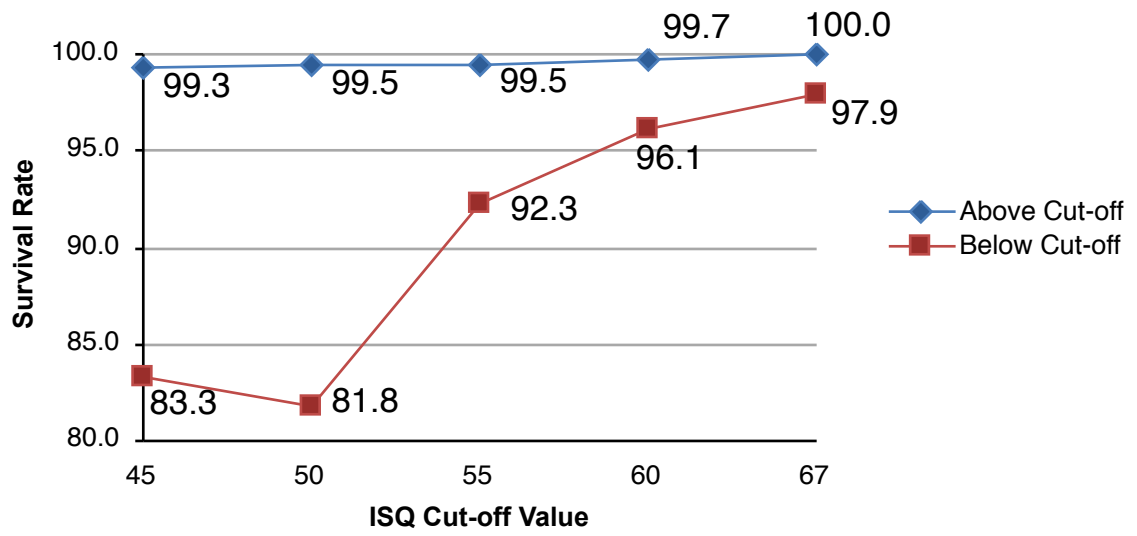**Early Loading ISQ Cut-off Values vs. Survival Rates**

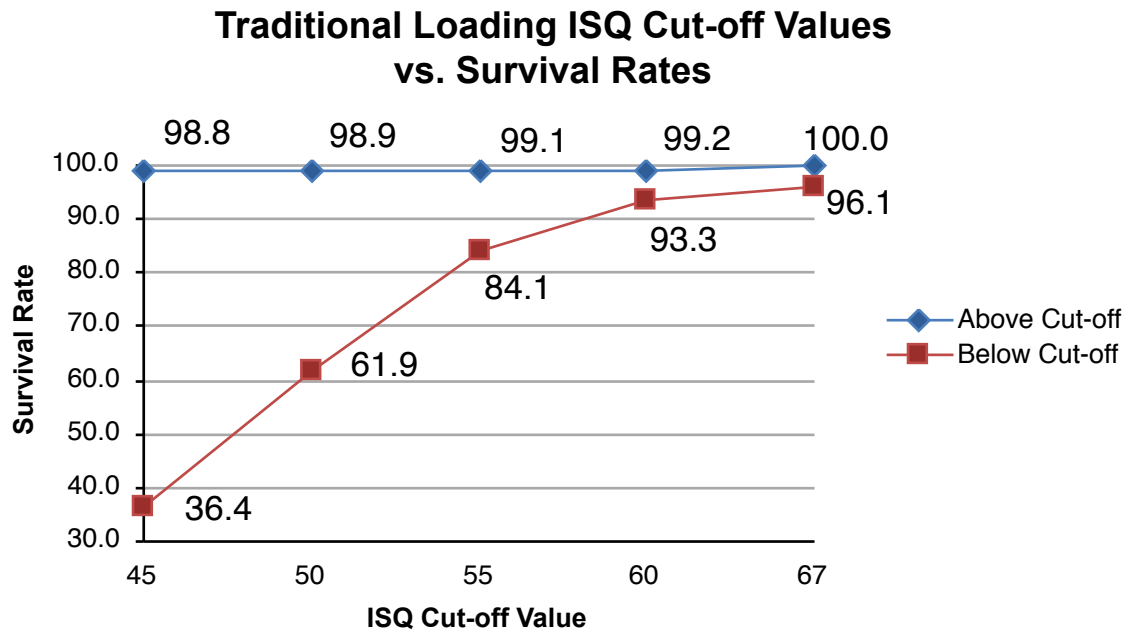**Figure 5:** Early loading ISQ cut-off values vs. survival rates.

Figure 6: Traditional loading ISQ cut-off values vs. survival rates.

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