STABILITY OF IMPLANTS PLACED AT SITES TREATED WITH BONE ALLOGRAFT

by

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ABSTRACT

Objective:

A retrospective chart review was performed to assess the stability of implants in a variety of clinical situations, including placement at sites with a history of bone augmentation using bone allograft.

Methods:

The study included 286 implants placed by an experienced practitioner and by Graduate Periodontics residents at the University of British Columbia. Implants included a variety of Nobel Biocare, Straumann, and Astra Tech designs. The Osstell ISQ device was used to measure implant stability (RFA) by emitting magnetic pulses that cause a SmartPeg attached to the implant to resonate according to the stability of the implant. Results were displayed in Implant Stability Quotient (ISQ) units and were recorded in triplicate, from the buccal, lingual, mesial, and distal. Measurements obtained at second surgery were compared with factors related to bone grafting, as well as patient demographics, implant site, and physical implant characteristics (significance $p<0.05$).

Results:

The overall implant survival rate was 98.9% with 3 implant failures. There was good reproducibility of measurements taken in triplicate and measurements taken from the buccal were significantly lower than those taken from either the mesial or distal. A significantly higher ISQ was obtained in the mandible than the maxilla, with significantly lower values at incisor sites compared with both premolar and molar sites. A higher ISQ was obtained for short implants and this reached statistical significance in the mandible, where shorter implants tended to be wider. Significantly lower ISQ values were obtained for narrow implants in both arches. ISQ values in soft bone were significantly lower, as were values at sites with a

history of lateral ridge augmentation using xenograft. No significant difference was observed between ISQ and age, gender, Type 2 diabetes, smoking, implant type, insertion torque, buccal bony dehiscence, surgeon's level of experience, or whether the site had a history of lateral ridge augmentation, socket preservation, or sinus lifting.

Conclusions:

Implant stability, as measured using the Osstell ISQ device, is not significantly affected by a history of bone grafting using bone allograft. Stability is, however, affected by implant dimensions, implant site, and bone density.

PREFACE

The Clinical Research Ethics Board (the University of British Columbia) approved the present study (Approval number H10-00464).

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1. INTRODUCTION

Dental implants are a common treatment option to replace missing teeth and have been shown to have a high degree of predictability and clinical success. One of the key factors in implant success is achieving osseointegration with the surrounding bone[1, 2]. Establishment of osseointegration relates to the stability of implants, since stable implants have been shown to have increasing bone-to-implant contact over a 9-month period, whereas unstable implants showed no true osseointegration[3]. Several methods are available to measure implant stability clinically, including insertion torque, reverse torque, radiography, percussion, damping capacity assessment and resonance frequency analysis (RFA). RFA is a relatively new technology and was introduced commercially in 1994 as the Osstell device. Using this device, the implant stability is reported in Implant Stability Quotient (ISQ) units.

For successful implant therapy, an adequate bone volume is also needed. Exposed implant surfaces can increase the risk of recession, thus compromising esthetics and making proper oral hygiene more difficult[1]. In order to achieve this, bone augmentation may be performed prior to, or in conjunction with, implant placement. A variety of graft materials are available to perform bone augmentation, including autogenous bone, allograft, xenograft, and alloplast.

Very few studies have specifically investigated the impact of bone augmentation on implant stability, as measured by RFA. Further, the majority of the studies have included only autogenous bone and these have generally reported no significant difference in ISQ from non-grafted sites[4-6]. Bone allograft is another common product used prior to implant placement but no studies have compared ISQ values of sites grafted with bone allograft with non-grafted sites. The primary objective of the present study was to measure the effect of bone augmentation using bone allograft on implant stability (ISQ values). Secondary objectives included evaluation of other clinical, implant- or patient-related factors, which may impact implant stability, as measured with RFA.

2. REVIEW OF THE LITERATURE

2.1 Measurement of Implant Stability

Ostman et al (2006) [7] defines implant stability as the "capacity to withstand loading in the axial, lateral, and rotational directions." The result of any test of stability therefore depends on the direction in which the force is applied[8]. Resonance frequency analysis, for example, reflects the lateral stability, which is thought to mimic normal bending forces on dental implants[7]. In contrast, reverse torque is a measure of shear force[8]. Implant stability is described as primary or secondary. Primary stability relates to the level of bone contact[9], which is influenced by the shape of the implant, the surgical technique, and the quantity and quality of the bone[10-12]. Bone quality involves mechanical physiologic properties, including the bone density, hardness, and stiffness, as well as the bone's capacity for healing and regeneration[10]. Secondary stability results from contact of woven bone and then lamellar bone with the implant[9] and is affected by primary stability, bone remodeling and implant surface characteristics[12]. Secondary stability influences the time of functional loading[12] and is necessary to facilitate stress distribution during loading[13]. Implant stability is expected to be at its lowest several weeks after implant placement, at which time secondary stability begins to increase[12]. The healing pattern, however, depends on many factors so implant stability shows considerable inter-individual variation[12].

Lioubavina-Hack et al (2006) [3] investigated the significance of initial (primary) stability for implant osseointegration in the mandibular ramus of 16 rats. One side had implant placement that ensured primary stability but the other side did not achieve primary stability and implants were easily movable. The animals were sacrificed at 1, 3, 6, and 9 months for histometric analysis. The stable implants showed increasing bone-to-implant contact (BIC) over the observation period, from 28.1% at 1 month to 69.6% at 9 months. Although peri-implant bone formed around the mobile implants, histology showed that there was no actual osseointegration of the implants. The results indicated that achievement of primary stability is essential for successful osseointegration. When the implants did not have primary stability, the histologic evaluation showed a layer of connective tissue between the bone and implant.

Several methods have been used to measure implant stability and osseointegration but the clinical usefulness of many testing modalities is limited due to their destructive or technique-sensitive nature. Some methods that have been used, either in experimental studies or in clinical practice are the pull-out or push-out technique, insertion or removal torque, radiography, histology and histomorphometry, percussion, damping capacity assessment, and resonance frequency analysis.

2.1.1 Radiography

Radiographs are often used pre-operatively to assess the implant site and post-operatively to count the number of exposed threads above the bone level[14]. However, radiography has unreliable reproducibility and the radiograph must be taken at the exact same angle each time for comparison[15]. Standard radiography also does not allow assessment of the 3-dimensional structure of the bone, which could affect implant stability[13, 15], and does not provide information on demineralization until at least 40% of the bone mineral has been lost[12]. Further, buccal bone loss is likely to precede mesiodistal bone loss but is not visible on standard intraoral radiographs[12].

2.1.2 Insertion torque

Insertion torque has also been used to quantify bone density[16]. In this method, the torque needed to thread the implant site or place a self-threading implant is measured, thus providing an indication of the site's capacity for primary stability[14]. While this method provides information about bone density and is simple to use in clinical practice, it can only provide information at the time of implant placement[12].

2.1.3 Reverse and removal torque

Reverse torque refers to the application of torque in a reverse direction at the time of abutment connection, to ensure a minimum level of stability has been achieved[14] and to provide indirect information regarding the bone-implant contact area[12]. However, measuring reverse torque to assess osseointegration is potentially quite damaging to the interface between the implant and surrounding bone[17]. Rotational mobility may indicate incomplete healing of the bone surrounding the implant, rather than soft tissue encapsulation[14]. Additionally, the threshold torque value that should be used is unclear and is likely to depend on the bone density and implant-related factors[12].

Removal torque is an invasive test used in research and refers to the shear force needed to disrupt the bone-implant interface[18]. Removal torque depends on the bond strength between the implant and bone and also on the geometry and size of the implant, meaning that comparisons should not be made between different implant designs or dimensions[18].

There are a number of less invasive tools for assessment of the bone-implant interface. Some of these are based on measurement of the natural frequency of a system in resonance[12]. The displacement of the system can be initiated by steady-state waves or by a transient impulse force, and the response is detected and used to evaluate implant mobility[12]. Specific techniques include percussion, impact hammer methods (Periotest and Dental Mobility Checker), pulsed oscillation waveform, and resonance frequency analysis.

2.1.5 Percussion

A simple clinical tool is percussion of the implant to listen for a characteristic sound indicating stability, but this is quite subjective[17] and does not allow discrimination between extremes of stability[14]. In this method, the clinician listens for a clear ringing sound, indicating that the implant has osseointegrated or a dull sound indicating a lack of osseointegration[12].

2.1.6 Damping capacity assessment

The Periotest (Siemens, Bensheim, Germany) is an electronic instrument, which was designed to measure mobility of natural teeth. In this method, an 8 gram rod taps the implant 4 times per second for 4 seconds[19]. The contact time of the slug with the tooth relates to the tooth's mobility[17]. Results range from -8 (indicating stability) to +50 (indicating mobility). When this instrument is used for implants, rather than natural teeth, values typically have a narrow range (for example, -5 to +5 for ITI implants) [13, 17]. The low Periotest values (PTV) are not surprising, given the stiffness of the bone-implant interface compared with the periodontal ligament surrounding a tooth[17]. Further, the difference between implants placed in soft and dense bone has been shown to be less than 2 units[18]. Meredith and others have discussed how the Periotest can be technique sensitive, with differences found depending on the position and angle of the device, the height of the abutment, the jaw position, and the distance between the handpiece and the implant[15, 18, 20]. The Periotest has been widely used in experimental and clinical research but the prognostic value has not been determined[20]. Negative PTV indicate implant stability, whereas high positive values suggest a loss of stability and possible bone resorption. Unfortunately, PTV changes are delayed and occur once clinical changes have already taken place[20]. The sensitivity of PTV is therefore quite low but it does have a high specificity[20]. Clinical usefulness is limited to repeated measurements of a given implant and, considering there is no consensus on normal values and a range of PTV likely indicates stability, routine use of the Periotest is not justified[20].

Both the DMC and the Periotest are impact hammer methods, in which excitation is provided by an impact force to the implant. With the DMC, the transient force is generated by impact of a small hammer and the response is detected by a microphone[12]. It is possible, however, that the physical contact with the implant could damage the interface and interfere with osseointegration[12].

2.1.7 Pulsed oscillation waveform

Kaneco[21-23] has described another non-invasive method to assess the bone-implant interface. A high frequency mechanical vibration is transmitted to the implant through a transmucosal piezoelectric puncture needle and the resulting resonance is measured by another needle and displayed. The sensitivity of this method, however, has been questioned[17] and it is likely that results depend on the direction of loading[12, 18].

2.1.8 Resonance frequency analysis (RFA)

Clinical use of resonance frequency was developed by Neil Meredith and Peter Cawley **(http://www.osstell.com/about-us.aspx)** and introduced, in relation to implant stability, by Meredith in 1994[24]. In this method, a stainless steel or titanium transducer is screwed to the implant fixture. The transducer consists of a beam and two piezoceramic elements. A computer-generated sinusoidal signal with amplitude of 1 volt excites one of the elements, which causes the transducer to vibrate[17]. An extremely small bending force is transferred to the implant in order to mimic conditions of clinical loading[8]. The purpose of the second element is to receive and measure the response as resonance frequency (RF) [17, 18].

