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Implant stability measurements using resonance frequency analysis: biological and biomechanical aspects and clinical implications

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Osseointegrated implants for prosthetic rehabilitation of the edentulous patient show high success rates if certain preconditions are fulfilled. Implant stability plays a critical role for a successful critical outcome since short implants and implants placed in soft bone are more prone to failure (13, 49). In the original protocols for implant placement, primary implant stability was ensured by new bone formation and remodelling, termed osseointegration, which was accomplished during an initial healing period in which implants remained non-loaded to secure undisturbed bone formation onto the implant surface. The process of osseointegration increases the stiffness of the bone around the implant, and the bony interlock with the implant surface prevents micro-movement and the formation of fibrous scar tissue at the time of implant loading. However, the development of new implant surfaces and clinical techniques has enabled a marked reduction of the initial healing period, even to the point of an immediate ⁄ early loading of implants that show high primary stability (7, 37). Thus, the success of immediate ⁄ early loading implant techniques is dependent on the ability of the clinician to determine the degree of primary implant stability and changes in stability along with new bone formation and remodelling.

The clinical perception of primary implant stability is frequently based on the cutting resistance of the implant during its insertion. The feeling of 'good' stability may be accentuated if there is the sense of an abrupt stop at the seating of the implant. Root forms of tapered implants often have a geometry that will provide a firm stop and perhaps a false perception of high stability. A percussion test has also been used to assess implant stability. The percussion test may involve the tapping of a mirror handle against the implant carrier and is designed to elicit a ringing sound from the implant as an indication of good stability or osseointegration. Percussion tests probably provide more information about the tapping instrument, and will at best only yield poor qualitative information. Insertion torque measurements are sometimes used to determine primary implant stability (6). Application of a reverse or unscrewing torque has also been proposed for the assessment of implant stability at the time of abutment connection (53). Implants that rotate under the applied torque are considered failures and are then removed. However, an implant surface in the process of osseointegrating, albeit slowly, may fracture under the applied torque stress. Moreover, as animal experiments have demonstrated the re-integration of loosened and rotationally mobile implants (26), the reverse torque testing has fallen into disrepute. Other techniques, such as the Periotest and resonance frequency analysis, aim to provide an objective measure of implant stability and osseointegration that is noninvasive and does not damage the implant–tissue interface (6, 28). The resonance frequency analysis technique has been extensively used in experimental and clinical research for the last 10 years. The purpose of this review is to present the current knowledge about the resonance frequency analysis technique and to discuss the clinical utility of resonance frequency analysis measurements.

What is implant stability?

Implant stability can be defined as the absence of clinical mobility, which is also the suggested definition of osseointegration. Achieving and maintaining implant stability are prerequisites for successful clinical outcome with dental implants (2). Nonetheless, a clinically stable implant also exhibits mobility on the micro-scale when loaded. For instance, if applying a lateral load (bending) to a bone-integrated implant, the implant will be displaced but will return to its original position as soon as the load is removed (Fig. 1). Thus, a stable implant can display a varying degree of stability (i.e. different degrees of displacement or resistance to load), depending on factors relating to the bone, the surgical technique and the implant design. During clinical function, loading is applied in axial, lateral and rotational directions (Fig. 2). Furthermore, axial loads can be in intrusive or extrusive directions. Lateral loads can principally occur from any 360° direction around the implant. Rotational loading can be either clockwise or counter-clockwise. Thus, the outcome of an implant stability analysis is highly dependent on the type of test used and the direction and type of the applied force.

Resonance frequency analysis stability measurements essentially apply a bending load, which mimics the clinical load and direction and provides information about the stiffness of the implant–bone junction (Fig. 3). Implant stability measurements can also include a shear force, using, for example, a reverse

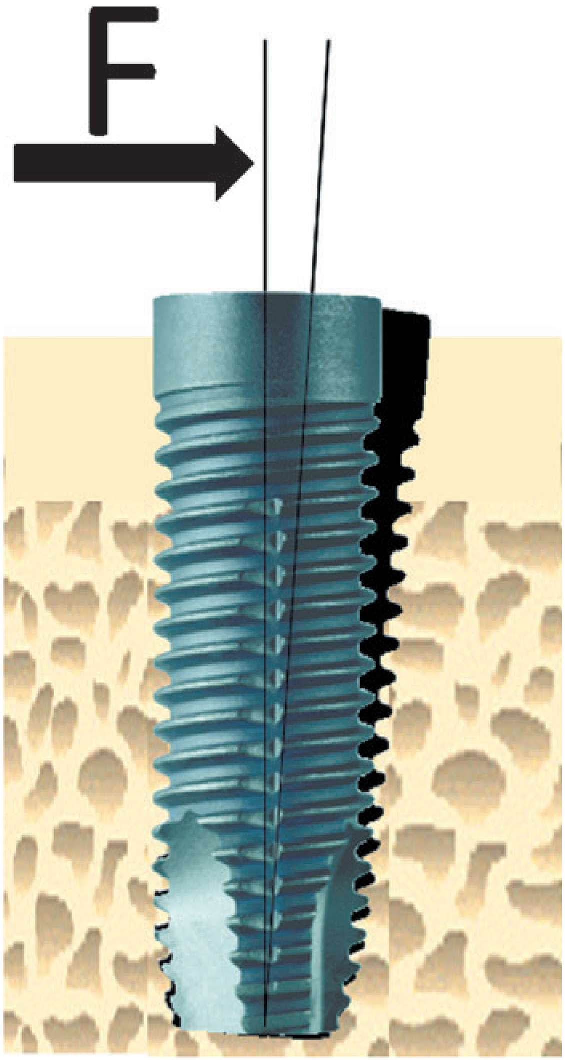

Fig. 1. A schematic showing displacement of an implant after application of a lateral load. F, force.

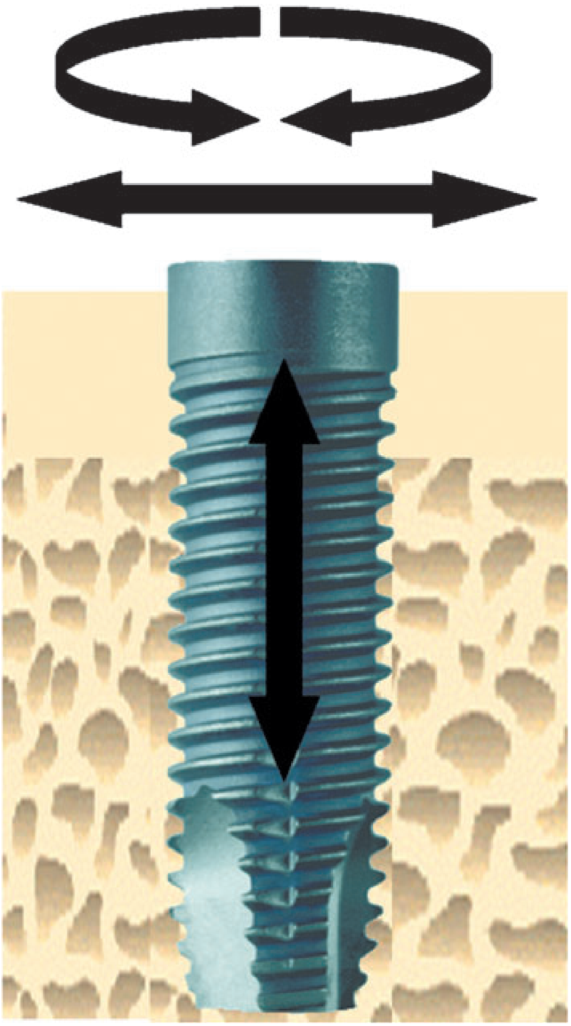

Fig. 2. A schematic showing different directions of loading for an implant in function.

