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Measurement of dental implant stability by resonance frequency analysis: A review of the literature

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Abstract
Dental implant treatment is an excellent option for prosthetic restoration that is associated with high success rates. Implant stability is essential for a good outcome. The clinical assessment of osseointegration is based on mechanical stability rather than histological criteria, considering primary stability (absence of mobility in bone bed after implant insertion) and secondary stability (bone formation and remodelling at implant-bone interface). The aim of this study was to review the literature on Resonance Frequency Analysis (RFA) as a method for measuring dental implant stability. An online search of various databases was conducted on experimental and clinical research published between 1996 and 2008. The studies reviewed demonstrate the usefulness of RFA as a non-invasive method to assess implant stability. Further research is required to determine whether this system is also capable of measuring the degree of dental implant osseointegration.

Key words: *Dental implants, resonance frequency analysis, stability.*

Introduction

In 1969, Bränemark et al. demonstrated that direct contact between bone and titanium implant surface was possible, defining osseointegration as "the direct, structural, and functional contact between live bone and the surface of a functionally loaded implant". The first clinical report on dental implants, published a few years later, clarified that establishment and maintenance of osseointegration depends on the capacity of the tissues for healing, repair, and remodelling (1). Shortly afterwards, Schröeder et al. defined this bone-implant union as a "*functional anchylosis"* (2).

The empirical nature of these initial formulations has now been recognised, and osseointegration is accepted as a histological term denoting direct bone apposition on the implant surface with no interposition of soft tissue. Clinical assessment is based on mechanical rather than histological criteria of stability (3), considering primary and secondary stability. Primary stability is the absence of mobility in the bone bed upon insertion of the implant and depends on the quantity and quality of bone, surgical technique and implant design. Secondary stability depends on bone formation and remodelling at the implant-bone interface and is influenced by the implant surface and the wound-healing time. Bone-healing is activated at the bone-implant interface after the surgical injury produced during preparation of the implant site (4).

The clinical definition of implant osseointegration considers the level of stable marginal bone and absence of mobility in the bone. Therefore, the diagnosis is based on radiographic and mechanical stability criteria. Peri-implant radiolucent areas and marginal bone height can be identified on X-ray, although only mesiodistal changes are detected. Sundén et al. (5) stated that high-quality radiography is necessary to optimise the irradiation geometry, density and contrast. Invasive and non-invasive clinical tests are available to objectively assess implant stability. Invasive tests to determine the extraction torque of the implant are largely used in experimental studies. Non-invasive systems include the Periotest and RFA. The Periotest® system (Periotest®, Siemens) was originally designed to quantify signs of stress resorption by the periodontal ligament surrounding the tooth, as a measure of mobility (6). It is a hand-held device with a metal bar that is attracted to the tooth by an electromagnet, giving an audible signal and showing the measurement digitally on a scale from -8 (low mobility) to 50 (high mobility) PTV units.

After the first studies on RFA by Meredith et al. (7) in 1996, Integration Diagnostics AB (Savedalen, Sweden) launched the Osstell® system in 2000. Researchers at the University of Taipei (Taiwan) (8) also developed an RFA system, the Implomates® (Bio TechOne) system.

In the initial studies published by Meredith et al. (3, 7), the units of measurement used were kilohertz in a range from 3500 to 8500 kHz. The Implant Stability Quotient (ISQ) was subsequently developed, converting kHz units to ISQ values on a scale of 1 to 100, with high values indicating high stability. The Osstell® system now features the Osstell Mentor®, a type of electronic tuning fork that automatically converts kHz to ISQ values. It is a portable, hand-held device that emits signals repeated by a transducer that is screwed directly into the implant or transepithelial abutment with a force of 5-10 Ncm, calculating the resonance frequency (in ISQ values) from the response signal.

In 1998, Meredith et al. (9) published a study on non-invasive techniques and their application for measuring endo-osseous implant stability and osseointegration. Salvi et al. (10) reviewed the literature published up to 2003 and analyzed the clinical, radiographic and biochemical parameters for monitoring peri-implant conditions, while Atsumi et al. (11) reviewed the literature on stability measurement techniques. The objective of the present study was to review studies on the use of RFA to measure dental implant stability.

Material and methods

The first studies on RFA as a method for measuring stability appeared in 1996. We reviewed the literature on RFA published between 2007 and February 2008. The key words used for the search were dental implant, resonance frequency analysis, stability.