Meredith et al (1996) [17] used the following equation to describe the variables affecting RF. Based on the equation, it was expected that, with a transducer of constant length, bone loss or an increased effective implant length would result in decreased RF[25]. The stiffness of the surrounding bone would also impact the RF, with lower values obtained with lower stiffness[25]. The design of the transducer itself is the third factor influencing RF[8] but the torque with which the transducer is attached to the implant fixture has been shown to have an insignificant effect on RF values, once a moderate torque has been reached[25].

$$R_f = \frac{1}{2\pi}\sqrt{\frac{3EI}{l^3 m}}$$

R_f: resonance frequency (Hz)

l: effective length of the beam

m: mass of the beam(g)

E: Young's modulus (GNm^{-2})

I: moment of inertia

The potential of resonance frequency to measure changes at the bone-implant interface was tested by Meredith et al (1996) [17]. Nobelpharma implants of various lengths (7, 8.5, 10, 15, 18, and 20mm) and 3.75mm diameter were placed in an aluminum block at various depths to examine the effect of changes in exposed implant height. Resonance frequency was measured for each implant and was repeated 5 times for 3 implants to assess repeatability. Since it was expected that there would be a difference in stiffness of the system depending how tightly the screws were placed, an electronic torque controller was used to compare RF at different torques (10, 20, 32, and 45Ncm). To assess the sensitivity of the transducer to changes in stiffness, an implant was placed in a hole filled with polymethyl methacrylate (PMMA) and the RF was measured every 30 seconds during setting. Clinical use was also assessed by measuring the RF for 4 implants in one patient. It appeared that the length of the fixture had no effect on RF, as long as the same height was exposed above the aluminum block. A likely explanation for this finding was the use of a very stiff model system – an aluminum block with an epoxy adhesive. A statistically significant difference was, however, found between implants of the same length placed with varying heights of exposed fixture. Repeatability was better than 1% based on the 5 measurements taken for each of 3 implants. The experiment with PMMA indicated that the system was sensitive to changes in stiffness. Results from the torque experiment demonstrated that, as long as a torque of at least 10Ncm was used, the RF would not be significantly affected. These types of in vitro tests are simple and reproducible ways to analyze the effect of a change in system stiffness; however, the findings are not entirely transferable to bone[8]. The clinical test showed that the procedure was well-tolerated but the values were lower than those found in aluminum.

Disadvantages of this first-generation RFA system included the high cost and size/weight of the instrument, as well as the time needed to perform the test (over 1 minute) [8]. Heo et al (1998) [26], however, noted that measurements were simple and quick, taking less than one minute to attach, measure and remove the transducer for each implant. The second-generation RF instruments were connected to a computer, which programmed the frequencies and collected/stored data. Both this and the first-generation system were flawed in that each individual transducer had a different resonance frequency and the machines needed to be calibrated to a standard prior to comparing measurements[8]. Adjustments were also needed for implants with different abutment lengths and this was possible since there was a linear relationship between RF and abutment length[20].

The third-generation system (Osstell, Integration Diagnostics AB, Savedalen, Sweden) was introduced to address some of these concerns. This device was designed to be used chair-side, avoiding the cumbersome attachment of a computer, and was run on battery power[8]. Additionally, Osstell was pre-calibrated by the manufacturer to provide a measurement known as the Implant Stability Quotient (ISQ). The ISQ values are based on the stiffness (N/μm) of the system, which is composed of the transducer, the implant and the bone, and on the calibration of the transducer[9]. The ISQ is expressed in values ranging from 1 to 100, with a value of 1 indicating the lowest stability and a value of 100 indicating the highest stability[8]. These devices are available with transducers adapted for various implant designs so that ISQ values can be compared among systems[8]. With the third-generation system, it is still possible to transfer data to a computer.

A more recent version (Osstell Mentor) is magnetic and wireless. With this device, a metal peg (rod), with a magnet at its top, is screwed to the implant[8]. Magnetic pulses are sent from a computer, causing this Smart Peg to vibrate in two perpendicular directions. The ISQ is reported in two numbers – the higher number represents the direction that resulted in the highest RF, and the lower number represents the direction that gave lowest RF[8]. Therefore, if bone was missing on one side of the implant, application of the vibrations in this direction should lead to a low ISQ[8]. The newest Osstell device is called the Osstell ISQ Instrument. According to the manufacturer, this device provides a faster measurement, a more attractive design and reduced sensitivity to electromagnetic noise. A cow rib model was used to compare RF measurements taken with the Osstell Mentor and the Osstell ISQ devices[27]. No significant difference was found between the devices, however the inter-observer reliability was poor, meaning repeated measurements should be performed by the same examiner. This likely relates to differences in positioning of the probe or tightness of the Smartpeg[27]. One major drawback of all RFA devices is that they cannot be used on cemented restorations[28].

Valderama et al (2007) [29] conducted a clinical trial to determine whether electronic and magnetic RFA devices provided similar findings and whether they were able to detect changes in stability during healing. Seventeen patients were included and each received 2 Straumann implants. ISQ was measured at the time of implant placement, as well as at 1, 2, 3, 4, 5, 6, and 12 weeks. Electronic RFA was used first and recordings taken in triplicate. The Osstell Mentor was then used and three measurements were taken and averaged. Both methods were found to detect changes in stability over time and correlated well with each other. On average, the magnetic ISQ values were 8-12 units higher than the electronic ISQ values, meaning that the two devices should not be directly compared. The authors proposed that the difference was due to the design of the devices, with the electronic one screwed on top of the implant and the peg of the wireless magnetic device screwed inside the internal hex of the implant. Electronic RFA had less variance in repeated measurements than the magnetic device. There was more variability in measurements at earlier time points, which could indicate that an exact value is difficult to obtain when the stability is low, or that there is learning curve for the examiners. Alternately, the variance could indicate that the implant is displaced slightly each time the transducer is attached and tightened. Increased height of exposed implant above the marginal bone resulted in a significantly lower ISQ with the magnetic, but not with the electronic, device[29].

Tözüm et al (2010) [30] compared three devices designed to assess implant stability in human cadavers. These included the previous RFA with cable (Osstell), Osstell Mentor, and the Periotest. All teeth were extracted from eight dried human mandibles and thirty 11mm long tapered implants were placed into the premolar sockets. Circular vertical bone defects were created incrementally (0-5mm) to mimic different sized areas of peri-implant bone loss. Osstell, Osstell Mentor, and Periotest measurements were taken after implant placement, and after each incremental increase in defect size up to 5mm. ISQ measurements decreased significantly as defect size was increased, meaning that both RFA devices were capable of detecting peri-implant bone loss. The Periotest was less sensitive to detect these changes and could not distinguish mobility changes for 2, 3, and 4mm defects. The three devices were all found to have significant correlation. The RFA with cable consistently showed lower ISQs than the wireless version. The overall mean ISQ (including defect measurements) found with cable was 46.5 ± 1, compared with 57.8 ± 9 for the wireless device. It is important to acknowledge, however, that these results were obtained in non-vital cadaver bone and vital bone may produce different results.

A synthetic bone model was used to measure the repeatability of measurements taken with the Osstell[31]. Synthetic jawbones of high and low density were used and 12 different Brånemark System implants (Nobel Biocare, Göteborg, Sweden) were placed in each type. ISQ values were measured in triplicate and, to determine if there were differences between the transducers, the tests were repeated with a separate transducer. Once these transducers were sterilized, the measurements were repeated. A final test was done by securing various abutments on the fixtures and measuring ISQ at the abutment-level. The transducers were found to be interchangeable and the sterilization process did not reduce accuracy. In a study of 32 implants placed in dry human mandibles[32], Osstell measurements were repeated by 1 examiner at 2 separate occasions and then repeated a third time by another examiner to assess intra- and inter-observer reliability. The intra-observer reliability was fair-to-good and the inter-observer reliability was between fair-to-good and excellent. Nedir et al (2004) [33] calculated the repeatability of the RFA device as 1.14% with 38 repeat measurements. In this experiment, 84.2% of the measurements were either identical or within 1 ISQ unit and only 5.3% had a 3-unit difference. Reproducibility was also investigated by Lachmann et al (2006) [28], who placed 8 implants into blocks of bovine bone and used Osstell to determine the primary stability. Multiple measurements, taken after loosening and retightening the screws, did not lead to significantly different values. RF measurements were about 1% higher when a torque control instrument was used at 10 Ncm, compared to hand tightening, but this was considered clinically insignificant. Reliability of the Osstell was good and variations in repetitions did not exceed 2% of the overall range of measurements. Lachmann[28] also found a standard deviation below 2% of the overall mean, when implants were polymerized into acrylic blocks. This is similar to the 1% difference found by Meredith[34], Barewal[9], and Nedir[33].

2.2 Agreement Between RFA and Other Measurement Techniques

With all these possible measurement techniques, many studies have been conducted to compare results and assess their validity. RFA has been compared with histological and radiologic findings, as well as insertion or removal torque and the Periotest.

2.2.1 RFA versus histology

Inflammation around an implant eventually leads to loss of peri-implant bone and osseointegration; the final stage in this process of peri-implantitis is mobility, which corresponds to a loss of direct BIC[35]. Histomorphometry is considered to be the 'gold standard' for evaluating BIC[36]. While some studies have shown a correlation between ISQ values and histological BIC, others have failed to find such a correlation; this may be since bone stiffness is not necessarily reflective of the BIC, particularly because a thin layer of bone may not contribute significantly to implant stability[8].

Scarano et al (2006) [37] found a significant correlation between ISQ and BIC. They conducted a retrospective histological and histomorphometrical study of 7 implants, which had been retrieved after 6 months for various reasons, including nerve pathology, psychological reasons, malalignment, hygiene problems, and restorative difficulty. All were stable with no mobility and were clinically osseointegrated. Osstell was used to determine the ISQ and then implants were retrieved with a 5-mm trephine bur and processed for histology. Mean reported ISQ ranged from 69 to 81, with a statistically significant positive correlation between ISQ and BIC. Histomorphometric BIC was 58.6% in one implant with an ISQ of 69, 68.1% for three implants with an ISQ of 71, 73.2% in one implant with an ISQ of 74, 78.2% for one implant with an ISQ of 79 and 87.5% for one implant with an ISQ of 81. In 2007, Scarano et al[35] again compared ISQ (Osstell) with histological findings for 37 implants that were removed, this time due to failure. The mean ISQ for these failed implants was 37, and histological evaluation revealed that there was no bone in close contact with the implants. In fact, there was a statistically significant correlation between the ISQ and replacement of BIC with soft tissue-implant contact. Strnad et al (2008) [38] followed implants placed in the tibiae of 3 dogs, with ISQ values (Osstell) obtained at 0, 1, 3, 9, and 12 weeks, before sacrifice for histological analysis. The BIC and ISQ values were proportional to each other only during the first 5 weeks of the study.

Kunnekel et al (2011) [39] determined the ISQ for 10 implants placed in goat femurs, either tightly or with a lack of primary stability. The distance between the bone and implant surface was measured histomorphometrically and compared to the resultant ISQ value. A negative relationship was found, with the ISQ decreasing as the implant to bone distance increased. Implants with primary stability were found to have higher ISQ values than those placed without primary stability.

In contrast to these studies, which found a correlation between histological findings and ISQ, other investigators have found that RFA does not reflect changes in histological parameters. Schliephake et al (2006) [36] compared ISQs with histomorphometric data (BIC and volume density of peri-implant bone) obtained for 80 implants placed in dogs. There was no significant increase in ISQ from 1 to 3 months, despite a significant increase in bone volume density and BIC during this time. The authors questioned the validity of RFA and concluded that caution is needed when using RFA to determine implant stability. Abrahamsson et al (2009) [40] also failed to find correlations between histological parameters (BIC and bone density) and ISQ (Osstell), for 160 implants placed in the premolar region of 20 dogs and followed for up to 3 months. When interpreting the results from animal studies, it is important to consider that, whereas rabbits may show increased stiffness and RF values over time, dog mandibles tend to have higher initial stability and fewer changes over time[8].

Degidi et al (2010) [41] failed to find a correlation between ISQ (Osstell) and BIC in humans. Sixteen clinically stable implants that had been removed from the posterior mandible during the first 4-8 weeks of healing were assessed histomorphometrically. No statistically significant correlation was found between ISQ and mineralized BIC. Proposed reasons for the lack of correlation included the dynamic nature of bone healing and the two-dimensional nature of histology.

Ito et al (2008) [42] conducted 2 related experiments to investigate and explain the reported discrepancy between RFA and other parameters of implant stability. In a simulation experiment, an implant was placed in a box and fixed with small screws at different heights. RF values decreased when screws were loosened at the neck, but not the middle or apical regions, of the implant. A second experiment was conducted in the tibiae of mini-pigs who received a total of 24 implants. RF of each implant was measured and the animals were sacrificed at 1, 2, and 4 weeks to determine BIC. There was no significant correlation between overall BIC and RF values but, when only the neck of the implant was considered, the correlation between the BIC and RF values was stronger (although still not statistically significant). From these results, it was concluded that RF values are most affected by the BIC in the neck region of the implant.