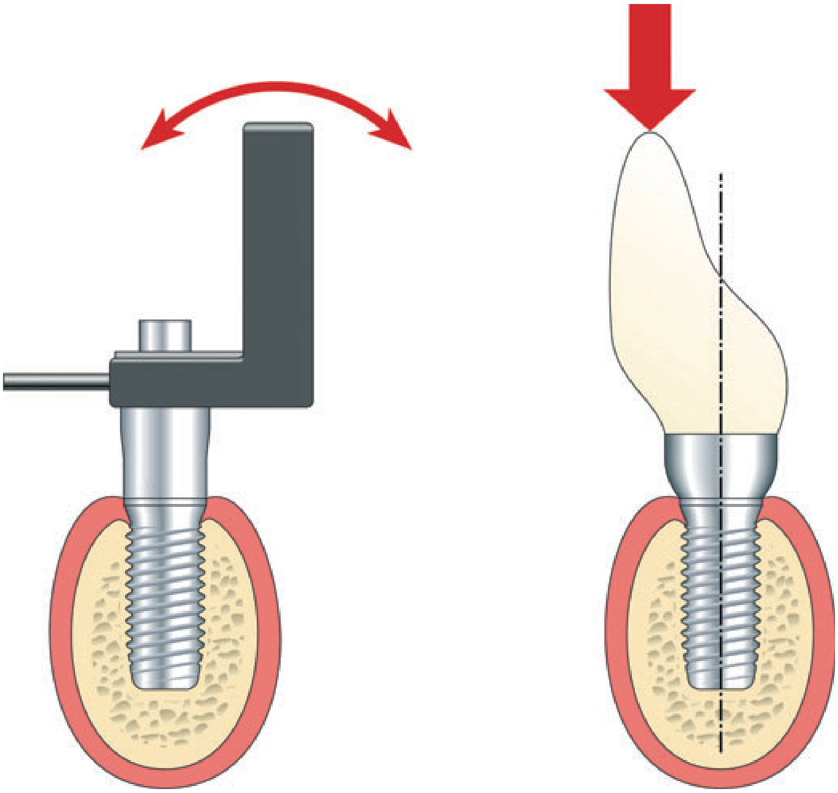

Fig. 3. **A schematic showing the principles of resonance frequency analysis. A microscopic bending force is applied to the transducer beam to measure its resonance frequency. Bending is the most common type of loading for a dental implant.**

torque test, which assesses the strength of the interface but which can also be potentially destructive. A newly placed implant can show a high degree of lateral stability but may be easily removed when applying reverse torque for an implant, where bone has not yet been formed and interlocked with its surface. With time, bone formation will lead to an increased interlocking with the implant surface and an increased strength of the implant–bone interface. The lateral stability is also likely to increase as a result of new bone formation and remodelling. Because most implants will be connected with a framework, reverse torque tests are probably less relevant than measurements of lateral stability.

The main determinants of implant stability are (i) the mechanical properties of the bone tissue at the implant site and (ii) how well the implant is engaged with that bone tissue. The mechanical properties of bone are determined by the composition of the bone at the implant site and may increase during healing because soft trabecular bone tends to undergo a transformation to dense cortical bone at the vicinity of the implant surface (Fig. 4A–D). The strength of the implant–bone interface is also influenced by the surgical technique and the design of the implant. For instance, the use of a thinner final drill or a wider or a tapered implant will force more of the implant threads into direct contact with the surrounding bone. Moreover, the healing process results in the formation of bone that reinforces the implant–bone interface by forming bony bridges between the implant surface and the surrounding bone.

Resonance frequency analysis

The resonance frequency analysis method analyses the first resonance frequency of a small transducer attached to an implant fixture or abutment (29). The resonance frequency of the resonance frequency analysis system is dependent upon three main factors (46): first, the design of the transducer itself; second, the stiffness of the implant fixture and its interface with the tissues and surrounding bone; and, third, the total effective length above the marginal bone level (Fig. 5). The effective length comprises the length of the transducer, which is fixed, the length of the abutment, which may vary but at fixed intervals, and the level between the top of the fixture and the surrounding bone. The resonance frequency analysis technique is a bending test of the implant–bone complex where a transducer applies an extremely small bending force. The bending force applies a fixed lateral force to the implant and measures the displacement, thus mimicking the clinical loading condition, albeit of a much reduced magnitude.

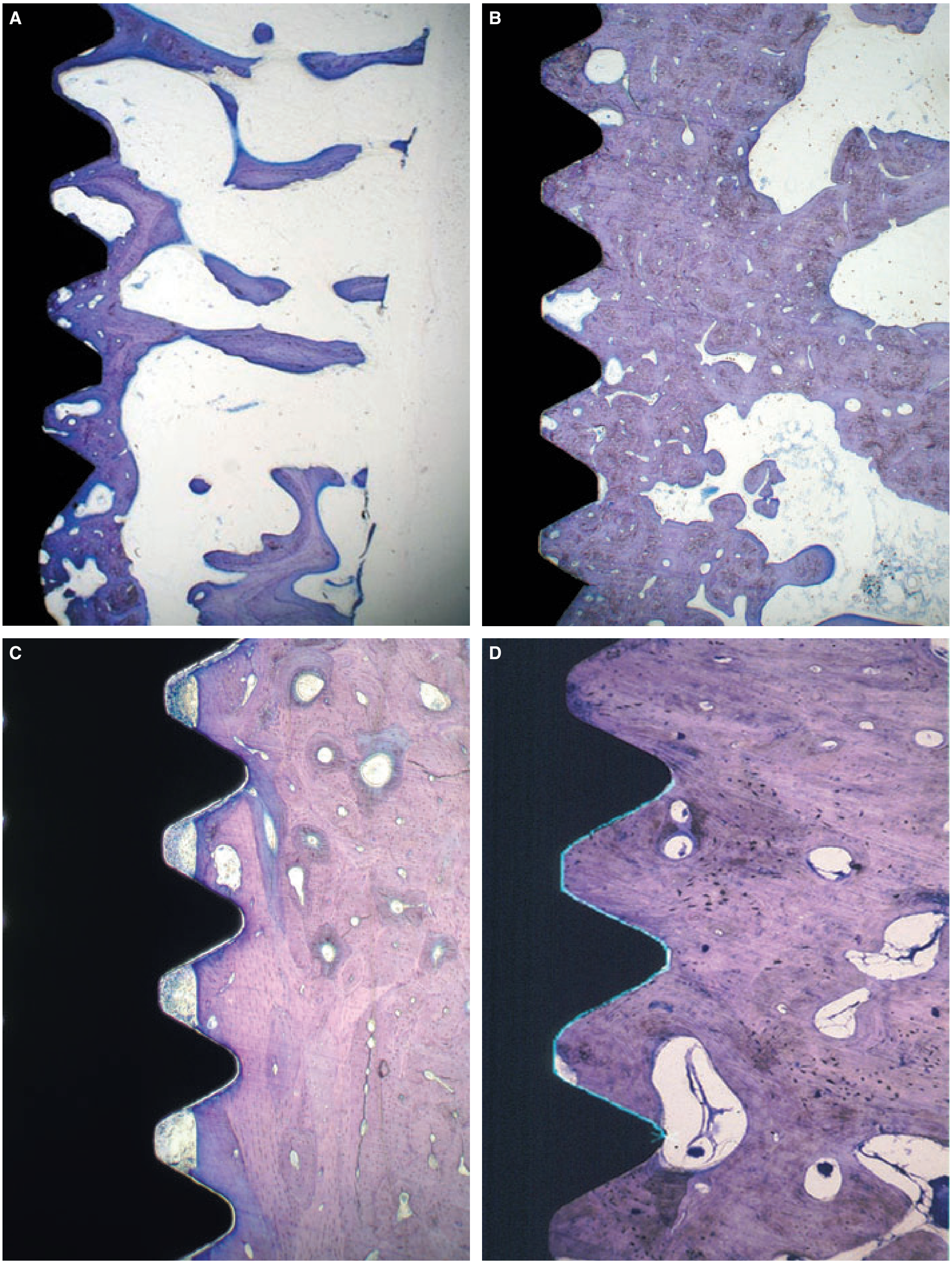

Fig. 4. (A) An implant placed in soft trabecular bone. (B) Over time the trabecular bone is transformed to a more cortical bone structure, which results in an increased stiffness of the implant–bone interface. (C) An implant placed in dense cortical bone. (D) No major changes of the bone density occur over time. The interfacial voids have been filled with bone.