We started with an online search of the PubMed (MedLine) database followed by a search of other databases, such as Scopus and ISI, to detect scientific studies on RFA. Search criteria were: nº publications per author, nº studies on RFA published each year, nº studies published in each journal, disciplines featuring these studies, and the most frequently cited publications (H index). RFA presented an H index of 21, obtained from the number of references received by each scientific study by an author. Doctoral theses in the TESEO and Digital Dissertation databases were also reviewed and, finally, the Cochrane Library was consulted.

Study inclusion criteria were: most cited publications (H index) and recent scientific research (between January 2007 and February 2008) which included articles on topics of clinical interest published in high-impact journals.

Results

In the first on-line database search, 154 published studies were found, constituting the initial study sample. A descriptive study was performed on: author, publication date, journal, and field of study.

Sennerby et al. have been responsible for the largest proportion (15%) of research papers on RFA, followed by Meredith et al. (9%) from the same research group).

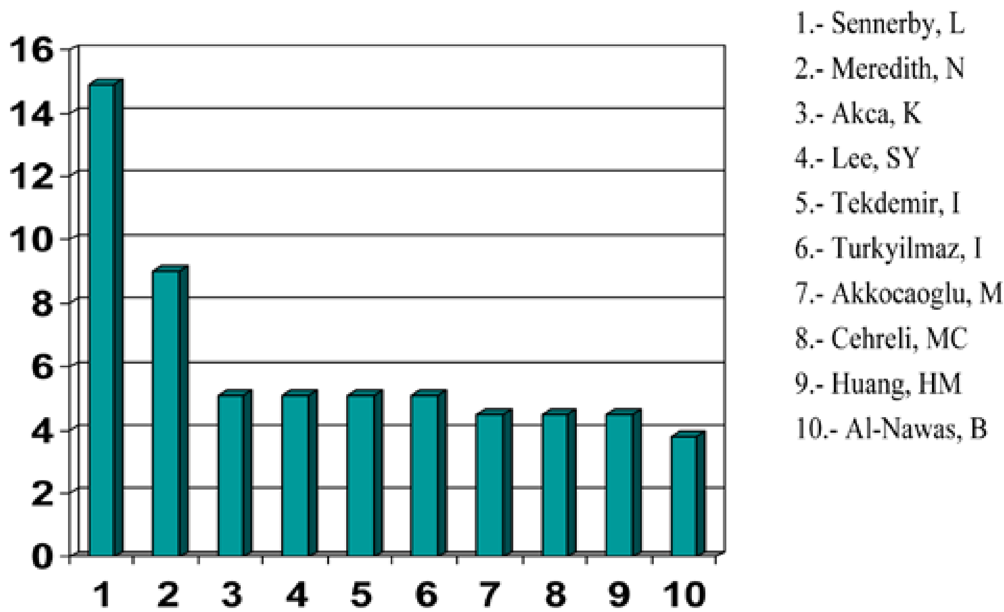

Fig. 1. Publications by author (%).

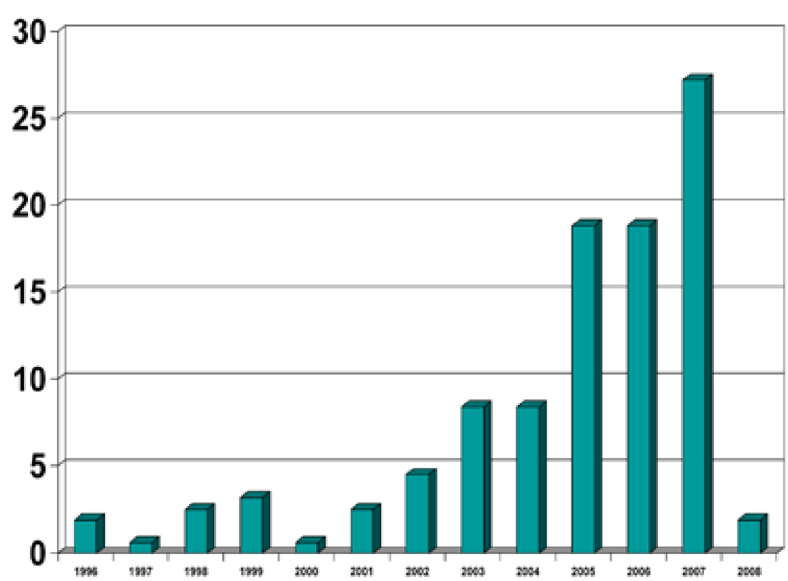

Fig. 2. Increase (%) in scientific research on RFA over time.

Table 1. Articles selected on the basis of the H index (n=21).