2.2.2 RFA versus insertion torque

The relationship between cutting torque and RF was investigated by Friberg et al (1999) [16], who followed maxillary TiUnite Brånemark implants up to 1-year. There was a significant correlation between the patient mean torque and RF values, but only for the upper/crestal third of the implant and only for the initial RF readings. Turkyilmaz et al (2006) [43] also found a significant correlation between insertion torque and RF when 30 edentulous patients each had 2 Brånemark TiUnite implants placed in the anterior mandible. The mean ISQ (Osstell) at time of fixture placement was 74 and there was a statistically significant correlation between this value and the insertion torque (OsseoCare, Nobel Biocare AB, Göteborg, Sweden). Similarly, Tözüm et al (2008) [44] found a significant correlation when the ISQ (Osstell Mentor) was compared to maximum insertion torque for 12 implants placed in resin models. A significant correlation was, again, found with the wireless Osstell, when Kahraman et al (2009) [45] followed 42 implants placed in 13 subjects.

Becker et al (2006) [46] found that, for a 1-unit increase in insertion torque, the baseline ISQ increased by 0.3, and the 3-month ISQ decreased by 0.2. In other words, greater insertion torque led to reduced implant stability after 3 months. They suggested that this may be due to pressure necrosis when implants are overtightened in an undersized osteotomy site. Nkenke et al[47] also suggested that high insertion torque might cause microfractures or pressure necrosis of the surrounding bone and ultimately lead to failure. Al-Nawas et al[48] found that ISQ values at time of fixture placement were significantly higher for successful implants but this was not reflected in the insertion torque values.

Peri-implant bone levels were compared with implant stability parameters (RF and insertion torque) for 84 Neoss implants placed immediately after extraction of mandibular teeth in 6 human cadavers[49]. A statistically significant correlation was found between insertion torque (OsseoSet, Nobel Biocare AB, Göteborg, Sweden) and RFA, and both testing modalities were sensitive to changing marginal bone levels.

Several studies have investigated the relationship between insertion torque and RF, with bone density, as determined radiographically. In a series of related studies, Turkyilmaz et al[50-52] found significant correlations between the bone density (measured on CT scans), insertion torque, and ISQ (Osstell) values. In contrast, Akça et al (2006) [53] conducted a study of Straumann and Astra Tech implants, placed in human cadaver jaws, and found that the correlation between insertion torque and bone parameters (volume and micro-architecture), as determined using micro-computed tomography, was greater than that between ISQ and the bone parameters. It was suggested that insertion torque is a more sensitive test than RFA when considering biomechanical properties of the bone-implant interface.

Some investigators have found no significant correlation between RFA and insertion torque, including da Cunha et al (2004) [10] with single tooth Brånemark implants, Çehreli et al (2005 and 2009) [54, 55] with 2 human cadaver studies, and dos Santos et al (2009) [56], who sometimes even found dichotomous results, depending on the implant design. Karl et al (2008) [57] questioned the utility of insertion torque, however, since most implant protocols do not involve bone tapping. Further, the insertion torque only provides information at the time of implant placement, whereas RFA can be used to monitor changes in implant stability over time.

2.2.3 RFA versus radiography

For comparisons of radiographic parameters and ISQ values, the reported results are not consistent. Song et al (2009) [58] found strong correlations between RFA (Osstell Mentor) and the quality and thickness of the compact bone (cone beam computed tomography). Roze et al (2009) [59] also found a correlation between RFA and cortical bone thickness, but no other parameters, when implants placed in human cadavers were analyzed with micro-computed tomography (CT). Cortical thickness was, therefore, suggested as an important factor leading to implant stability, as the thickness of cortical bone was significantly higher in a specimen that displayed higher ISQ values. In a preliminary clinical trial of 10 patients[60], bone density (CT scan), ISQ (Osstell Mentor), tactile sense, and histological measurements of bone cores were obtained for 23 implants. There was a significant correlation between ISQ and tactile sense for male patients and between ISQ values, trabecular bone volume, and tactile sense for female patients. The authors concluded that CT measurements of bone density (in Hounsfield units) could be helpful in predicting primary stability, prior to implant placement.

Other investigators have found no correlation between various radiographic parameters and ISQ values. Huwiler et al (2007) [61] found no correlation when the bone volume density and trabecular nature (micro CT) of bone cores were compared to RF measurements (Osstell) taken up to 12 weeks. Yang et al (2008) [62] investigated the relationship between ISQ values and bone loss during early healing of 43 Nobel Biocare implant in 19 patients. RFA measurements were taken at the time of surgery and then weekly for 12 weeks. Values were compared to findings from periapical radiographs taken at surgery, and at 4, 8, and 12 weeks. No correlation was found between marginal bone loss and ISQ changes. Lachmann et al (2006) [63] reported that the change in bone height must be at least 2mm in order for the ISQ to show significant differences. Since the marginal bone resorption was only approximately 1.3mm in Yang's study, it is not surprising that no statistically significant changes were found in the ISQ values.

2.2.4 RFA versus removal torque

Removal torque measures the shear strength of the bone-implant interface and values for removal torque appear to vary with changes in implant shape and topography[64]. This test has been used in human cadaver or animal studies and is sometimes compared to RF values. While the relationship between these two tests is not fully understood, RFA provides a clear advantage in that it is non-invasive and can be used to monitor changes in stability over time[64].

The stability of implants placed in rabbit tibiae was monitored using RFA and removal torque[64]. There was no statistically significant difference in either test, regardless of bone coverage of the implants. The inability of the RFA to pick up on the newly formed bone may mean that the bone was not yet supporting the implant. The authors suggested that this could be due to the bone not contacting the implant, to the immaturity of the bone or to the magnitude of the change not being sufficient to be registered by RFA.

In other animal studies, where RFA was compared to removal torque and histological findings, increases in RF values have been reflected in greater bone formation at the bone-implant interface. In one study, Brånemark implants were placed bilaterally in the tibiae of 10 rabbits, in either grafted or un-grafted sites[65]. RF measurements were taken at 0, 4, 8, 16, and 24 weeks and then removal torque and histomorphometric analysis were performed. Both the removal torque and RF values were higher for implants placed in grafted bone. The increase in stability over time was attributed to bone formation and maturation at the bone-implant interface, as was observed histologically. In a similar rabbit study, where implants were placed either simultaneously with bone grafting or after 8 weeks of healing[66], the RF values for delayed implants were significantly higher at all times but the removal torque showed no significant difference. Higher RF values in the delayed group were supported by the histological finding of greater BIC in this group, at the coronal part of the implant, which appears to be the region with the greatest impact on RF. The difference between removal torque and RFA in studies such as these has been attributed to the fact that they measure different parameters - the stiffness of the bone-implant interface under bending forces for RFA, versus the shear strength of this interface for removal torque[65].

More recent studies have also failed to find a correlation between removal torque and RFA. Akkocaoglu et al (2005) [67] used RFA, as well as insertion and removal torques, to assess the stability of implants placed immediately into extraction sockets of premolars in four human cadavers. There was no statistically significant correlation between ISQ and insertion or removal torque. These same parameters, as well as radiography and histomorphometry, were used to evaluate the stability of implants placed in various bones of fresh human cadavers[68]. The ISQ values were similar for all bones but differences were noted for insertion and removal torques, as well as for the histomorphometric and radiographic measurements, meaning that the RFA was not as sensitive as the other tests. Brouwers et al (2009) [32] compared 16 tapered and 16 cylindrical implants, placed in dry human mandibles and, again, found a significant difference in removal torque but not ISQ.

2.2.5 RFA versus Periotest™

Sakoh et al (2006) [69] evaluated the primary stability of implants placed in fresh porcine iliac bone blocks, using various placement techniques. Several stability tests were conducted, including insertion torque, Periotest, RFA, and push-out testing (applying force to the apical end of the implant in an axial direction). A significant correlation was found for Periotest and insertion torque with the push-out test but no correlation was found between RFA and the push-out test. Additionally, RFA and Periotest were not able to detect differences that were found with insertion torque. The authors speculated that the inability of RFA to detect differences which were found with other testing modalities could be due to the fact that all implants had sufficiently high primary stability and RFA is not sufficiently sensitive to detect such small differences.

In contrast, Alsaadi et al (2007) [70] found a significant relationship between ISQ (Osstell Mentor), Periotest, and bone quality assessment (Lekholm & Zarb index) as well as between ISQ, Periotest, and the surgeons' subjective tactile sensation. Oh et al (2009) [71] also found a strong association between the Periotest and ISQ (Osstell Mentor), when 48 implants were placed in the posterior jaws of 4 dogs, with follow-up at 3 and 6 weeks. The rate of new bone formation was assessed histologically and both measurement devices were found to be effective at evaluating the level of osseointegration. At 6 weeks, the ISQ value had increased and the PTV had decreased, compared to the 3-week values – both of these changes indicate that the measurement devices correlated with the degree of osseointegration. Nkenke et al (2003) [72] found a higher correlation between RFA and histomorphometric parameters than between the Periostest and histomorphometry, when 48 implants were placed in 3 human cadavers. In particular, RFA correlated with the BIC on the oral aspect and with the height of the cortical crestal bone surrounding the implants. However, no significant differences were found in RF values between the maxilla and mandible, despite differences found for Periotest.

Zix et al (2008) [73] also compared the ability of Periotest and RFA to measure implant stability. Sixty-five edentulous patients received 213 Straumann implants. Osstell and Periotest measurements were both taken in triplicate. The average ISQ for all implants was 57.7 (range 23-73) and the average PTV was -5.1 (range +5 to -7.7). The two parameters showed a moderate correlation with each other. The Periotest appeared to be less precise than the Osstell, likely due to the susceptibility of the Periotest to technical variables; however, the authors did find the Periotest to be less expensive and easier to use than the Osstell. Lachmann et al (2006) [63] placed 4 implants in each of 2 blocks of bovine bone (class 2 and 3 bone) and found a statistically significant difference in mean stability between the blocks and a good correlation between the Osstell and Periotest values. In a related study[28], implants were polymerized into acrylic blocks and material was removed successively around the implants to simulate peri-implant bone loss of 0-9mm. The results obtained with the Periotest and Osstell devices were similar and showed linear correlation. The increasing loss of implant support was reflected in statistically significant changes in values for both tests. The Osstell was more precise than the Periotest, with a threshold of about 2-3mm. Merheb et al (2010) [74] found that neither test was very sensitive in identifying peri-implant bone loss, other than in the marginal region. Both devices were able to detect marginal bone loss of 2mm or greater during staged removal of bone around 32 implants in 6 human cadavers. Winter et al (2010) [75] performed a simulated experiment (finite element analysis) comparing the Osstell Mentor and Periotest and found that values correlated when no bone loss was present.

Considering their respective drawbacks, the decision about whether to use the Periotest or RFA could be based on the potential damage caused to the implant. Seong et al (2009) [76] found that repeated use of the Periotest could damage the bone-implant interface of implants placed in jawbones of human cadavers. Six RF measurements were taken for each implant and all indicated stable measurements. The Periotest was then used 9 times for each implant (3 times from the BL, MD, and axial direction) and some specimens showed values indicating increasing mobility as measurements were repeated. The authors caution against using the Periotest, particularly when repeated or in low-quality bone.

2.3 Variables Influencing Implant Stability and Resonance Frequency

A number of factors have been found to influence ISQ values. These are mainly related to the bone-implant interface, the distance from the transducer to the first bone contact, and the orientation of the transducer[8]. RFA is also affected by factors such as the characteristics of bone, implant morphology and implant surface treatments.