The first-generation resonance frequency transducer was designed as a simple offset cantilever beam, which could be screwed to an implant fixture or abutment (Fig. 6). The beam was excited over a range of frequencies and the first flexural resonance was measured. The transducer was made of stainless

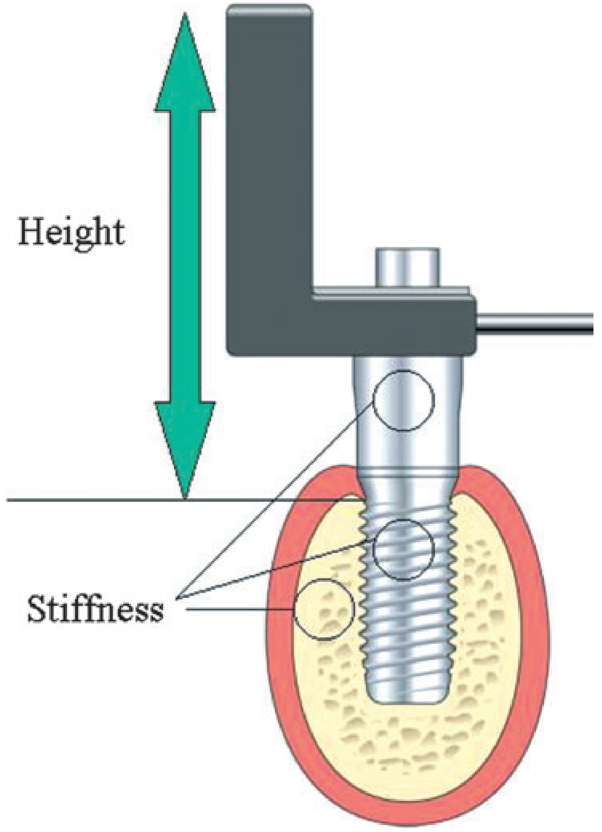

Fig. 5. A schematic showing the principles of resonance frequency analysis. The stiffness of the transducer, implant and bone influences the outcome as well as the effective length of the implant above the bone crest (length).

steel or commercially pure titanium, and comprised a small offset cantilever beam with two attached piezoceramic elements (Fig. 7A). The beam was vibrated by exciting one of the piezoceramic elements with a sinusoidal signal of varying frequency. The signal was synthesized by a frequency response analyzer that was programmed by a personal computer (Fig. 7B). The second piezoceramic element measured the response of the beam and the signal generated was amplified by a charge amplifier before being compared with the original signal by means of the frequency response analyzer. The excitation signal was a sine wave, varying in frequency typically from 5 to 15 kHz with a peak amplitude of 1 V. At the first flexural resonance of the beam, there was a marked increase in amplitude and a change in phase of the received signal. This can be illustrated graphically as a Bode plot of frequency against amplitude (Fig. 8).

Disadvantages with the first generation of resonance frequency analysis instrumentation included a large amount of cabling, the bulk and weight of the equipment, and the cost of the instrument. Another disadvantage was the sweep time of the frequency response analyzer. A coarse frequency sweep spanning 5–15 kHz in 100-Hz steps with a fine sweep of 25 points around the resonance peak typically took over 1 min to perform. For these reasons, it was decided to design a dedicated frequency response analyzer (Fig. 9). The key design features of this instrument were that it should be fast to use, light and portable, completely safe for patient use, and easy to program and to download data. These requirements were fulfilled with the design of a dedicated frequency response analyser, which made use of a standard medically approved power supply unit. The instrument communicated with a personal computer via a serial port, and the personal computer was used to both program the instrument to set frequency sweeps and limits, and to collect and store the data on the hard disk.

One major drawback of the first-generation and second-generation resonance frequency analysis instruments was that each transducer had its own fundamental resonance frequency. Therefore, different transducers had to be calibrated using a standard before measurements were comparable. It was not possible to interpret resonance frequency

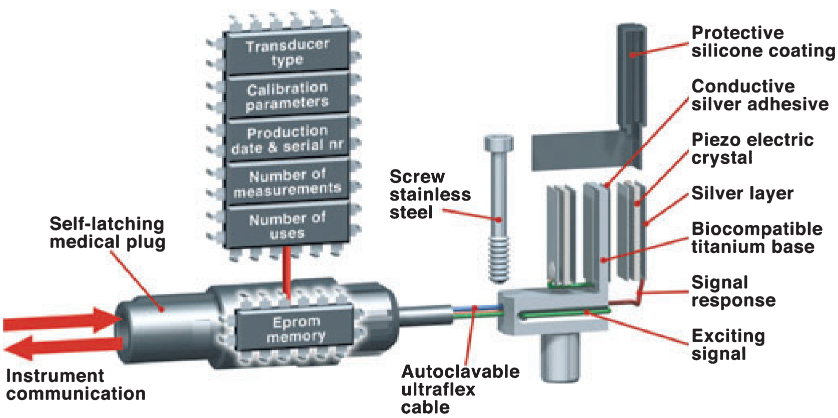

Fig. 6. A schematic showing the construction of the resonance frequency analysis transducer.

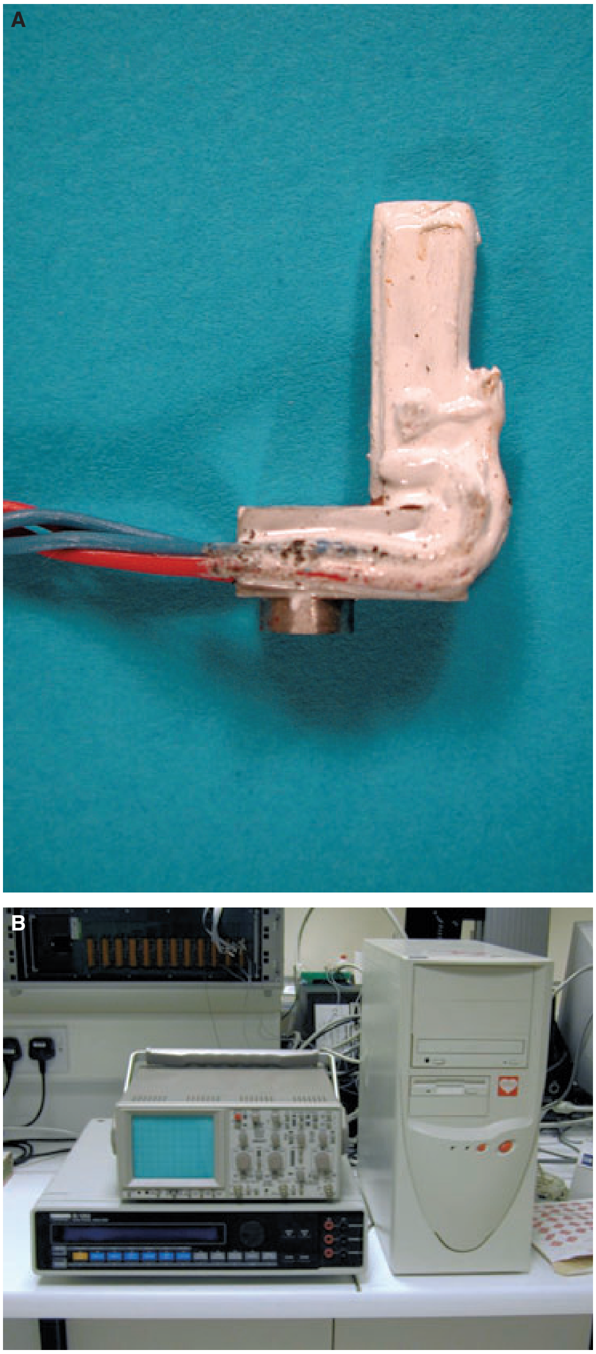

Fig. 7 (A) First-generation resonance frequency analysis transducer. (B) First-generation equipment, including a personal computer, an oscilloscope and a frequency response analyser.

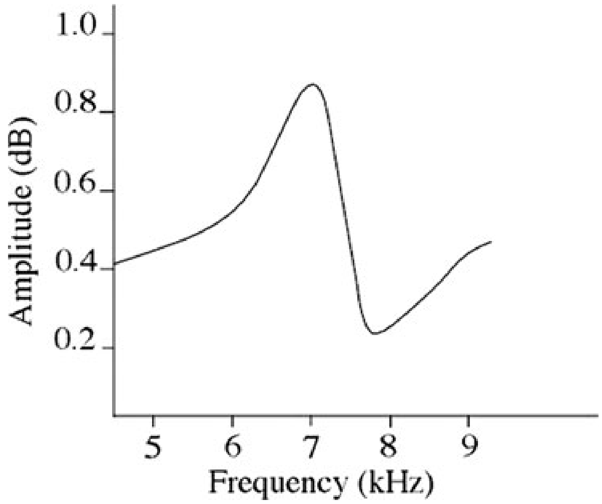

Fig. 8. A frequency-amplitude plot of a resonance frequency analysis measurement. The resonance frequency is seen as a peak in the diagram.