AUTHOR	OBJECTIVES	MATERIAL AND METHODS	CONCLUSIONS
Meredith et al. 1996 (7) In vitro 115 References	Critically analyze ra-diographic and Periotest methods	- Aluminium blocks implants - Polymethyl blocks implants	Close correlation between RFA and exposed implant height and rigidity.
Meredith et al. 1998 (9) In vitro 84 References	Analyze Periotest and Dental Fine Tester tech-niques	Concepts of primary and secondary stability	RFA quantitative method more effective
Friberg et al. 1999 (14) In vivo 73 References	Compare RFA and inser-tion torque during implant ation	Classification of eden-tulous maxillary bone types according to site RFA at surgery, at 8 months and 1.5 yrs	Stability improves over time even in soft bone
Friberg et al. 1999 (21) In vivo 69 References	- Assess stability changes using RFA - Assess changes in mar-ginal bone using radiog-raphy	- 3 different types of Bränemark implants inserted in a single sur-gical operation - RFA measurements at 2, 6, 15 and 30 weeks	Early diagnosis of implant failure possible (very low RFA values)
Meredith et al. 1997 (22) In vitro 69 References	Measure RFA stability during surgery and com-pare results with histomor-phometric measurements	- Implants in rabbit tibia - RFA on transepithelial abutment - Histomorphometric analysis	- RFA measurement possi-ble at any time - Stability changes related to increased bone rigidity
Sul et al. 2002 (35) In vitro 50 References	Observe whether oxida-tive properties of implants improve osseointegration at 6 wks	- 48 TiUnite implants in rabbit tibia - RFA and removal torque at 6 wks	- Oxidative properties of TiUnite implants improve bone tissue response
O´Sullivan et al. 2002 (16) In vitro 47 References	Compare primary stability between different implant designs	- 52 human cadaver implants - RFA and removal torque (RT) - Different bone qualities	High RFA and removal torque values obtained, indicating very hard bone-implant interface (except for bone type IV)
Glauser et al. 2004 (18) In vivo 35 References	Analyze RFA measure-ments in immediate and early loaded implants	- 81 Bränemark implants - RFA: during implant insertion surgery, at 1,2,3,6, and 12 months	Very low RFA values at 2 months appear to indicate future risk of failure
Barewal et al. 2003 (15) In vivo 32 References	Assess stability changes at initial phases of osseointe-gration using RFA	- 27 ITI SLA implants - 4 bone types - RFA measurements each week up to 10th week	At 5 weeks, no differences in stability among bone types
Sennerby et al. 1998 (12) 1998 32 References	Analyze need to develop new methods for measur-ing stability	Correlation between implant failure and bone properties	Resonance frequency possi-ble method for de-termining stability
Olsson et al. 2003 (19) In vivo 31 References	Evaluate stability of im-mediate and early loaded implants for edentulous maxillary teeth	- 10 patients with 6 or 8 TiUnite implants - RFA measurements: at surge-ry and implant placement	Despite limited number of cases, early loaded maxil-lary implants possible in 6 or 8 cases

Table 1. (continued) Articles selected using H index (n=21).

AUTHOR	OBJECTIVES	MATERIAL AND METHODS	CONCLUSIONS
Balleri et al. 2002 (23) In vivo 30 References	Measure stability using RFA during loading period	- 45 implants in 45 patients - RFA and Rx during year of loading - Different locations, lengths, and bone levels	ISQ values at 1 yr in 57-82 range indicate implant success
Huang et al. 2002 (13) In vitro 28 References	Evaluate implant behaviour under different bone conditions	- 3D model of finite elements developed - Implants in different types of bone - RFA	RFA a possible diagnostic tool to determine implant stability
Rasmusson et al. 1999 (36) In vitro 28 References	Study effects of barrier membranes and onlay grafts on stability	- 18 implants in 9 rabbits - 2 groups (with and without membrane) - RFA, removal torque, and histological analysis	No improvement in stability with use of non-resorbable membranes
Meredith et al. 1998 (9) In vitro 27 References	Compare different methods for evaluating implant stability	Analysis of electronic methods and RFA	Clinical applications of electronic methods for stability diagnosis discussed
Rocci et al. 2003 (37) In vivo 26 References	Evaluate histological analyses of TiUnite implants	- 5 implants extracted from 5 patients - Immediate loading - RFA. - Inserted in posterior mandibular area	This type of implant highly integrated in both hard and soft tissue
Calandriello et al. 2003 (38) In vivo 25 References	Evaluate stability of immediately loaded implants	- 50 Bränemark implants in posterior areas - RFA y RX during 1 year	In posterior regions, immediate loading a highly effective treatment option for type IV bone
Bischof et al. 2004 (39) In vivo 24 References	- Determine factors affecting RFA - Monitor changes in first 3 months - Evaluate differences between immediate and delayed loading of implants	- ITI implants - 2 groups: immediate loading (IL) and delayed loading (DL) - RFA every 2 weeks - Different variables	- Initial stability measured by RFA affected by bone quality and location - No differences between IL and DL after 3 months
Nkenke et al. 2003 (40) In vitro 23 References	Determine relationship between stability, bone density, and histological analysis	- 48 human cadaver implants - RFA, insertion torque, and Periotest	Stronger relationship between RFA and histomorphometric than Periotest parameters
Glauser et al. 2005 (41) In vivo 22 References	Describe TiUnite surface at immediate loading in different locations	- 102 maxillary and mandibular Bränemark implants - RFA, torque, and radiography at 1, 6 and 12 months	High level of success (97.3%) with immediately loaded TiUnite implants
Nedir et al. 2004 (20) In vivo 22 References	- Evaluate RFA for diagnosis of mobile and stable implants - Determine predictive ISQ values for osseointegration - RFA predictability in immediate load (IL) and delayed load (DL) implants	- Immediate load (IL) and delayed load (DL) ITI implants - RFA: at 1,2,4,6,8,10,12 weeks	These data can help the surgeon to choose load protocol and establish healing phases