2.3.1 Transducer orientation

Meredith et al (1996) [77] found that RF measurements are affected by the orientation of the transducer. In a rabbit study[34], RF measurements were taken in both parallel and perpendicular directions. Clearer resonance peaks were obtained with the transducer perpendicular to the bone. In a synthetic bone model, Balshi et al (2005) [31] also found that the orientation of the transducer influenced the recorded ISQ value. Some of the measurements taken perpendicular to the ridge resulted in higher ISQ readings than the corresponding measurements taken in a parallel orientation. For this reason, the authors recommend maintaining the same orientation for all measurements.

Kramer et al (2005) [78] used serial ISQ values to monitor the stability of implants. ISQ values were significantly lower when the transducer was used in a bucco-lingual orientation, compared to a mesio-distal orientation. In the bucco-lingual direction, values increased from 66.0 at implant placement, to 67.4 at exposure, to 72.1 by 12 months. The corresponding values for the mesio-distal direction were 74.1, 75.4, and 79.9. The orientation of the transducer was found to have a large influence on the RF values measured with Osstell in a guinea pig model[79], with higher RF values obtained when the transducer was placed parallel to the long axis of the bone. Capek et al (2009) [80] used finite element analysis to investigate the effect of transducer orientation on RFA values obtained with Osstell. Results indicated that, if RFA measurements are taken with the transducer perpendicular to the alveolar crest, ISQ values are not changed significantly by a rotation of less than 30°, and the first resonance frequency is obtained. If, however the rotation is between 30° and 80°, the second resonance frequency is recorded. Similarly, if a parallel orientation is used then the deviation must be less than 10°.

The effect of transducer orientation was also assessed by Veltri et al (2007) [81], by measuring the ISQ (Osstell) of 55 clinically stable implants from the buccal, palatal, mesial and distal. Significant differences were found between measurements taken with a perpendicular or parallel orientation but no significant differences were found between buccal (61) and palatal (63), or between mesial and distal (both 71). When the transducer is oriented perpendicular to the bone crest, ISQ values appear to be up to 8-10 ISQ units lower than in a parallel orientation. As such, it has been recommended to standardize transducer orientation so that ISQ values can be compared. Fischer et al (2008) [82] also found a difference of about 10 ISQ units - with a buccal-palatal (perpendicular) transducer orientation, the early and delayed values were 56.7 and 56.2 versus with a mesial-distal (parallel) orientation, the values were 66.6 and 65.0. It was suggested that the lower ISQ value in the buccal-lingual direction was due thinner bone in this direction.

Park et al (2010) [83] conducted a prospective clinical trial to determine if it is necessary to take measurements from both the mesiodistal and buccolingual directions when using the wireless Osstell Mentor. Fifty-three patients were included, and received 71 implants in the posterior mandible. Two measurements were taken from each direction with the buccolingual measurements from the buccal and the mesiodistal measurements from the mesial. There were no significant differences between the buccolingual and mesiodistal measurements but there were significant differences between the ISQs representing the higher and lower values. This is supported by the claim that the peg vibration in this system is equal in all directions, with the higher and lower ISQ values representing the most and least stable directions[8]. The authors discuss the advantage of having both the upper and lower values with the Osstell Mentor, which may be more useful to detect a change in the ISQ pattern compared with having only one measurement. Ohta et al (2010) [84] also investigated the effect transducer orientation with the Osstell Mentor, using a pig cortical bone model and 6 measurements for each implant – parallel, perpendicular and at 45° to the smart peg, as well as parallel, perpendicular and 45° to the long axis of the bone. No significant differences were found between the different probe orientations. The authors discussed the limitations of the model system used and indicated that the shape and length of the model was different from human jaws. Similarly, Merheb et al[74] found no significant differences between measurements taken in the mesiodistal and buccolingual directions, using the Osstell Mentor. The manufacturer, however, recommends taking 2 measurements, with the probe perpendicular and parallel to the jaw line, to ensure that both the highest and lowest stability values are detected.

2.3.2 Bone density

Lekholm & Zarb (1985) [85] define type I bone as homogenous compact bone occupying nearly the entire jaw. Type II bone has a thick layer of compact bone surrounding a core of dense trabecular bone. Type III bone has a thin layer of cortical bone surrounding a core of dense trabecular bone. Type IV bone has a thin layer of cortical bone surrounding a core of low-density trabecular bone. Lower success rates have been reported for implants placed in type IV bone, which is often found in the posterior areas of the jaws[86]**.** In a prospective human clinical trial, Barewal et al (2003) [9] placed 27 posterior implants in 20 patients in order to monitor early healing. Bone was classified according to Lekholm and Zarb; 30% of the implants were placed in type 1, 37% in types 2 and 3 (combined due to difficulty distinguishing the types), and 33% in type 4 bone. RF (Osstell) was measured in triplicate at placement, 1, 2, 3, 4, 5, 6, 8, and 10 weeks. The lowest mean RF value was obtained at 3 weeks for implants placed in all types of bone and, at this time, implants placed in type 1 bone were significantly more stable than those placed in type 4 bone. Type 4 bone had the largest drop (8.6%) in RF value from baseline to 3 weeks but this was followed by a large increase from 3 to 10 weeks (26.9%). The low values for type 4 bone were not surprising, considering that most of the implant was surrounded by low-density bone. In contrast, there were no significant differences in stability for type 1 bone at any point. At 5 weeks, there were no longer any significant differences between groups.

Balshi et al (2005) [31] followed 344 immediately loaded Brånemark implants up to 90 days and found successful osseointegration with all 4 bone types. Significantly different ISQ values were obtained between types 2 and 3 and between types 3 and 4 bone but not between types 1 and 2 bone. Type 1 bone had the highest initial stability but also had the biggest decrease over the first 30 days. The ISQ of type 2 bone decreased initially and then returned to baseline values by 60 days. For type 3 bone, the return to baseline values took 90 days. The finding that implants placed in different bone qualities have similar RF values after a period of healing supports the idea that an extended period of healing is beneficial when implants are placed in less dense bone[86]. The stability of implants placed in the anterior mandible, however, has been shown to be similar over time, implying that maximal stability is reached at the time of fixture placement in this area[87].

Sençimen et al (2011) [88] used CT scanning software to classify bone at implant sites. ISQ values decreased for the first 21 days after implant placement, but by 60 days were shown to have increased to the initial placement values. The bone density, however, did not appear to impact the ISQ values at any stage up to 60 days post-placement.

Friberg et al (1999) [87] found significantly lower initial RF values for implants placed in soft and medium, compared to dense bone. The subsequent measurements (at abutment connection and 1 year), however, showed no significant differences between the groups, indicating that the stability of all implants equalized over time, regardless of bone density or initial stability. Sennerby et al (2010) [89] also found that, despite a significant correlation between bone quality and ISQ at placement and abutment connection, there was no longer a significant difference in ISQ for different bone densities at 1-year. Even at 12 weeks, Bischof et al[90] no longer found a difference in stability based on bone density, despite differences found at 0, 1, 2, 4, 6, 8, and 10 weeks. This was supported by Sim & Lang (2010) [91] who longitudinally monitored the stability of Straumann implants placed in the posterior jaws of 32 patients. Implants placed in types III and IV bone had similar ISQ readings (Osstell Mentor), which were significantly lower than those for type II bone at 0, 1, 2, 3, 4, 5, 6, and 8 weeks. At the end of the study, the difference was no longer significant.

Turkyilmaz et al (2008) [92], placed 300 implants in 111 patients and evaluated RF at implant placement, 6 and 12 months. Bone density was assessed from CT scans, and a significant correlation was found with ISQ value. In a similar study, Turkyilmaz et al (2008) [52] again found a statistically significant correlation between RF and bone density. Pre-operative CT determination of bone density was also significantly correlated with the ISQ of 24 implants placed in human cadaver mandibles[93]. Higher ISQ values were obtained in the anterior (mean 73.5), compared to the posterior (mean 66.8) and, again, this correlated with mean bone density.

In a study of 50 edentulous subjects, Miyamoto et al (2005) [94] found that there was a strong linear correlation between ISQ values (Osstell) and cortical bone thickness, as determined from pre-operative CT scans. The correlation between implant length and ISQ was weak, indicating that the effect of cortical bone thickness is greater than implant length. The importance of preserving the cortical bone during implant site preparation was further demonstrated by Andrés-Garcia et al (2009) [95], who measured the primary stability (Osstell Mentor) of implants placed in 15 cow ribs of intermediate bone quality. A standard drilling protocol was used, with or without eliminating the cortical bone using a countersink. Higher ISQ values were obtained when the cortical bone was maintained.

In a study where implants were placed in artificial jawbone models with different values of elastic modulus[96], Huang et al found that the elastic modulus of trabecular bone influences the ISQ (Osstell). This study used pig rib bone of two different densities, combined with three placement techniques: compaction, self-tapping and tapping. ISQ values were always higher in type 1 bone (thick cortical and dense cancellous bone) than type 2 bone (less cortical and loose cancellous bone). The compaction method had a slightly, but not statistically significantly, higher mean ISQ value than self-tapping. The lowest values were obtained with tapping. Finite element analysis was also used to evaluate the effect of bone quality surrounding the implant, and demonstrated higher ISQ values with greater bone density[97]. Hsu et al (2011) [98] placed implants in synthetic material designed to mimic bone with varying cortical thicknesses and trabecular strength. There was a strong correlation between the cortical thickness and the ISQ value, as well as the elastic modulus of the trabecular bone and the ISQ value. The authors suggest that this provides an argument for performing bone augmentation to increase the cortical thickness.

2.3.3 Implant site

Regional differences in stability are thought to be due to differences in bone density and ratios of cortical to trabecular bone[99]. In a study of 27 implants, Barewal et al (2003) [9] found that mean RF values were higher in the mandible at all time points (0, 1, 2, 3, 4, 5, 6, 8, and 10 weeks) and speculated that this was likely due to the higher density of the mandibular bone. In fact, no maxillary implants were placed in type 1 bone and 40% of maxillary implants were placed in type 4 bone (compared with 31% in the mandible). Balshi et al (2005) [31] also found a significantly higher mean ISQ for implants placed in the mandible at all time points (0, 30, 60, and 90 days). Becker et al (2005) [100] and Bogaerde et al (2010) [101] found a slight difference in ISQ values between the maxilla and the mandible. In Becker's study[100], 73 implants (57 maxillary and 16 mandibular) were placed in 52 patients. On average, the primary stability was 4 ISQ units higher in the mandible versus the maxilla but the difference was reduced by follow-up. No significant differences were found for anterior compared to posterior sites at either time point.

Bischof et al (2004) [90] found a mean initial ISQ value of 59.8 for mandibular implants, compared with 55.0 for maxillary, indicating a significant difference between the jaws. The final ISQ measurements were taken at 12 weeks and the difference between mandibular (63.9) and maxillary (57.9) implants was still significant. In comparing the initial and 12 week values, it can be seen that the increase was higher for the mandible (4.1) than the maxilla (1.9) and the timing of the increase was different between the jaws; for maxillary implants, the increase was moderate and became significant only after 12 weeks whereas for mandibular implants, the stability did not increase much over the first 4 weeks but showed a significant increase over baseline by 6 weeks. Horwitz et al (2007) [102] also found significantly higher secondary stability (12-month ISQ value) for mandibular implants (70.2 versus 64.1).

The ISQ values were measured for 905 Brånemark implants, placed in 267 patients[99]. The mean ISQ was higher in the mandible (71.4) than the maxilla (63.0), which was attributed to the lower quantity of stiff cortical bone in the maxilla. Although higher ISQ values were expected in the anterior, the opposite was found, with higher values in the posterior (68.7 versus 65.2). However, since the ISQ was higher for wide-platform implants (73.1), compared to regular- or narrow-platform implants (67.1), the difference between anterior and posterior implants was attributed to placement of more wide-diameter implants in the posterior.