Fig. 9. Second-generation frequency response analyser.

analysis results chairside when, for instance, attempting to follow implant stability over time in a given patient. Moreover, the system with the response analyser and a personal computer was considered to be too heavy and not user-friendly. The aim of the third generation of resonance frequency analysis instruments was therefore to provide a small battery-driven system, which enables quick and simple measurements to be made with the possibility of chairside interpretation (Fig. 10). The new resonance frequency analysis system (Osstell^{TM}; Osstell AB, Gothenburg, Sweden) comprises a battery-driven frequency response analyser and a new generation of transducer that was pre-calibrated from the manufacturer. The result of a measurement is presented as a dedicated parameter – the implant stability quotient. The implant stability quotient unit is based on the underlying resonance frequency and ranges from 1 (lowest stability) to 100 (highest stability). Transducers are available for different implant systems and abutments (Figs 11 and 12), making all resonance frequency analysis measurements comparable, irrespective of the type of implant or abutment. In addition, the results can be transferred into a

Fig. 10. The third generation and the first commercially available resonance frequency analysis equipment (Osstell™).

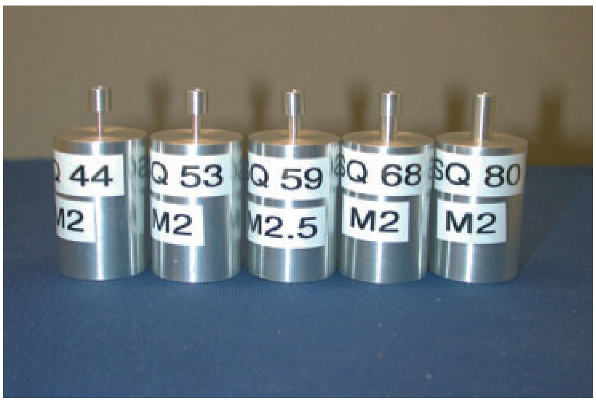

Fig. 11. Aluminium blocks representing different resonance frequencies used in the calibration of the third-generation transducers in order to measure implant stability quotient (ISQ) units.

Fig. 12. Clinical use of an Osstell™ transducer.

Fig. 13. Clinical use of a Smartpeg™ and a Mentor™, the fourth generation of the resonance frequency analysis system.

personal computer for further analysis and storage via a serial cable or infrared port.

The most recent version of resonance frequency analysis is wireless, where a metal rod (a peg) is connected to the implant by means of a screw connection (Osstell Mentor™; Ostell AB) (Fig. 13). The peg has a small magnet attached to its top, which is excited by magnetic pulses from a handheld computer. The peg vibrates in two directions, which are approximately perpendicular to each other. The vibration takes place in the direction that gives the highest resonance frequency (first mode) and in the direction that gives the lowest resonance frequency (second mode). Thus, two implant stability quotient values are provided, one high and one low (Fig. 14). For instance, an implant with buccally exposed threads may show one low value, reflecting the lack of bone in the buccal–lingual direction, and one high value, reflecting good bone support in the mesial–distal direction.

Factors influencing resonance frequency analysis

Stiffness of the implant–bone interface

In vitro studies to measure changes in mechanical properties and stiffness that simulate those occurring in bone during remodelling and healing around implant fixtures are difficult to perform. Although not strictly comparable with bone, resin polymerization offers a simple and reproducible model system for evaluating the transducer system in relationship to changes in stiffness. A significant increase in stiffness accompanies the polymerization of a resin as it cures

Fig. 14. In several implant systems, the Mentor™ gives one low and one high implant stability quotient value, reflecting the highest and the lowest level of stability of an implant.

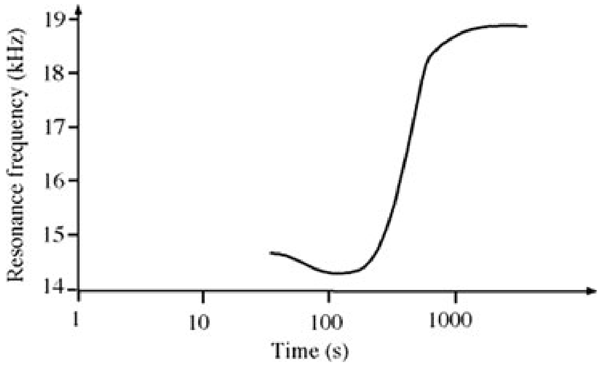

Fig. 15. Change of resonance frequency with time for an implant placed in curing resin.

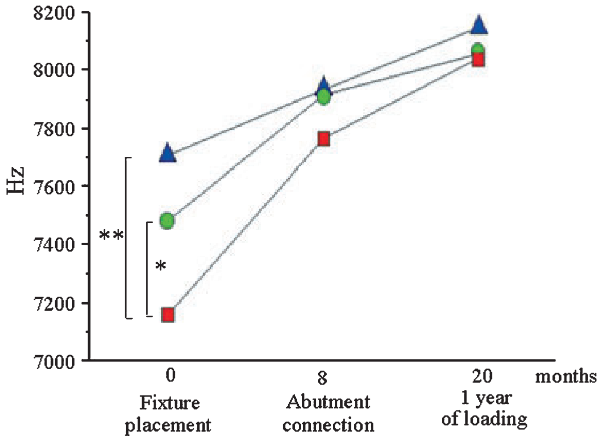

Fig. 16. Resonance frequency for maxillary implants placed in different bone densities.

and changes from a liquid or gel to a solid phase. The frequency response of a transducer–implant system embedded in various resins has been measured at predetermined intervals (Fig. 15) (29).

Early clinical work indicated a relationship between bone density and primary implant stability. Friberg et al. (18) correlated cutting resistance (i.e. bone density) with primary stability for maxillary implants (Fig. 16). Follow-up measurements performed at the time of abutment connection (6–8 months later) and after 1 year in function indicated that all implants, irrespective of initial stability, tended to reach a similar level of stability. Andersson et al. (5) examined 102 Neoss implants and found an inverse relationship between cutting torque (bone density) and changes in implant stability during a study period of 12 months. They also identified a correlation between bone quality, measured according to Lekholm & Zarb (27), and primary stability. Implants in soft bone with low primary stability showed a marked increase in stability compared with implants in dense bone (Fig. 17). In fact, implants placed in dense type 1 and type 2 bone revealed a slight decrease in stability, probably as a result of marginal bone remodelling, but all implants reached a comparable level of stability after 1 year. Similar findings have also been reported by other researchers (10, 11, 33, 36, 51, 52). The data indicate that the stiffness of the implant–bone interface is high in dense bone and low in soft bone. Moreover, the healing and remodelling process of soft trabecular bone seems to result in an increased stiffness of the peri-implant bone.

The resonance frequency analysis technique has also been used in animals to study implant healing in normal bone (31), in grafted bone (42–44) and in membrane-induced bone (45). In rabbits, 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 (47, 48). In an *in vitro* study of human

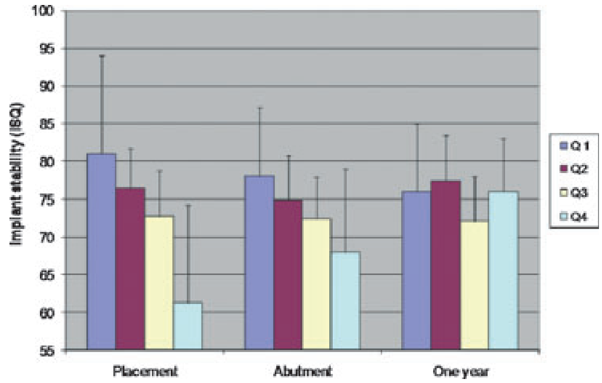

Fig. 17. Implant stability quotient values for 102 implants placed in different bone densities and followed from the time of placement to abutment connection and to the first annual follow-up examination. ISQ, implant stability quotient.

bone, a positive linear correlation was found for resonance frequency analysis and insertion torque and for resonance frequency analysis and Hounsfield Units, as evaluated in computed tomography scans of the jaws (54), which lends further credence to the ability of resonance frequency analysis to measure the mechanical properties of bone. In an *in vitro* experiment, Ito et al. (26) used three screws to stabilize an implant at four different levels. The resonance frequency decreased when unscrewing the most coronal screws but not with the loss of the more apical screws, which suggests that the marginal region is the most important for the outcome of resonance frequency analysis measurements. The results of Ito et al. (26) also indicated that implant length may not have a significant impact on resonance frequency analysis measurements, a notion that has also been espoused in *in vitro* (19) and in clinical (8, 12, 40) studies.