Table 2. Articles published between January 2007 and February 2008 selected using H index (n=10).

AUTHOR	OBJECTIVES	MATERIAL AND METHODS	CONCLUSIONS
Cannizzaro et al. 2007 (24) In vivo	Compare conventional sinus augmentation (particulate bone) with new internal sinus block inlay graft technique	- Control group: block graft implants - Test group: particulate bone graft implants - RFA and Periotest measure-ments: 6-12 months.	- Similar stability levels in both groups - Block graft technique is an effective option for sinus augmentation
Ozkan et al. 2007 (25) In vivo	Compare stability and marginal bone levels in atrophied mandibular implants using bone augmentation and non-graft bone implant techniques	- Control group: 18 non-graft bone implants - Test group: 17 graft implants placed 4 months previously - RFA measurements at 1, 4 and 12 months - Radiographic monitoring	No differences in RFA-measured stability between graft and non-graft implants
West et al. 2007 (26) In vivo	Evaluate changes in stability between immediate and delayed load implants Compare 2 implant designs for extraction sockets	- Control group: 11 delayed load implants - 2 experimental groups: 28 standard and tapered implants - RFA measurements every 2 weeks up to 24th week	Similar levels of stability attained for both standard and tapered implants in extraction sockets
Lang et al. 2007 (27) In vivo	Compare use of standard, cylindrical, and tapered Straumann implants for immediate placement in extraction socket	- 9 study centres: randomized clinical trial - 208 immediate load implants - RFA measurements: at surgery, 1, 2, 6 and 12 weeks	SLA Straumann cylindrical and tapered implants can both be used in extraction socket
Cannizzaro et al. 2007 (28) In vivo	Evaluate success/failure of immediately loaded transmucosal implants in edentulous superior maxilla	- 202 implants (53 immediately loaded). - RFA measurements: at surgery and 12 months after insertion	Immediate loading of transmucosal maxillary implants a predictable treat-ment option
Huwiler et al. 2007 (30) In vivo	Monitor RFA measurements in relation to bone characteristics during early phases of osseointegration	- 23 Straumann SLA implants - RFA measurements: at 1, 2, 3, 4, 5, 6, 8, and 12 weeks	ISQ values of 57- 70 indicate stability. No pre-dicttive RFA values for implant success
Ito et al. 2008 (31) In vitro	Observe possible correlation between RFA and histology (BIC)	- 24 pig implants - RFA measurements: at 1,2 and 4 weeks - Histological analysis	No correlation between RFA and BIC, whose values only increased in bone around the neck of the implant
Al-Nawas el al. 2008 (32) In vitro	Evaluate osseointegration condi-tions in animal trial and for loaded implants with different surfaces	- 196 implants - 6 surface types - Histological analysis - RFA measurements	Benefit of rough surfaces histologically proven
Karl et al. 2008 (33) In vivo	Evaluate RFA of ITI implants using retrospective clinical analysis	- 385 ITI implants - RFA measurements at 12 weeks in superior maxilla and at 6 weeks in inferior maxilla - Variables: length, diameter, and location	Repeated RFA measure-ment appears to facilitate diagnosis of implants with limited stability. Specific effect of variables unclear.
Verdonck et al. 2008 (34) In vitro	Monitor implant stability during placement and at osseointegration stage in irradiated and non-irradiated bone	- 120 implants placed in pigs - RFA measurements: at 8,16, and 24 weeks	Negative effect of irra-diation on bone vasculariza-tion and implant stability confirmed