Miyamoto et al (2005) [94] found a mean ISQ of 71.7 in the mandible and 63.5 in the maxilla. A significant difference between the arches was also found by Akca et al (2006) [53], when 6 Straumann and 6 Astra Tech implants were placed in a human cadaver. Mean mandibular ISQ was 82.8, versus 73.5 in the maxilla. The mean ISQ values for implants placed in maxillary incisor, premolar, and molar sites were 81, 75, and 73 for Straumann and 81, 69, and 62 for Astra Tech implants. The corresponding values for the mandible were 81, 81, and 83 for Straumann and 85, 86, and 81 for Astra Tech implants.

In contrast, Nkenke et al (2003) [72] and Alsaadi et al (2007) [70] found no significant differences in RF values between the maxilla and mandible. In one study[70], the mean ISQ values (Osstell Mentor) at placement and abutment connection were 67.8 and 72.0 in the maxilla, and 72.2 and 69.5 in the mandible. Although many studies have shown that the ISQ is higher in the mandible during the early healing stages, this study demonstrated that the difference decreases during the osseointegration process. It was suggested that the higher marrow content in the maxilla increases bone deposition[70]. Roze et al (2009) [59] also found no significant differences whether implants were placed in the mandible or maxilla but ISQ values were significantly higher for the posterior region of both arches (mean ISQ 63, range 56-65), compared with the anterior (mean ISQ 55, range 51-59). Karl et al (2008) [57] also found higher values in the posterior. ISQ (Osstell Mentor) was determined for 385 implants (181 patients) at fixture placement and after a period of healing (at least 12 weeks in the maxilla and 6 weeks in the mandible). The highest scores were obtained in the posterior mandible (76.0 initially, and 79.5 after healing) and the lowest in the anterior maxilla (69.4 initially, and 73.4 after healing).

Other studies have found higher ISQ values in the anterior. Seong et al (2008) [19] placed 28 implants placed in 4 human cadavers and found that mandibular implants had significantly higher initial stability (73.0 in the anterior and 71.0 in the posterior) than maxillary (66.5 in the anterior and 53.4 in the posterior). The difference between anterior and posterior values was only significant for the maxilla. It was noted, however, that all cadavers were male, with a mean age of 83 and were not representative of the population as a whole. Turkyilmaz et al (2009) [49] evaluated the stability of 84 implants placed in 6 human cadavers. Higher ISQ values were obtained in the anterior, with ISQ values being about 10 units higher than those in the posterior. Use of wider implants in the posterior was recommended to compensate for the reduction in density.

Yamaguchi et al (2008) [103] conducted a long-term evaluation of 328 implants placed in the posterior mandible of 113 patients. RF measurements (Osstell) were taken every year for 10 years. The implant success rate was 100% over the follow-up period. The mean ISQ value was 75.3 (range 66-83), indicating good stability. No significant differences in the pattern of ISQ changes were detected among the different bone qualities or quantities, and no significant differences were found between the sides, sites (second premolar, first molar, or second molar) or genders. Kahraman et al (2009) [45] also found no significant difference in stability between anterior and posterior regions.

2.3.4 Bone quantity and effective implant length

Several studies have used in vitro, animal, or cadaver studies to evaluate changes in RF values associated with incremental peri-implant defects. Meredith et al (1996) [77] placed Nobelpharma implants in each tibia of a rabbit, such that they engaged only one cortex and left threads exposed on one surface. One side was treated with a membrane as an attempt to enhance new bone formation. After 16 weeks of healing, RF measurements were taken and the animals were sacrificed. Histology showed a thin layer of mineralized tissue where the membrane had been placed, and this was supported clinically by a lack of thread exposure. The side that was not treated with the membrane had threads exposed and a lower RF value, indicating that RFA was useful to detect this difference.

Lachmann et al (2006) [28] placed Frialit Synchro implants in blocks of bovine bone and created incremental marginal bone defects around each implant. The reduction in stability was statistically significant but not linear. The particular model system used was not ideal to conduct this experiment, however, since the implants were not osseointegrated and the cortical layer was removed with the first couple of millimeters of bone removal. Similar results were obtained when implants were polymerized into acrylic blocks and material was removed successively around the implants to simulate peri-implant bone loss of 0-9mm[63]. The increasing loss of implant support was reflected in statistically significant changes in RF values, with a threshold of about 2mm for machined surface Brånemark implants and 3mm for Frialit 2 Synchro implants.

Detection of progressive peri-implant support loss was found by Tözüm et al[44] when 12 Swiss Plus tapered, screw-type micro-textured implants were placed in resin models with incremental defects of 0-5mm. For 3.7mm diameter implants, the ISQ dropped progressively from 72.6 at baseline to 69.8 with a 1mm defect and 57.2 for a 5mm defect. The corresponding decrease for 4.8mm implants was 76.5 to 74.5 and 63.4.

The effect of buccolingual bone width was assessed for forty implants placed in acrylic resin models[104]. Statistically significant decreases in ISQ were obtained when the width was reduced. Cautious interpretation of the results was advised since in vivo osseointegrated implants may respond differently than those in artificially created defects in acrylic[44].

Rasmusson et al (2001) [105] also found a correlation between BIC and RF values. Mandibular premolars were extracted in six dogs and 3 implants were placed bilaterally. One side had buccal defects to expose 3-4 implant threads and the opposite side served as a control. RF measurements were taken at the time of implant placement and 4 months later, prior to sacrifice. The sides with defects tended to have a lower initial stability but the difference was not statistically significant.

Sennerby et al (2005) [106] used RFA, radiography and histology to investigate alterations in the bone tissue and implant stability that occurred in response to peri-implantitis. Mandibular premolars were extracted in 4 dogs, followed by placement of 6 implants in each dog. After 3 months of healing, peri-implantitis was induced using cotton ligatures. Four weeks later, the dogs were treated with antibiotics and surgery then followed for an additional 25 weeks, at which time biopsies were obtained. A linear relationship was found between radiographic findings and RF values taken at 9 time points, from ligature placement to final examination. During the peri-implantitis period, there was a marked loss of marginal bone, which correlated with reduced RF values. After therapy, there was an increase in RF values, which followed histometric measurements indicating re-osseointegration. Since the RF value is determined by the bone-implant interface stiffness and the distance from the transducer to the marginal bone, it is likely that most of the change in RF value was due to marginal bone loss and an increase in the effective implant length. It was estimated that each millimeter of bone loss resulted in an RF value decrease of 413 Hz. The authors concluded that RFA was a sensitive technique that could be used to detect even small changes in marginal bone level. In a study using pig mandibles, Ohta et al (2010) [84] found significantly lower ISQ readings with each incremental increase in defect size; the average ISQ values for defects measuring 0, 1, 2, and 3mm were 77.3, 72.6, 67.3, and 63.0 respectively.

The threshold for changes in RF values was also investigated by Merheb et al[74]. Implants (n=32) were placed in 6 human cadavers and randomly assigned to different types of bony defects: marginal bone loss, peri-apical bone loss, and constant width or length dehiscences. Staged bone removal was done with repeated Osstell Mentor measurements. Significant differences were found after 2mm of marginal bone removal, 5mm of peri-apical bone removal, 180° of bone removal around the perimeter of 6-mm long dehiscences, and 10mm of bone removal for 3-mm wide dehiscences. The authors concluded that the Osstell was not very sensitive in identifying peri-implant bone loss, other than in the marginal region, where it was able to detect marginal bone loss of 2mm or greater.

Similar studies in human cadavers support the sensitivity of ISQ to detect changes in peri-implant bone level. For placement of Neoss implants at depths of 1-5mm, Turkyilmaz et al (2009) [49] found a marked decrease in ISQ (about 2.7 ISQ units per mm). This sensitivity to changing marginal bone levels is supported by manufacturer information that claims that a change of 3 ISQ/mm is expected if implants are placed in the same bone density. Tözüm et al (2010) [107] placed 30 MIS implants in fresh premolar extraction sockets of dried human mandibles. Circular vertical bone defects were created incrementally (0-5mm) to mimic different sized areas of peri-implant bone loss. ISQ measurements, taken with both Osstell and Osstell Mentor, decreased significantly as defect size was increased, meaning that both RFA devices were capable of detecting peri-implant bone loss.

For implants placed in human jaws, Tözüm et al (2008) [107] found a consistently negative correlation between RF values (Osstell) and marginal bone level changes. Similarly, Turkyilmaz et al (2006) [108] found a statistically significant correlation between stability and marginal bone resorption from baseline to 6 months, but not from 6 to 12 months. During the first 6 months, the decrease in ISQ value was due to a loss of marginal bone and an increase in effective implant length. After 6 months, bone formation appeared to balance out the loss of stability due to marginal bone loss. Within the limitations of these studies, it appeared that the Osstell devices were suitable to assess implant stability and decreased values were likely to indicate progressive peri-implant defects.

2.3.5 Healing time

In general, a high ISQ over time indicates maintenance of stability, and a reduction in ISQ indicates a loss of implant stability. In 1994, Meredith et al[24] used RF to measure the integration between implants and surrounding bone. Titanium implants were placed in the tibiae of 12 rabbits and monitored with the device at 1, 2, 3, 4, 8, and 12 weeks. An initial decrease from baseline to 1 week was noted, followed by a progressive mean increase of 1.5 kHz throughout the healing period. The initial decrease in stability, after implant placement, could have been due to lateral compression of the surrounding bone which may have caused microfractures or elastic adaptation, remodeling which reduced the stiffness of the implant-bone interface, or crestal bone loss or dehiscences which increased the effective implant length[109]. According to Meredith[18], primary stability is affected mainly by the BIC and compressive stresses of the bone-implant interface. Some degree of stress is beneficial to compress the bone surrounding the implant but, with excessive force, necrosis and ischemia of bone can occur.

Friberg et al (1999) [16] found the largest increase in mean RF value over time for implants with low initial RF values. Similarly, Cornelini et al (2004) [110] concluded that, when good primary stability is achieved, there is no further significant increase during the period of osseointegration. In 2005, Sjöström et al[6] found that, while implants with a low initial ISQ tended to increase in stability over time, those with a high initial stability showed decreasing ISQ values. In a multi-center prospective clinical trial of 52 patients[100], 73 implants were placed immediately following extraction. Implants with a higher initial ISQ had a slight decrease over time, whereas those with an initial ISQ <60 increased. The reduction in ISQ for implants with an initially high stability may relate to mechanical relaxation and possibly bone resorption since it is likely that these implants were placed at high torque values. These findings support the idea that all implants eventually reach a similar level of stability, regardless of the primary stability.

Balshi et al (2005) [31] investigated the stability of 276 immediately loaded Brånemark implants. ISQ values indicated a decrease in mean stability during the first month, from 70.4 at implant placement to 66.4 at 30 days. This was followed by an increase to 68.0 at 60 days and 68.8 at 90 days. Statistically significant differences were noted from baseline to 30 days and from 30 to 60 days, but not from 60 to 90 days. In general, results indicated that implants with high initial stability do not necessarily return to their initial values after a decrease in the early healing period. In contrast, implants placed with lower primary stability tend to return to, or even exceed, the initial values. The same tendency was found by Veltri et al[111], who took RFA measurements repeatedly for 50 Astra Tech implants placed in 8 edentulous maxillas. The mean ISQ (Osstell) values at second surgery (6 months), and 1 and 3 years were 65 (range 50-78), 66 (range 53-76), and 64 (range 53-77). No statistically significant differences were noted between the time points but this was likely related to measuring the ISQ only at second stage and later and not between placement and second stage, when the greatest changes were expected. There was a tendency for implants with a lower ISQ value at second surgery to show an increase at subsequent follow-up appointments, and for those with a higher initial ISQ value to show a decrease over time but this was not statistically significant.

Valderrama et al (2007) [29] took measurements with both the electronic and magnetic RFA devices. Both showed a similar pattern over time, with an initial decrease of about 3 units in the first 3-4 weeks, followed by a gain of about 5 (electronic) to 8 (magnetic) units by 12 weeks. When the implants with higher initial ISQ were compared with implants with a lower initial ISQ, it was found that the group with the higher initial stability showed more consistent readings with fewer fluctuations between time points. It was suggested that a lower initial stability could indicate a higher proportion of trabecular bone, which will remodel more quickly than dense cortical bone. All implants, however had similar ISQ readings by 12 weeks, regardless of their initial ISQ.