The Osstell technique has demonstrated higher implant stability in maxillary bone than in mandibular bone (8–12, 32, 40). Also, as discussed above, a correlation between bone quality (25) and implant stability quotient values has been identified by several investigators (5, 9, 12, 40), but not by all (59). Based on resonance frequency analysis measurements of 905 consecutive screw-shaped implants, Östman et al. (40) found primary implant stability to be dependent on the jaw, bone density, gender, implant diameter and the anterior ⁄ posterior position of the implant. Interestingly, Östman et al. (40) found decreasing stability with increasing implant length. Miyamoto et al. (32) made a similar observation. This may be explained by the fact that some long implant designs have a reduced diameter (negative tolerance) in the coronal part to reduce friction heat and facilitate easy insertion. However, Bischof et al. (12) found that implant position, implant length, implant diameter and vertical position did not affect the implant stability quotient values of 106 implants placed in the maxilla and the mandible. Zix et al. (60) studied maxillary implants and reported higher implant stability in male patients than in female patients.

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 (10, 21, 23, 41). The initial decrease in implant stability is probably caused by the start of the healing and remodelling process, which includes resorption and thereby a temporary weakening of the bone, and also because of the extra burden of implant loading during this period of time (23). However, a recent study that used a tapered implant design for immediate ⁄ early loading did not show an initial decrease in implant stability (15). Rather, resonance frequency analysis measurements increased from implant placement to 1 year after initial loading (15). Implant design and surface structure may have an impact on implant stability during initial healing. In dogs, Rompen et al. (47) showed that surfaced-modified implants maintained stability, whilst machined implants experienced a decrease in stability during the early healing period. Glauser et al. (22) 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.

Histometric correlations

Most studies have failed to show a correlation between the degree of implant–bone contacts and resonance frequency analysis measurements (1, 25, 31). This may relate to the nature of the test, because the degree of bone contacts does not necessarily reflect the stiffness of the surrounding bone. In modern implant dentistry using moderately rough implants, the surface is often covered by a thin layer of bone, which is probably not important for the biomechanical support of implants. Most researchers have not found rough or smooth implant surfaces to impact on implant stability (3, 4, 19, 48, 50), although, as discussed above, some researchers have reported different implant stability with different implant surfaces (44).

Myiamoto et al. (32) observed a strong, positive correlation between cortical bone thickness, as judged from computed tomography scans and initial implant stability quotient values for 225 screw-shaped implants placed in the maxilla and the mandible. Similarly, Nkenke et al. (34) and Gedrange et al. (20) found a positive correlation between the height of the crestal cortical bone and implant stability quotient values in cadaver studies.

Distance to first bone contact ⁄ marginal bone loss

The relationship between the length of an implant abutment and resonance frequency analysis data has been examined in various model systems. Meredith et al. (29) measured the frequency response of the transducer attached to an implant fixture in an aluminium block using abutments of various lengths (Fig. 18). In a dog study on peri-implant breakdown, Sennerby et al. (48) demonstrated a negative correlation between radiographic bone loss and resonance frequency. It should be noted that marginal breakdown was initiated after healing and integration of the implants.

Meredith et al. (30) studied 52 maxillary implants after at least 5 years in function and revealed a significant, positive relationship between effective implant length (abutment length + bone loss) and resonance frequency. The study implants showed a similar degree of stability after 5 years of function (30). In a study on one-stage implants in dense mandibular bone, a small, but significant, decrease in stability was detected over a 15-week period, which was probably caused by marginal bone loss and an increased exposure of the implant above the bone crest (17).

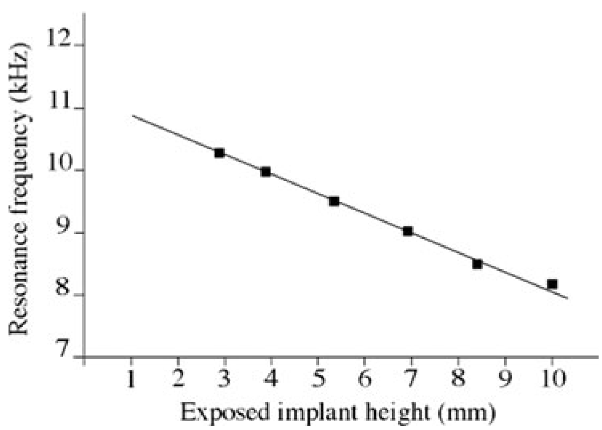

Fig. 18. The relationship between resonance frequency and the effective length of the implant above the bone crest.

Turkyilmaz et al. (55) 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 (55). The authors suggested that the effect of bone loss was compensated for by an increased interfacial stiffness resulting from bone formation and remodelling. However, Fischer et al. (15) 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, positive correlation between marginal bone resorption and low implant stability quotient values. This is in line with Meredith et al. (30), who suggested that variations in implant stability after 5 years in function could be explained by differences in marginal bone height.

Turkyilmaz et al. (56) demonstrated a negative correlation between exposed implant height and implant stability quotient 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.

Orientation of the resonance frequency analysis transducer

The orientation of the transducer influences the resonance frequency analysis measurements. Veltri et al. (59) and Fischer et al. (14, 16) found that implant stability quotient values increased by approximately 10 units when performing measurements with the transducer parallel to, rather than perpendicular to, the alveolar crest. The implant–bone complex probably displays varying degrees of stiffness in different load directions. Low implant stability quotient values obtained in the buccal–palatal direction are a reflection of thinner bone than in the mesial–distal direction. According to the manufacturer, the new wireless resonance frequency analysis technique (Mentor^{TM}; Osstell AB) measures the highest and the lowest resonance frequency whenever the difference exceeds 3 implant stability quotient units. This may explain the observed difference in stability readings between the new and the old resonance frequency analysis technique. Valderrama et al. (57) found that the two resonance frequency analysis techniques can differ by up to 10 implant stability quotient units, with higher stability values obtained in the mesial–distal direction with the wireless technique and lower values obtained in the buccal–palatal direction with the old technique. The specific orientation of the old resonance frequency analysis transducer may be the cause of the different resonance frequency analysis readings. Fig. 19 shows the results of stability measurements in 12 different transducer directions using the old resonance frequency analysis instrument and a direction-dependent transducer. Also, the new resonance frequency analysis technique, as shown in Fig. 19, yielded two different values, one recording the highest and one recording the lowest implant stability quotient value. In sum, it needs to be appreciated that implant resonance frequency analysis stability readings vary, depending on which direction the measurements are made using the transducer.

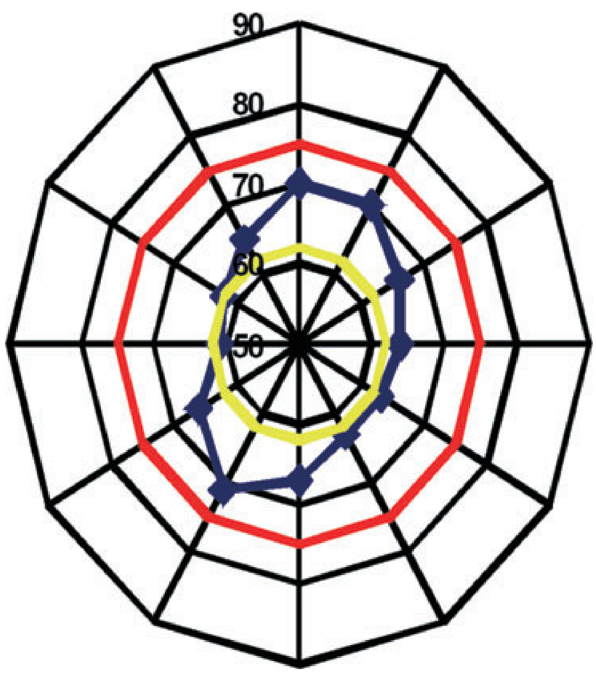

Fig. 19. Resonance frequency analysis measurements of an implant in 12 directions using an Osstell™ instrument. The red and yellow circles indicate the results from one measurement using the new wireless Mentor™ technique. It is obvious that implant stability varies with the direction of the applied load and that the new resonance frequency analysis technique indentifies the lowest and the highest levels of implant stability.

The utility of the resonance frequency analysis technique to predict implant failure

Friberg at al. (17), in 1999, evaluated 75 one-stage implants in the edentulous mandible by means of repeated resonance frequency analysis measurements. 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 asking the patient to refrain from wearing the denture, the implant stability increased for two implants and was maintained at the same level for one implant (Fig. 20). The same research group followed 56 implants in the maxilla of nine patients and demonstrated, for all but two failing implants, an increase in implant stability from the time of placement to abutment connection (18). The data point to an increase in stiffness of the implant–bone complex over time, except for soft-tissue-encapsulated failed implants.