No other authors accounted for more than 5% of the total (Fig. 1).
The first studies of RFA appeared in 1996 but there was little scientific research (around 3% of the total) over the next five years. Scientific interest in this area grew considerably in 2005, when studies accounted for 18% of all studies on RFA, and this level was maintained in 2006. There was further increase in 2007 (27% of the total), and this trend continued in the first two months of 2008 (Fig. 2).
The largest number of articles on RFA were published by Clinical Oral Implants Research (21.5%), International Journal of Oral & Maxillofacial Implants (13%) (the two journals with highest impact); Clinical Implants Dental Related Research (9.7%), Journal of Oral Maxillofacial Surgery (4.5%), and Journal of Periodontology (4.5%).
RFA studies were found in a wide range of disciplines. The largest proportion appeared in the field of oral surgery and dentistry (72%), followed by dental engineering (27%), general surgery (13%), biophysics (11.6%), and psychology (7.7%).
The following studies met our selection criteria:
1º- The 21 most cited articles were selected on the basis of the H index (H index=21). Table 1 shows: author, year of publication, type of study (clinical or experimental), number of references, objectives, material and methods, and conclusions.
2º- Recent scientific work from January 2007 to February 2008. The 10 RFA studies of clinical interest selected were published in the two journals with highest impact: Clinical Oral Implants Research and the International Journal of Oral & Maxillofacial Implants (Table 2).

Discussion

According to our findings, Resonance Frequency Analysis as a technique for measuring dental implant stability has attracted considerable scientific interest in recent years, with a constant increase in the volume of scientific research and studies published in prominent journals. The 21 *in vitro* and *in vivo* studies selected on the basis of the H index (Table 1) reflect the effectiveness of RFA as a method for measuring dental implant stability. In 1998, Meredith et al. (3) and Sennerby et al. (12) both concluded that resonance frequency was a highly effective qualitative method and proposed its use to assess implant stability. In 2002, Huang et al. (13) reached similar conclusions after evaluating implant behaviour in different types of bone.
Using RFA, the stability of implants was even found to improve over time in soft bone (14), and no differences in stability were observed between different bone types at week 5 (15). However, O'Sullivan et al. (16) compared insertion torque and bone properties in a cadaver study and obtained high values for all bone types except type IV; this was in line with the findings of Boronat et al. (17), who reported higher ISQ values for implants inserted in areas of more compact bone.
Other authors used RFA to determine the effects of immediate or early loading (18-20) or assess changes in stability over time (21). Resonance frequency can also be measured at any time during the process (22), allowing implant failure to be diagnosed at an early stage. Very low RFA values at 2 months appear to indicate risk of future implant failure, while ISQ values of 57-82 at 1 year indicate implant success (23).
Recent articles in this review (Table 2) represent a small sample of the abundant ongoing research. In 2007, various authors examined the use of bone augmentation techniques for sinus elevation (24) and mandibular atrophy treatment (25), using RFA to test implant stability in regenerated zones.
In relation to different implant designs and their behaviour in specific clinical situations, West et al. (26) and Lang et al. (27) used RFA to demonstrate the similar stability of cylindrical and tapered implants in immediate implants inserted into extraction sockets, while Cannizzaro et al. (28) was able to show that immediate loading of transmucosal maxillary implants is a successful treatment option. RFA was also used to determine whether implant length and diameter influence primary stability (29), leading to the conclusion that ISQ values were not significantly related to implant length or diameter.
Bone biology and osseointegration in implantation continue to attract considerable scientific interest. Huwiler et al. (30) applied RFA at early stages of osseointegration and reported that ISQ values of 57-70 indicate stability. Using *in vitro* histomorphometric analysis, Ito et al. (31) found no correlation between bone-implant contact (BIC) and RFA, while Al-Nawas et al. (32) confirmed the benefits of a rough implant surface for increased RFA-measured stability.
Karl et al. (33) compared the different locations of mandibular and maxillary ITI implants and found a significant correlation between these variables. They also observed that RFA measurements can identify unstable implants. Verdonck et al. (34) carried out experimental studies using RFA to determine the stability of implants placed in irradiated bone and found that irradiation had an adverse effect on bone vascularisation and hence on implant stability.
As evidenced by this review, objective assessment using the RFA method has made it possible to quantitatively and qualitatively analyze the stability of various types of implants and examine their behaviour under different bone and loading conditions.

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