An initial decrease in ISQ after placement appears to be a common finding. For example, Froberg et al (2006) [112] noted a decrease in mean ISQ, for both Turned Brånemark and TiUnite (Nobel Biocare) implants, from about 67 at 10 days to 63 at 3 months. This was followed by a slight increase reaching about 64 by 18 months. Other studies, however, have detected a steady increase in stability over time, depending upon which time intervals ISQ measurements were obtained. The Neoss implant system was evaluated by following 218 micro-rough implants up to 1 year[89]. Mean ISQ values (Osstell Mentor) obtained at baseline, abutment connection, and 1 year were 73.7, 74.4, and 76.7, respectively. There was a statistically significant increase from baseline and abutment connection to 1-year. Bornstein et al (2009) [113] presented a case series of 56 mandibular Straumann implants, loaded after 3 weeks. The mean ISQ at placement was 74.3 (range 57-87). The ISQ then showed significant increases over baseline at all time points: 77.7 at week 3 (range 49-87); 77.9 at week 4 (range 51-86); 81.1 at week 7 (range 70-88); 82.2 at week 12 (range 73-89); and 83.8 at week 26 (range 72-91). A decreasing trend was not found in the early healing and this could be due to RFA being done only at baseline and 3 weeks. In a study of 32 Straumann tissue-level implants[91], ISQ values were found to increase continuously over the 12-week period, rising from an average of 65.1 at surgical placement to 73.2 at week 6 to 74.7 at week 12. Measurements taken at weeks 6, 7, and 12 were significantly higher than at baseline.

Similar patterns of ISQ values over the first 12 weeks of healing were found by Huwiler et al (2007) [61] and Han et al (2010) [114] with Straumann implants. RFA

(Osstell) measurements were taken for 24 Straumann SLA implants and, for 4.1mm diameter implants, the mean initial ISQ was 61.4 (range 55-74) [61]. The mean increased at 1 week (63.4) then decreased to 59.6 at 2 weeks and reached a low of 59.4 at 4 weeks. The value then increased linearly to reach 63.8 after 12 weeks. For 4.8mm diameter implants, mean initial ISQ was 63.3 (range 57-70). There was an increase at 1 week (64.6), then a decrease at 2 and 3 weeks reaching a low of 59.1, followed by an increase to about 62.3 from 4-6 weeks and to 67.9 by 12 weeks. The changes in ISQ value over time were not significant for either diameter implant. Han et al (2010) [114] placed 25 Straumann implants in 23 patients. The 4.1mm diameter SLA implants had a mean initial ISQ (Osstell Mentor) of 72.6 (range 64-78), which then decreased to a low of 69.9 at 3 weeks and 70.2 at 4 weeks, followed by a steady increase to 75.2 by 8 weeks and 76.5 by 12 weeks. The SLActive implants showed a similar pattern, with an mean initial ISQ of 75.7 (range 65.3-81.3), a low of 71.4 at 3 weeks and an increase to 76.2 by 8 weeks and 78.8 at the last measurement. Finally, the 4.8mm diameter implants had an initial mean ISQ of 74.4 (range 65.3-81.3), which decreased to 69.8 at 3 weeks, then increased to 76.9 at 8 week, with a final value of 77.8. Despite the consistency in the pattern of change in ISQ over time for all groups, the differences over time were not statistically significant since the mean ISQ values fell within the range of initial ISQ values. Because of the initial decrease in ISQ at 3-4 weeks and the recovery by about 8 weeks, the authors recommend measuring the ISQ at the time of surgery as well as at 3 weeks and 8 weeks to monitor implant stability and tissue integration.

ISQ values were obtained for 43 Nobel Biocare implants in 19 patients at baseline, and at 4, 8, and 12-weeks[62]. When all implants were considered, the corresponding mean ISQ values were 75.6, 75.7, 76.3, and 76.8. Although the mean value didn't change significantly, the ISQ in the maxilla increased significantly from 4 to 12 weeks (69.2 to 73.0). Zix et al (2005) [115] measured the RF values for successfully osseointegrated ITI implants in the maxilla. Implants were divided into 3 stages of restoration: those which were unloaded (n=41), loaded 12 months or less (n=31) or loaded longer than 12 months (n=48). All implants had been left to heal for at least 3 months before loading. The mean ISQ for all implants was 52.5 (range 40-68) and there was no significant difference between the 3 groups. The mean ISQ for the unloaded implants was 48.8 and those for implants loaded less than or greater than 12 months were 54.1 and 53.1, respectively. These results indicate that loaded implants have a slightly higher ISQ value than unloaded implants. The value of 52.5 should not be used to represent osseointegrated implants, however, since it includes measurements taken from implants in the early stages of healing. Farzad et al (2004) [116] treated 34 patients with 105 Brånemark implants, placed in mandibular premolar and molar sites. These implants were used to support 40 fixed partial dentures (FPD) and, after 2-6 years, the prostheses were removed to measure the RF. Only one implant didn't survive to follow-up. The mean ISQ was 70.1 (range 59-90), indicating good stability had been achieved after 2-6 years. The mean ISQ was significantly higher when FPDs were supported by 3 implants (70.9), rather than 2 implants (67.9).

2.3.6 Patient characteristics: age, gender, and nicotine

Turkyilmaz et al (2006) [50] found that bone density and insertion torque were strongly correlated with ISQ values, and were significantly higher in men and in older patients. The age difference was attributed to the fact that older patients receive more implants in the anterior mandible compared to younger patients, who tended to receive implants in posterior areas. The gender differences were attributed to hormonal differences, rather than implant site distribution or patient age. For 42 self-tapping implants placed in 13 subjects[45], primary stability was also found to be significantly greater in patients older than 50, compared to those aged 19-50 but there was no significant difference in secondary stability. In a separate study of 30 patients who received mandibular overdentures, however, Turkyilmaz et al (2006) [43] did not find a statistically significant difference between genders and ages. The average ISQ at placement was 75.0 for males, compared with 73.3 for females. When patients were divided based on age, younger patients (average age 57) had a mean ISQ of 74.3, compared with 73.5 for older patients (average age 68).

Although statistical significance was not reached, it did appear that age and gender have an effect on insertion torque and ISQ values, with higher measurements in male and younger patients.

In a study of 276 Brånemark implants, Balshi et al (2005) [31] found that the initial ISQ value was lower for females but there was no significant difference after 30 days. Ostman et al (2006) [99] also obtained a higher mean ISQ for Brånemark implants placed in males (68.5 versus 66.5 for females), despite a similar distribution of other parameters (implant length, diameter, and surface treatment). Only one measurement was available for each patient, however, so no comparison over time was possible. Zix et al (2005) [115] also found that gender had a significant effect for ITI implants placed in the maxilla. There was a significantly lower stability in post-menopausal women (48.7) than in men of similar age (56.3). Similarly, Krhen et al (2009) [117] evaluated the 6-week ISQ values (Osstell) for 53 Standard Plus Straumann implants placed in 30 patients. Results showed a significant difference in ISQ between males and females (79 vs 72) but no significant correlations were found for patient age.

In contrast to these studies, Aksoy et al (2009) [60] found a mean ISQ of 72.3 for 10 patients who received a total of 23 implants. A significantly lower value was found in men (70.2), compared to women (77.6); however, it was noted that the sample size was quite small, and that female patients received more mandibular implants than male patients.

Balatsouka et al (2005) [118] used RF and removal torque testing to analyze the impact of systemic nicotine on the osseointegration of titanium implants placed in the femur and tibia of 16 rabbits. Animals received either subcutaneous nicotine or saline (control) for 2 months and 32 implants were placed after 4-6 weeks of exposure. RF was measured at time of placement and at time of sacrifice, 2 or 4 weeks after implant placement. No significant differences were found for either removal torque testing or RF values between the groups.

2.3.7 Implant dimensions

Several studies have shown that implant length has little influence on ISQ values. Barewal et al (2003) [9] conducted a clinical trial in 20 patients, where all implants were 4.1mm in diameter, 10 or 12mm in length, and placed in the posterior mandible or maxilla. ISQ values obtained up to 25 weeks demonstrated no significant differences in RF between implant lengths. Valderrama et al (2007) [29] also found implant length to have no bearing on stability values. It was suggested that the effect of an additional 2mm in implant length (from 8 to 10mm) is insignificant once marginal stability is established, particularly since the apical 2mm of the implant is typically surrounded by trabecular bone.

Sim & Lang (2010) [91] longitudinally monitored the stability of 4.1mm wide Straumann Standard Plus implants of different lengths and placed in various bone structures. Thirty-two patients were included and each received one 8- or 10-mm long implant in the posterior maxilla or mandible. Implant length appeared to have an effect on ISQ but the study was underpowered to determine clinical significance. The ISQ values obtained for 10mm implants were higher than those for the 8mm implants but there were large standard deviations. By 2 weeks, the groups had similar values and this trend continued with 8mm implants showing a significant increase and 10mm implants showing less significant changes. Bone structure was found to be a more important variable than implant length.

Bischof et al (2004) [90] also found that neither implant diameter, nor implant length affected the primary (baseline) or secondary (12 week) stability. Karl et al (2007) [57] found a significant correlation between implant length and ISQ value in the anterior mandible at insertion, and in the anterior and posterior mandible at follow-up. A significant correlation was also found between implant diameter and ISQ in the anterior mandible at insertion, and in all regions except the anterior maxilla after healing.

Pattjin et al (2007) [79] obtained slightly lower RF values for longer implants in bone with a high stiffness. This may be due to the fact that, for bone with such a high stiffness, an increase in the length of the implant does not further increase the stability. The authors concluded that ISQ values should not be interpreted in an absolute sense due to the influence of the type of anchoring (trabecular or cortical), the implant dimensions, and the bone stiffness. Friberg et al (1999) [16] found a significant correlation between the patient mean cutting torque and RF, but only for the crestal third of the implant and only for the initial RF readings. This finding explains why short and long implants have similar RF values. Ostman et al (2006) [99] found a higher ISQ for shorter implants. This was likely due to a modified design of the longer implants, with reduced diameter in the coronal area, which has the greatest effect on implant stability[16]. It is also possible that the reduction in ISQ value was due to more prolonged drilling times for longer implants.

The effect of implant diameter on ISQ is less clear. For ITI implants placed in the maxilla, Zix et al (2005) [115] found that diameter had a slight effect on ISQ, with standard (4.1m) implants having a greater ISQ value than either 3.3 or 4.8mm implants. In 2008, Zix et al[73] treated 65 edentulous patients with 213 Straumann implants, varying in length from 6 to 14mm. The average ISQ for all implants was 57.7 (range 23-73). There was no significant correlation with the implant length but there was with implant diameter.

A single regular or wide platform Southern implant, or Neoss regular diameter (4 mm) implant, was placed in the midline of 36 edentulous mandibles for an overdenture[119]. Primary stability was determined using Osstell Mentor. The mean ISQ values were 84.8 for the Southern wide implants, 82.3 for the Neoss regular width implants, and 75.3 for the Southern regular width implants. The value for the regular diameter Southern implant was significantly lower than that of the other 2 implants but no significant differences were found between the other implants. Another study[104] found that wider diameter implants showed a trend of higher ISQ values, for both MIS Seven and Tidal Spiral implants. Ohta et al (2010) [84] found a trend of higher ISQ values for wider implants but the differences did not reach statistical significance. Krhen et al (2009) [117] found a significant difference in ISQ values based on implant diameter (73 for 3.3mm, 80 for 4.1mm, and 67 for 4.8mm). However, the lower ISQ obtained for the 4.8mm diameter implants is based on a sample size of only 5.