In an immediate loading study, Glauser et al. (23) monitored the resonance frequency analysis stability of 81 implants from placement to 1 year in function. A total of nine implants failed during the 1-year observation period. All implants showed a high degree of initial stability, around implant stability quotient 70, but the group of future failures showed a continuous decrease in implant stability. After 1 month, the mean implant stability quotient value of 52 was statistically lower for the group of future failures than for the successful implants, which

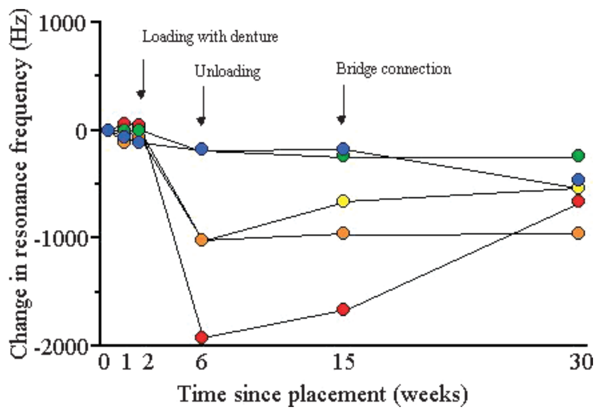

Fig. 20. Implant stability in one patient with five non-submerged implants in the mandible. Three implants showed a marked decrease of stability, which, however, recovered after unloading of the removable denture.

showed an implant stability quotient of 68. Also, implant stability quotient values of 49–58 were associated with an 18.2% risk of failure. Evidently, the lower the implant stability quotient value after 1 month of immediate loading, the higher the risk for future failure. Some of the failing implants may have been rescued by unloading and allowing a period of healing. However, the study of Glauser et al. (23) analyzed the resonance frequency analysis measurements retrospectively and no intervention could be taken chairside. In a follow-up study on implants placed in extraction sockets and subjected to immediate/early loading, Vanden Boagerde and co-workers (58) 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. (52) found lower primary stability for 17 implants (implant stability quotient 54.6) that failed during the first year of function compared with 195 implants (implant stability quotient 62.0) that were successful installed in grafted maxillae. Nedir et al. (33) 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 implant stability quotient 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 implant stability quotient value corresponding to the second resonance frequency (28).

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

Fischer et al. (15) 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 implant stability quotients, and one failed implant showed a value of 56 implant stability quotients, which was the fifth lowest value of the 53 implants.

Fischer (14) performed resonance frequency analysis measurements in 24 patients with 139 maxillary implants at 3 and 5 years following implant surgery. Four implants were lost during the third to the fifth year. At year 3, the failing implants showed lower implant stability quotient values than the average implant (i.e. 44 implant stability quotients, 53 implant stability quotients, 54 implant stability quotients and 54 implant stability quotients vs. an average of 57.7 implant stability quotients for all other implants in the study). An assessment of the risk for implant failure showed that implant stability quotient values below 44, 53 and 54 were associated with failure rates of 100%, 6.7% and 9.5%, respectively. None of 97 implants with implant stability quotient values higher than 54 failed from study year 3 to study year 5.

Possible clinical implications

The resonance frequency analysis technique has the potential to provide clinically relevant information about the state of the implant–bone interface at any stage of the treatment. The question is how to benefit most from information obtained by a single resonance frequency analysis measurement in clinical practice. To date, there is a lack of studies that document clear clinical benefits from therapeutic decisions based on resonance frequency analysis measurements. Obviously, one major goal in implant dentistry is to avoid implant failure. Although the failure rate of implants used in two-stage procedures is rather low, it is likely that higher failure rates are associated with immediate loaded or grafted implants. Moreover, increasingly more implant procedures are being performed by relatively inexperienced clinicians, who will be confronted with a variety of complications during their learning curve. As implant failures are often related to biomechanical factors, an assessment of implant stability may significantly lower the risk of failure. Studies have shown that high resonance frequency analysis values are indicative of a successful implant treatment with a small risk for future failure. Conversely, low or decreasing resonance frequency analysis values point to an increased risk for implant complications, although the exact resonance frequency analysis threshold values have yet to be identified.

It appears that implants of every system will, with time, approach a similar level of stability, which for Brånemark type implants seems to be an implant stability quotient of 65–75, and for Straumann type implants seems to be an implant stability quotient of 55–65. It seems reasonable to assume that this degree of stability at any time during the lifetime of an implant would indicate a safe level of stability. An implant stability quotient value below 55 (Brånemark) or 45 (Straumann) should be regarded as a warning sign, and measures to increase implant stability should be considered. Primary stability can be improved by modifying the surgical technique and by selecting a wider, longer or tapered implant. For instance, the use of thinner drills and wider and tapered implants will increase primary implant stability (35). The current trend is to use short healing periods also for two-stage procedures, which, however, may result in inadequate healing for implants in soft bone. Extending the healing period after implant placement constitutes a simple approach to gain additional stability. A low implant stability quotient value at a postloading examination may indicate disintegration of the implant–bone interface and ongoing failure (Fig. 21). In such a case, the crown ⁄ bridge construction of the implant may be removed in order to determine the stability of the fixture. An unloaded healing period of 6 weeks or longer may give the implant sufficient time to regain stability. A declining implant stability quotient value

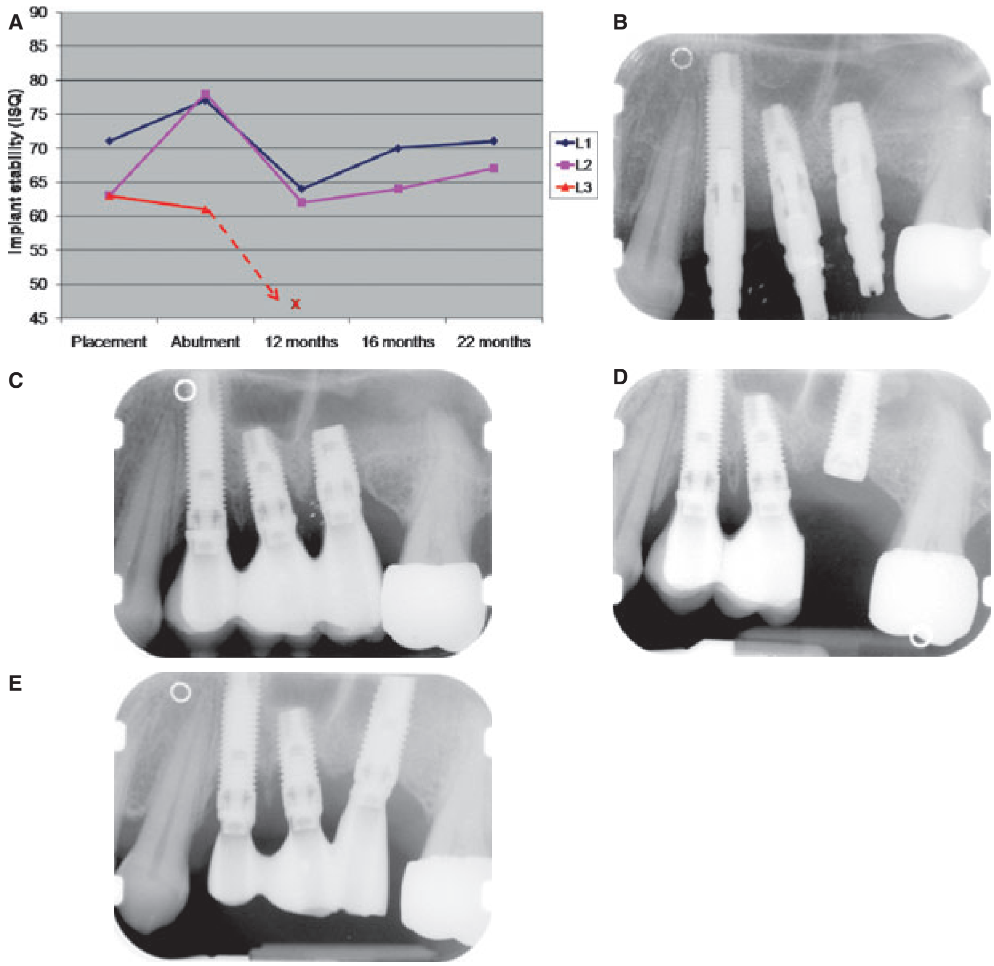

Fig. 21. (A) Resonance frequency analysis measurements from implant placement to 22 months of loading. ISQ, implant stability quotient. (B) Of the three implants in the posterior maxilla, L1 and L2 exhibited increased stability, whereas L3 showed no stability increase. (C) At the first annual follow-up, the implant in the first molar region was clinically mobile and the other two implants showed extensive marginal bone loss as a result of misfit, soft bone and overload. These two implants showed a marked decrease in implant stability quotient owing to the marginal bone loss and disintegration. (D) The bridge was shortened and loading was controlled. A new implant was placed in conjunction with a membrane-elevation procedure. Implant stability had increased. (E) The new final prosthetic construction including the new implant. L1 and L2 showed increasing stability, even though some marginal bone loss remained.

can also be the result of ongoing marginal bone resorption, and radiographs should be obtained to assess the status of the periodontal bone. For a Brånemark type implant, a 10 unit drop from implant stability quotient 75 to 65 may not be as alarming as a decline from implant stability quotient 60 to 50. The manufacturer advises that a decrease of about 3 implant stability quotient units ⁄ mm can be expected. With peri-implantitis, implant stability can still be high, but the future of the implant is threatened by ongoing and untreated marginal bone loss. In summary, the resonance frequency analysis technique may be used in follow-up examinations of implants, and only implants with low or decreasing implant stability quotient values need to be radiographed. One drawback with this approach is that prosthetic constructions need to be removed in order to perform the resonance frequency analysis measurements.

The resonance frequency analysis technique may be useful for assessing immediate loading implants during the various stages of treatment. For instance, a certain implant stability quotient value can be used as an inclusion criterion for immediate loading of implants. Östman et al. (38, 39) reported low failure rates when using implant stability quotient 60 as an inclusion criterion for immediate loaded implants in totally edentulous maxillae and in posterior mandibles. The authors of the present study find the resonance frequency analysis technique to be helpful in deciding when to replace an immediately loaded temporary prosthesis with a permanent prosthesis after implant placement. Values above implant stability quotient 65 indicate a favourable response to immediate loading, whilst low implant stability quotient values may be indicative of overload and ongoing failure. In such cases, unloading and perhaps placement of additional implants before inserting the permanent prosthesis should be considered.

Finally, the resonance frequency analysis technique may serve as a valuable tool for documenting the clinical outcome of implant treatments. This may be particularly important in a medico-legal setting. Also, for the implant surgeon, who receives referred patients for implant placement for later prosthetic treatment by the referring dentist, the resonance frequency analysis technique may help to assure the referring dentist and the patient of sufficient implant stability prior to commencing the prosthetic treatment phase. In other words, the resonance frequency analysis technique can be used to provide a 'fingerprint' of inserted implants.

Conclusions

The resonance frequency analysis technique can supply clinically relevant information about the state of the implant–bone interface at any stage of the treatment or at follow-up examinations. The resonance frequency analysis technique evaluates implant stability as a function of the stiffness of the implant–bone interface and is influenced by factors such as bone density, jaw healing time and exposed implant height above the alveolar crest. Studies indicate that implants with high implant stability quotient values during follow-up examinations are successfully integrated, whilst low and decreasing implant stability quotient values may be a sign of ongoing implant failure and ⁄ or marginal bone loss. However, more clinical studies and case reports are needed to formulate clear guidelines for clinical use of the resonance frequency analysis technique.

References

1. Akca K, Chang TL, Tekdemir I, Fanuscu MI. Biomechanical aspects of initial intraosseous stability and implant design: a quantitative micro-morphometric analysis. *Clin Oral Implants Res* 2006: **17**: 465–472.
2. Albrektsson T, Zarb GA. Current interpretations of the osseointegrated response: clinical significance. *Int J Prosthodont* 1993: **6**: 95–105.
3. Al-Nawas B, Groetz KA, Goetz H, Duschner H, Wagner W. Comparative histomorphometry and resonance frequency analysis of implants with moderately rough surfaces in a loaded animal model. *Clin Oral Implants Res* 2007: **18**: 1–8.
4. Al-Nawas B, Hangen U, Duschner H, Krummenauer F, Wagner W. Turned, machined versus double-etched dental implants *in vivo*. *Clin Implant Dent Relat Res* 2007: **9**: 71–78.
5. Andersson P, Verrocchi D, Viinamäki R, Sennerby L. A one-year clinical, radiographic and RFA study of Neoss implants. *Appl Osseointegration Res* 2008: **6**: 23–26.
6. Aparicio C, Lang NP, Rangert B. Validity and clinical significance of biomechanical testing of implant ⁄ bone interface. *Clin Oral Implants Res*. 2006: **17**: 2–7.
7. Attard NJ, Zarb GA. Immediate and early implant loading protocols: a literature review of clinical studies. *J Prosthet Dent* 2005: **94**: 242–258.
8. Balleri P, Cozzolino A, Ghelli L, Momicchioli G, Varriale A. Stability measurements of osseointegrated implants using Osstell in partially edentulous jaws after 1 year of loading: a pilot study. *Clin Implant Dent Relat Res* 2002: **4**: 128–132.
9. Balshi SF, Allen FD, Wolfinger GJ, Balshi TJ. A resonance frequency analysis assessment of maxillary and mandibular immediately loaded implants. *Int J Oral Maxillofac Implants* 2005: **20**: 584–594.
10. Barewal RM, Oates TW, Meredith N, Cochran DL. Resonance frequency measurement of implant stability *in vivo*

on implants with a sandblasted and acid-etched surface. *Int J Oral Maxillofac Implants* 2003: **18**: 641–651.