Han et al (2010) [114] conducted a longitudinal assessment of Straumann implants to investigate the stability characteristics of implants with different surface treatments and diameters. Twenty-three patients received twenty-five 10mm long implants – 12 were SLA (sandblasted, acid etched) 4.1mm, 8 were SLActive (chemically modified sandblasted, acid etched) 4.1mm and 5 were SLA 4.8mm. ISQ values were taken with the Osstell mentor at baseline, 4 days, and 1, 2, 3, 4, 6, 7, and 12 weeks. The results for both diameters of implants (4.1 and 4.8mm) and both surface treatments (SLA and SLActive) were not significantly different and the authors concluded that implant diameter and surface treatment were not significant factors influencing ISQ readings.

Akkocaoglu et al (2005) [67] compared implants of various designs and diameters, placed immediately into premolar extraction sockets of cadavers: 4.1/4.8mm diameter ITI TE as well as 4.1mm and 4.8mm diameter screw synOcta ITI implants. The TE implants were designed for immediate placement, with a 4.8mm diameter neck and a 4.1mm diameter body to maximize surface area. The ISQ value of the TE implants was significantly higher than the 4.1mm diameter implants but similar to the 4.8mm implants. It was therefore concluded that it is the diameter at the neck of the implant that determines ISQ. It is possible that a regular diameter implant with good bone contact at the collar region may have a higher ISQ than a wider implant without such bone contact. Radiographic evaluation of BIC in this study supports this concept.

RF values were obtained 0, 3, 12, and 16 months after immediate loading of 105 expanded-platform Osseotite (Biomet 3i) implants[120]. These implants are based on the concept of platform switching, with the coronal aspect slightly wider than the straight-walled body, to result in greater engagement of the bone crest and improve primary stability. The mean 16-month ISQ (Osstell Mentor) values for 4mm- and 5mm- diameter implants were both about 76, indicating no significant difference based on implant width. Similarly, no significant differences in ISQ value were found for implants of length 8.5, 10 or 13mm.

2.3.8 Implant geometry and surface characteristics

Sul et al (2002) [121] used RFA and removal torque to evaluate bone response to implants with a wide range of oxide properties (thickness, pore configuration, crystal structure, chemical composition, and surface roughness). Turned implants were used as a control. Forty-eight implants were placed in the tibiae of 12 rabbits and followed for 6 weeks. Implants with an oxide thickness over 600nm had significantly higher removal torque values compared with thicknesses less than 200nm. There was a trend of increasing RF values as the thickness of the oxide layer increased but differences did not reach statistical significance.

In 2004, Sul et al[122] used RFA and removal torque to evaluate the integration of a calcium-incorporated oxidized implant in rabbit femurs. Ten rabbits each received one turned implant (control) and 1 test implant. Results after 6 weeks indicated a statistically significant improvement in osseointegration with the calcium-incorporated implants, compared with controls. At 6 weeks, the mean RF for the test implants was 69.4 (range 67-72) and for the control implants was 66.1 (range 63-73). The calcium-incorporated implants also had a significantly higher removal torque. Results indicate that the calcium composition of the implant surface may affect the implant's integration in bone. The authors suggest that this may have implications for immediate or early loading in compromised bone.

Göransson et al (2005) [123] used RF and histomorphometry to compare isotropic and anisotropic implant surfaces of similar roughness. Isotropic implants do not have any dominating direction of irregularities and are fabricated by blasting with titanium oxide particles of medium grain. Anisotropic turned implants were used as controls. Nine of each type of implant were placed in the femurs of 9 rabbits and followed for 12 weeks. RF values indicated that implant stability had increased significantly with time. There was no statistically significant difference in RF value or in any histomorphometric parameter between the two groups. In a study of 40 implants placed in acrylic resin models, Tözüm et al (2009) [104] found that MIS Seven implants, with more threads and a roughened surface, had higher ISQ values than Tidal Spiral implants that had fewer threads and a smoother surface.

In addition to the effect of implant texture, the surface chemistry is also thought to contribute to implant stability. Strnad et al (2008) [38] compared implants with a turned versus a modified biosurface (sandblasted, acid- and alkali-treated surface; Lasak), placed in the tibiae of 3 dogs. RFA values were taken at 0, 1, 3, 9, and 12 weeks (Osstell). The initial mean RF values were similar for turned and modified implants (74.5 verus 74.0). The modified group had no statistically significant changes in ISQ over time, whereas the turned group showed a significant decrease at 3 and 9 weeks with a return to a similar level as the modified implants by 12 weeks. Histological results indicated that the alkali-treated surface had faster bone formation, which enhanced the secondary stability. Cannizzaro et al (2007) [124] noted a different bone response when one Zimmer Spline self-tapping implant coated with crystalline hydroxyapatite (HA) was compared with other Swiss Plus (Zimmer Dental) implants. The HA-coated implant had the lowest ISQ value at baseline (53) but the highest value at 12-months (78); however it is important to note that this observation is based on only one HA-coated implant.

The stability of 6 different types of implants was compared by Al-Nawas et al[125]: Brånemark machined Mk III (minimally rough); oxidized TiUnite Mk III and Mk IV, ZL Duraplant Ticer, and Straumann SLA (moderately rough); and Straumann TPS (rough). A total of 196 implants were placed in 16 dogs and allowed to heal for 8 weeks before being loaded for 3 months. ISQ values were obtained at 3 months

(Osstell). The median ISQ value was above 60 for the Brånemark and ZL Ticer implants, but below 60 for the 2 Straumann implants. Histological analysis showed a benefit to rough surfaces, compared to minimally rough ones, but the RF values appeared to be largely influenced by the different transducers used and therefore could not be compared. Results for the various moderately rough surfaces demonstrated only minor differences.

Al-Nawas et al (2007) [126] performed a retrospective study of machined (Mk II, Nobel Biocare) and etched (3i, Implant Innovations Inc) implants, that were macroscopically very similar. No significant differences were found between the implants for survival, RF or PTV. The mean RF values were 64 and 63 for the turned and the etched implants, respectively. Fröberg et al (2006) [112] found no difference in ISQ between immediately loaded turned Brånemark and TiUnite implants placed in dense bone in the anterior mandible and followed up to 18 months. Schincaglia et al (2007) [109] also found no difference between turned and TiUnite implants at placement. A split-mouth study of 10 patients was conducted to compare immediate loading of fixed partial dentures supported by implants with either machined or TiUnite surfaces. The success rate for all implants was 95%, with no failures in the group that received TiO surface implants. There were no significant differences in radiographic bone level, peak insertion torque or ISQ values between the groups. The mean ISQ at baseline was 73.0 for machined implants and 74.0 for TiUnite. The ISQ values decreased after insertion, with the machined implants reaching their lowest value at 3 months and the TiUnite implants at 6 months. Stability was then regained until final measurement at 12 months. Ostman et al[7] found a slight difference between turned and oxidized Brånemark implants at baseline (74.6 and 71.8, respectively) but the difference decreased by 6 months (71.8 and 72.7). The slightly lower primary stability of the oxidized implants may have been due to grinding of the bone by the rough surface during placement, leading to a looser fit.

Sennerby et al (2005) [106] placed 6 ITI implants (3 SLA and 3 smooth surface) in each of 4 dogs. Ligature-induced peri-implantitis around the implants resulted in a greater decrease in stability for SLA implants (1,424 Hz), than for turned implants (1,266 Hz). During the healing phase, the increase in RF values was also greater for SLA implants (483 versus 238). The final RF values, however, were similar for the two types of implant – 5,099 Hz and 5,119 Hz. Abrahamsson et al[40] found a higher initial ISQ for SLA implants, compared to turned, but no significant difference at 12 weeks. Primary stability was achieved in all 160 implants (half SLA surface and half turned surface) placed in the premolar region of 20 dogs. Histological findings and RF measurements were similar for both groups initially. The BIC was nearly twice as high for the SLA implants by one week, and the difference between groups was statistically significant for all time points from 1 to 12 weeks. After 12 weeks, the mean ISQ was 58.6 for SLA implants and was similar to that of turned (59.9)

A randomized-controlled clinical trial of modified and standard SLA surface implants (Straumann Orthosystem), was conducted to determine the effect of these surface treatments on the stability of palatal implants placed for orthodontic anchorage[127]. Forty patients were treated and RF values obtained at 0, 7, 14, 21, 28, 35, 42, 49, 56, 70, and 84 days. There were no significant differences between the standard and modified SLA implants at baseline (73.8 versus 72.7) and both groups showed a slight decrease in ISQ over the first 2 weeks. The modified SLA implants showed increasing ISQ values after 28 days, which reached values similar to baseline at 42 days. For standard SLA implants, an increase in ISQ was seen at 35 days, reaching levels similar to baseline after 63 days. At 84 days (12 weeks), the ISQ was significantly higher for the modified SLA implants (77.8 versus 74.5).

Valderama et al (2007) [29] treated 17 patients with 34 implants in the posterior jaws. All implants were Straumann 4.1mm diameter and each patient was randomized to receive one SLA and one SLActive. The effect of implant surface on ISQ values was nearly significant for mandibular implants, with the SLActive implants being consistently more stable. The authors commented that it is possible that there truly is no difference in stability in the early phase of healing but it is also possible that the RFA device is not sufficiently sensitive to detect such small differences. It is also important to note that the study was not powered to compare stability between the two systems.

dos Santos et al (2009) [56] investigated the effect of implant design and surface treatment on primary stability. High molecular weight polyethylene cylinders were used in place of bone to isolate the effects of implant design from other confounding variables. Cylindrical and conical implants with 3 different surface finishes (anodized, acid-etched, or machined) were used. Surface treated implants were found to have higher insertion torque and ISQ values, compared to machined. Sul et al[128] evaluated different surface properties, by placing a variety of implants in 10 rabbit tibia and following with RFA (Osstell) for 6 weeks. Two oxidized, cation-incorporated experimental implants (magnesium-incorporated with or without micropatterns), and 4 commercially available implants (TiUnite, Osseotite, SLA, and TiOblast) were included. Baseline ISQ values were not significantly different among the various implants, other than being significantly lower for the magnesium-incorporated micropatterned implants. At 6 weeks, however, this group of implants had the highest ISQ values, suggesting that bone had grown into the micropatterned threads. At 6 weeks, all implant types had significantly greater ISQ values than at baseline. The surface-chemistry modified implants (both magnesium-incorporated implants, and TiUnite) had higher mean ISQ values than topographically changed etched and/or blasted implants (Osseotite, SLA, and TiOblast).

2.3.9 Implant design

An initial objective in the development of the RFA device was to enable clinical comparisons of different implant systems and designs[18] and a number of studies have used RFA for this purpose. However, Zix et al (2005) [115] noted that comparison of ISQ values between implant systems is not reliable. Brånemark implants tend to have a higher ISQ than the ITI implants and this is likely due to differences in design[115]. For example, differences in the diameter, materials, and tightness of components, can all impact the stiffness of the system[115]. Park et al (2012) [129] studied 81 implants placed in 41 patients. The implants placed either had an external design (Branemark, Nobel Biocare) or an internal design (ITI, Straumann) and the insertion ISQ value was significantly higher for the external-type implants. A possible explanation was given as the 3mm supracrestal shoulder present on the internal design implants used in this study. This would increase the effective length of the ITI implants, leading to lower RF compared with placement of the Brånemark implants at the bone level[9]. Kessler-Liechti et al (2008) [130] also recommends caution when comparing ISQ values between different implants. For example, an ISQ of 64 was found to represent a stable healthy value for Straumann implants supporting mandibular overdentures, whereas Balleri et al (2002) [131] found a mean ISQ of 73 after 1 year of loading of Brånemark mandibular implants.