11. Becker W, Sennerby L, Bedrossian E, Becker BE, Lucchini JP. Implant stability measurements for implants placed at the time of extraction: a cohort, prospective clinical trial. *J Periodontol* 2005: **76**: 391–397.
12. Bischof M, Nedir R, Szmukler-Moncler S, Bernard JP, Samson J. Implant stability measurement of delayed and immediately loaded implants during healing. *Clin Oral Implants Res* 2004: **15**: 529–539.
13. Esposito M, Hirsch JM, Lekholm U, Thomsen P. Biological factors contributing to failures of osseointegrated oral implants. I. Success criteria and epidemiology. *Eur J Oral Sci* 1998: **106**: 721–764.
14. Fischer K. On immediate ⁄ early loading of implant-supported prostheses in the maxilla. Thesis, Sweden: Gothenburg University, 2008.
15. Fischer K, Bäckström M, Sennerby L. Immediate and early loading of oxidized tapered implants in the partially edentulous maxilla. A one-year prospective clinical, radiographic and resonance frequency analysis study. *Clin Implant Dent Relat Res* 2008: in press
16. Fischer K, Stenberg T, Hedin M, Sennerby L. Five-year results from a randomized, controlled trial on early and delayed loading of implants supporting full-arch prostheses in the edentulous maxilla. *Clin Oral Implants Res* 2008: in press
17. Friberg B, Sennerby L, Linden B, Gröndahl K, Lekholm U. Stability measurements of one-stage Brånemark implants during healing in mandibles. A clinical resonance frequency study. *Int J Oral Maxillofac Surg* 1999: **28**: 266–272.
18. Friberg B, Sennerby L, Meredith N, Lekholm U. A comparison between cutting torque and resonance frequency measurements of maxillary implants. A 20-month clinical study. *Int J Oral Maxillofac Surg* 1999: **28**: 297–303.
19. Fröberg KK, Lindh C, Ericsson I. Immediate loading of Brånemark System Implants: a comparison between TiUnite and turned implants placed in the anterior mandible. *Clin Implant Dent Relat Res* 2006: **8**: 187–197.
20. Gedrange T, Hietschold V, Mai R, Wolf P, Nicklisch M, Harzer W. An evaluation of resonance frequency analysis for the determination of the primary stability of orthodontic palatal implants. A study in human cadavers. *Clin Oral Implants Res* 2005: **16**: 425–431.
21. Glauser R, Lundgren AK, Gottlow J, Sennerby L, Portmann M, Ruhstaller P, Hämmerle CH. Immediate occlusal loading of Brånemark TiUnite implants placed predominantly in soft bone: 1-year results of a prospective clinical study. *Clin Implant Dent Relat Res* 2003: **5**: 47–56.
22. Glauser R, Portmann M, Ruhstaller P, Lundgren AK, Hämmerle C, Gottlow J. Stability measurements of immediately loaded machined and oxidized implants in the posterior maxilla. A comparative study using resonance frequency analysis. *Appl Osseointegration Res* 2001: **2**: 27–29.
23. Glauser R, Sennerby L, Meredith N, Rée A, Lundgren A, Gottlow J, Hämmerle CH. Resonance frequency analysis of implants subjected to immediate or early functional occlusal loading. Successful vs. failing implants. *Clin Oral Implants Res* 2004: **15**: 428–434.
24. Huwiler MA, Pjetursson BE, Bosshardt DD, Salvi GE, Lang NP. Resonance frequency analysis in relation to jawbone characteristics and during early healing of implant installation. *Clin Oral Implants Res* 2007: **18**: 275–280.
25. Ito Y, Sato D, Yoneda S, Ito D, Kondo H, Kasugai S. Relevance of resonance frequency analysis to evaluate dental implant stability: simulation and histomorphometrical animal experiments. *Clin Oral Implants Res* 2007: **18**: 1–6.
26. Ivanoff CJ, Sennerby L, Lekholm U. Reintegration of mobilized titanium implants. An experimental study in rabbit tibia. *Int J Oral Maxillofac Surg* 1997: **26**: 310–315.
27. Lekholm U, Zarb GA. Patient selection and preparation. In: Brånemark PI, Zarb GA, Albrektsson T, editors. *Tissue-integrated prostheses: osseointegration in clinical dentistry*. Chicago: Quintessence, 1985: 199–209.
28. Meredith N. Assessment of implant stability as a prognostic determinant. *Int J Prosthodont* 1998: **11**: 491–501.
29. Meredith N, Alleyne D, Cawley P. Quantitative determination of the stability of the implant-tissue interface using resonance frequency analysis. *Clin Oral Implants Res* 1996: **7**: 261–267.
30. Meredith N, Book K, Friberg B, Jemt T, Sennerby L. Resonance frequency measurements of implant stability *in vivo*. A cross-sectional and longitudinal study of resonance frequency measurements on implants in the edentulous and partially dentate maxilla. *Clin Oral Implants Res* 1997: **8**: 226–233.
31. Meredith N, Shagaldi F, Alleyne D, Sennerby L, Cawley P. The application of resonance frequency measurements to study the stability of titanium implants during healing in the rabbit tibia. *Clin Oral Implants Res* 1997: **8**: 234–243.
32. Miyamoto I, Tsuboi Y, Wada E, Suwa H, Iizuka T. Influence of cortical bone thickness and implant length on implant stability at the time of surgery – clinical, prospective, biomechanical, and imaging study. *Bone* 2005: **37**: 776–780.
33. Nedir R, Bischof M, Szmukler-Moncler S, Bernard JP, Samson J. Predicting osseointegration by means of implant primary stability. *Clin Oral Implants Res* 2004: **15**: 520–528.
34. Nkenke E, Hahn M, Weinzierl K, Radespiel-Tröger M, Neukam FW, Engelke K. Implant stability and histomorphometry: a correlation study in human cadavers using stepped cylinder implants. *Clin Oral Implants Res* 2003: **14**: 601–609.
35. O'Sullivan D, Sennerby L, Meredith N. Measurements comparing the initial stability of five designs of dental implants: a human cadaver study. *Clin Implant Dent Relat Res* 2000: **2**: 85–92.
36. Olsson M, Urde G, Andersen JB, Sennerby L. Early loading of maxillary fixed cross-arch dental prostheses supported by six or eight oxidized titanium implants: results after 1 year of loading, case series. *Clin Implant Dent Relat Res* 2003: **5**: 81–87.
37. Östman PO. Immediate ⁄ early loading of dental implants. Clinical documentation and presentation of a treatment concept. *Periodontol 2000* 2008: **47**: 90–112.
38. Östman PO, Hellman M, Sennerby L. Direct implant loading in the edentulous maxilla using a bone density-adapted surgical protocol and primary implant stability criteria for inclusion. *Clin Implant Dent Relat Res* 2005: **7**: S60–S69.
39. Östman PO, Hellman M, Sennerby L. Occlusal loading of implants in the partially edentate mandible: A prospective 1-year radiographic and 4-year clinical study. *Int J Oral Maxillofac Implants* 2008: in press

40. Östman PO, Hellman M, Wendelhag I, Sennerby L. Resonance frequency analysis measurements of implants at placement surgery. *Int J Prosthodont* 2006: **19**: 77–83. Discussion 84.
41. Rao W, Benzi R. Single mandibular first molar implants with flapless guided surgery and immediate function: preliminary clinical and radiographic results of a prospective study. *J Prosthet Dent* 2007: **97**: S3–S14.
42. Rasmusson L, Meredith N, Cho IH, Sennerby L. The influence of simultaneous versus delayed placement on the stability of titanium implants in onlay bone grafts. A histologic and biomechanic study in the rabbit. *Int J Oral Maxillofac Surg* 1999: **28**: 224–231.
43. Rasmusson L, Meredith N, Kahnberg KE, Sennerby L. Stability assessments and histology of titanium implants placed simultaneously with autogenous onlay bone in the rabbit tibia. *Int J Oral Maxillofac Surg* 1998: **27**: 229–235.
44. Rasmusson L, Meredith N, Kahnberg KE, Sennerby L. Effects of barrier membranes on bone resorption and implant stability in onlay bone grafts. An experimental study. *Clin Oral Implants Res* 1999: **10**: 267–277.
45. Rasmusson L, Meredith N, Sennerby L. Measurements of stability changes of titanium implants with exposed threads subjected to barrier membrane induced bone augmentation. An experimental study in he rabbit tibia. *Clin Oral Implants Res* 1997: **8**: 316–322.
46. Rompen E, DaSilva D, Lundgren AK, Gottlow J, Sennerby L. Stability measurements of a double-threaded titanium implant design with turned or oxidised surface. *Appl Osseointegration Res* 2000: **1**: 18–20.
47. Sennerby L, Meredith N. Resonance frequency analysis: measuring implant stability and osseointegration. *Compend Contin Educ Dent* 1998: **500**: 502.
48. Sennerby L, Persson LG, Berglundh T, Wennerberg A, Lindhe J. Implant stability during initiation and resolution of experimental periimplantitis: an experimental study in the dog. *Clin Implant Dent Relat Res* 2005: **7**: 136–140.
49. Sennerby L, Roos J. Surgical determinants of clinical success of osseointegrated oral implants. A review of the literature. *Int J Prosthodont* 1998: **11**: 408–420.
50. Shalabi MM, Wolke JG, Jansen JA. The effects of implant surface roughness and surgical technique on implant fixation in an *in vitro* model. *Clin Oral Implants Res* 2006: **17**: 172–178.
51. Sjöström M, Lundgren S, Nilson H, Sennerby L. Monitoring of implant stability in grafted bone using resonance frequency analysis. A clinical study from implant placement to 6 months of loading. *Int J Oral Maxillofac Surg* 2005: **34**: 45–51.
52. Sjöström M, Sennerby L, Nilson H, Lundgren S. Reconstruction of the atrophic edentulous maxilla with free iliac crest grafts and implants: a 3-year report of a prospective clinical study. *Clin Implant Dent Relat Res* 2007: **9**: 46–59.
53. Sullivan DY, Sherwood RL, Collins TA, Krogh PH. The reverse-torque test: a clinical report. *Int J Oral Maxillofac Implants* 1996: **11**: 179–185.
54. Turkyilmaz I, Sennerby L, McGlumphy E, Tözüm TF. Biomechanical aspects of primary implant stability: A human cadaver Study. *Clin Implant Dent Relat Res* 2008: in press
55. Turkyilmaz I, Sennerby L, Tumer C, Yenigul M, Avci M. Stability and marginal bone level measurements of unsplinted implants used for mandibular overdentures: a 1-year randomized prospective clinical study comparing early and conventional loading protocols. *Clin Oral Implants Res* 2006: **17**: 501–505.
56. Turkyilmaz I, Sennerby L, Yilmaz B, Bilecenoglu B, Ozbek EN. Influence of defect depth on RFA and insertion torque values for implants placed in fresh extraction sockets. A human cadaver study. *Clin Implant Dent Relat Res* 2008: in press
57. Valderrama P, Oates TW, Jones AA, Simpson J, Schoolfield JD, Cochran DL. Evaluation of two different resonance frequency devices to detect implant stability: a clinical trial. *J Periodontol* 2007: **78**: 262–272.
58. Vanden Bogaerde L, Rangert B, Wendelhag I. Immediate/early function of Brånemark System Ti Unite implants in fresh extraction sockets in maxillae and posterior mandibles. An 18-month prospective clinical study. *Clin Implant Dent Relat Res* 2005: **7**(suppl. 1): 121–130.
59. Veltri M, Balleri P, Ferrari M. Influence of transducer orientation on Osstell stability measurements ofosseointegrated implants. *Clin Implant Dent Relat Res* 2007: **9**: 60–64.
60. Zix J, Kessler-Liechti G, Mericske-Stern R. Stability measurements of 1-stage implants in the maxilla by means of resonance frequency analysis: a pilot study. *Int J Oral Maxillofac Implants* 2005: **20**: 747–752.