Al-Nawas et al (2006) [48] placed 160 implants in 16 dogs, including 3 types of Brånemark (machined MKIII, TiUnite MkIII, and MkIV) and 2 types of Straumann (SLA and TPS). RFA was measured at implant placement, at 8 weeks, and after 3 months of loading. There was no significant difference in ISQ value between Brånemark and Straumann implants at time of placement. From fixture placement to loading, all implant systems displayed a significant decrease in median ISQ values but the decrease was smaller for Straumann implants. At study completion, high ISQ values were obtained for the self-tapping MkIII and MkIV implants but the non-self-tapping Straumann implants had significantly lower ISQ values after 3 months of loading. The authors believe, however, that the difference between implant designs may have more to do with the type of transducer than with the type of implant.

Ersanli et al (2005) [132] evaluated 3 types of implants: Xive (Dentsply, n=64), Camlog (n=28), and ITI (Straumann, n=30). ISQ values were obtained at the time of surgery, 3 and 6 weeks post-operatively, and 3 (mandible) or 6 months (maxilla) after surgery, at the time of loading. In general, the ISQ values for all implant types were higher for the mandible and the ISQ readings at 3 or 6 weeks were significantly lower than those obtained at baseline. For Xive implants, the decrease from placement to 6 weeks was significant for both arches. For Camlog implants, the decrease from baseline was significant for both 3 and 6 weeks and for both jaws. For ITI implants, the initial decrease was only significant at the 3-week measurement and only for the maxilla. Although the absolute baseline ISQ was lower for the ITI implants, the recovery period began at 3 weeks and, by the time of implant loading, the values for all implant types were approximately recovered to baseline levels. The authors concluded that RFA is useful to determine the healing phases and changes in stability of implants, but that ISQ values must be calibrated for each type of implant as a standardized range for all systems is unlikely.

Rabel et al (2007) [133] treated a group of 263 patients with random assignment to receive a total of 408 non-self-tapping Ankylos and 194 self-tapping Camlog implants. RFA at baseline and 3 months was available for 63 patients. The mean ISQ value for all implants at time of placement was 66.5 (67.9 for Ankylos and 64.4 for Camlog). At 3 months, the mean for all implants was 66.8 (66.5 for Ankylos and 67.3 for Camlog). Within each implant system, a correlation over time was found. The maximum insertion torque was significantly higher for the non-self-tapping Ankylos implants but the RFA did not detect any differences between the groups. The authors concluded that ISQ values should not be compared between different implant systems and that RFA should be used to monitor stability over time, rather than as a single measure to quantify implant stability.

Lang et al (2007) [134] compared the outcome of standard cylindrical screw-shaped and tapered transmucosal implants (Straumann), placed in extraction sockets. The transmucosal implants are root-shaped and designed to engage native bone in the apical part of the socket. This was a multicenter randomized, controlled clinical trial with a 3-year follow-up period; however, this report includes data only from the first 3 months. In total, 208 implants were placed and patients were randomly assigned to receive either the standard or the novel implant design. Most (84%) of the implants were placed in the maxilla. If there was over 1mm between the implant and the socket wall, simultaneous guided bone regeneration was performed. RF measurements (Osstell) were taken at implant placement and after 3 months. The mean initial ISQ values for the standard and tapered implants were 55.8 and 56.7, respectively, and increased to 59.4 and 61.1 after 3 months. No statistically significant differences were noted between the implants. The design of the novel implant was thought to reduce the need for bone augmentation and to provide increased primary stability due to the tapered design and decreased pitch of the threads. However, 90% of the implants in both groups required bone augmentation and there were no significant difference in stability.

Six Straumann (4.1 x 10mm, SLA) and 6 Astra Tech (4.0 x 9mm, TiO blast) implants were placed into each arch of a completely edentulous human cadaver[53]. The mean ISQ values for Straumann (79.0) and Astra Tech (77.3) implants were similar and no significant differences were found between the systems. Similarly, Kahraman et al (2009) [45] found no significant differences were between Straumann Standard Plus with sand-blasted, large-grit, acid-etched surface and MIS Seven implant with sand-blasted acid-etched surface.

Chong et al (2009) [135] placed 10 implants with self-tapping blades in the apical third (Biohorizons) and 10 without self-tapping blades (Nobel Biocare) in polyurethane blocks with different densities and at different depths. When non-self tapping implants were fully inserted in medium- or high-density blocks, the initial mean stability (Osstell Mentor) was significantly greater than that for self-tapping implants. When the implants were not fully inserted, however, there were no differences between the implant designs. The ISQ readings obtained in low-density blocks were unreliable and were excluded from analysis. Insertion depth showed the strongest association with ISQ value, followed by block density. Only a weak association was found for implant design, indicating that, if bone quality and quantity is optimal, the implant design is less important. The non-self tapping implant had a greater surface area, due to a higher number of threads, as well as a rough surface and an osteotomy protocol requiring fewer cutting burs. In contrast, the self-tapping implant had fewer threads, a smooth surface, and a more extensive drilling sequence. This study did not consider these factors when comparing the 2 implant systems.

Fifty-six patients were randomly assigned to receive either Osstem SSII or Standard Straumann implants to replace 1 or 2 mandibular molars[136]. Implant stability was monitored at baseline, and after 4 and 10 weeks. A significantly higher ISQ (Osstell Mentor) was obtained for the Osstem SSII, possibly due to the differing thread designs. There were no statistically significant differences in ISQ at 10 weeks between the implants, indicating no significant differences in secondary stability. The effect of thread design was also demonstrated by Roze et al (2009) [59], who placed 22 implants (12 Ankylos and 10 Straumann) in both arches of human cadavers. Following the first drill, the titanium cylinders were placed and an initial ISQ reading was taken – this step was done to compare smooth cylinders with threaded implants and investigate the effect of implant geometry. The drilling protocol was then resumed, implants placed, and RF measurements obtained. No difference was found between Straumann and Ankylos implants but there was a significantly higher stability for both types of threaded implants compared with the customized plain cylinders.

2.4 Clinical Use of Resonance Frequency Analysis

Measurement of ISQ values over the course of implant therapy has several clinical uses. It may help when determining the loading protocol (immediate, early, or delayed) and in individualizing healing periods[137]. Changes in stability can be monitored over time and, with early detection, alleviation of occlusal forces may be able to rescue failing implants[137]. The ISQ can also be useful when evaluating new implants or surface treatments, and new surgical techniques or materials.

2.4.1 Immediately placed implants

Lindeboom et al (2006) [138] investigated the outcome when implants were placed immediately after extraction of maxillary anterior teeth or premolars with chronic periapical infections. Primary stability, defined as a torque of at least 25 Ncm, was a pre-requisite for inclusion. Implants were not restored until at least 6 months, at which time ISQ was measured. The survival of immediately placed implants was 92% and that for the delayed placement was 100%. The mean ISQ at 6-months was 64.5 for both groups of implants.

Nordin et al (2007) [139] evaluated the clinical and radiographic outcome after 116 Straumann implants were placed in 19 patients to support rigid, passive-fit permanent fixed complete dentures. Implants were placed either in fresh extraction sockets (66%) or in healed bone (34%). The prostheses were loaded after 10-14 days and patients were followed for 2-3 years. During the follow-up period, there were no significant differences in ISQ (Osstell) between implants placed in sockets (57.1) and healed bone (57.2). Only 2 implants failed, and this was attributed to framework fracture.

Bogaerde et al[101] focused on implants placed in the maxilla or posterior mandible (areas characterized by poor bone quality) and measured the ISQ of 69 Neoss implants which were loaded within 7 days. Sixteen of the implants were placed in extraction sockets and 7 additionally received bone grafting. Survival was 98.5%, with one implant failing in an extraction site in the maxilla. The mean ISQs at placement, 1, 2, and 6 months were 68.1, 66.0, 69.1 and 73.6, indicating a steady increase with osseointegration. The ISQ was lower in extraction sockets (65.8 at placement and 67.5 after 6 months).

Immediate implant placement and restoration was compared to delayed placement (8 weeks after extraction) with immediate restoration for Straumann tapered implants placed in the esthetic zone of 16 patients[140]. Baseline ISQ values were significantly lower for the implants placed immediately (65 versus 74) but this did not appear to affect the treatment outcome (final ISQ values 72 versus 73).

2.4.2 Immediate and early loading

Osseointegration is a dynamic process during initial establishment, as well as during maintenance[141]. After initial placement of implants, necrosis, resorption, and new bone healing all occur around the fixture[141]. Loading is thought to have an important role in early osseointegration, as the peri-implant tissue reacts and remodels in response to functional forces[141]. Many studies have investigated the potential of RFA to be used in determining when to load implants and to indicate which implants may be amenable to immediate or early loading.

It was hypothesized by De Smet et al (2005) [141] that controlled early loading would be beneficial for osseointegration and stability values. Astra Tech implants were placed in the tibiae of 10 guinea pigs and loaded after 7 days. Unloaded controls were used for comparison. A controlled, gradually increasing, cyclical load was applied to the test implants for 10 minutes per day, 5 days a week, for 6 weeks. RF was measured at the time of implant placement and weekly for 6 weeks. All implants displayed good osseointegration. Early-loaded implants showed a gradual increase in stability over time, whereas unloaded implants had a decrease in stability. At 3 weeks, the difference between test and control implants reached 300 Hz, but this was not statistically significant. By 6 weeks, however, both groups had similar RF values. The authors concluded that controlled early loading is beneficial for implant stability in the early healing stages.

Glauser et al[142] hypothesized that the surface texture of tapered Brånemark TiUnite implants would provide good primary stability and improve healing for immediate loading. Thirty-eight patients received 102 implants. If threads were exposed upon implant placement, the patients were treated with guided bone regeneration (GBR). The success rate after 1-year of loading was 97.1%. RF measurements were taken at time of placement, as well as at 1, 4, and 6 weeks and 3, 6, and 12 months. At placement, the mean ISQ was 71 and this decreased by 8 units at 1-week. The ISQ then increased until 1 year, when it was similar to the initial value (70). A 4-year follow-up study[143] showed no additional failures. The RF measurements at 2, 3, and 4 years remained stable, hovering around 66. The 5-year results, published in 2007[144], revealed a mean ISQ of 66. The minimal decrease from 1 to 5 years was thought to reflect the minimal marginal bone remodeling during this time period.

Calandriello et al (2003) [145] also found consistently high ISQ values for 50 Brånemark single molar implants, placed using GBR as needed for exposed implant threads. All implants were followed for 6 months with 100% survival. ISQ values were obtained at surgery, and then monthly for 6 months. The initial mean ISQ was 76 and this dropped slightly to 72 at 3 months then returned to near-baseline (75) by 6 months. The 7 implants treated with GBR had slightly lower values at baseline and 3 months (68 and 66) compared to implants without GBR (77 and 77) but both groups had an ISQ of 75 by 6 months. It was suggested that the lower initial ISQ values for sites treated with GBR was due to the exposed implant threads but, once the bone matured, the stability increased from 3 to 6 months.

A number of other studies have also shown an initial decrease in RF values after placement and immediate loading, followed by a steady increase to values approximating initial placement. In a study of machined Brånemark implants loaded either immediately or within 11 days of placement, Glauser et al (2004) [146] found that the mean initial ISQ of 68 dropped to 60 at 3 months then increased until it reached the initial value by one year. Froberg et al (2006) [112] noted mean initial ISQ values around 67-68 for turned Brånemark or TiUnite (Nobel Biocare) implants placed in the anterior mandible of 15 patients. Implants were immediately loaded and followed for 18 months. A decrease to about 63 was noted at 3 months and a final mean value just over 64 was found at 18 months. In a study of Zimmer Screw-Vent implants (Zimmer Inc., USA) loaded before 15 days[137], all implants had a baseline ISQ over 50, however the ISQ decreased until 30 days then increased to near-baseline levels by 90 days. It was noted that implants with a baseline ISQ over 65 maintained this value or experienced a slight decrease; however, implants with a baseline ISQ of 50-60 increased over time. Based on these findings, it seems that extending the healing period for implants with an already high ISQ is not beneficial. These implants may be suitable for immediate loading.

The initial drop in ISQ observed in several studies has been attributed to bone relaxation following compression at placement, bone resorption associated with bone remodeling, microfractures associated with loading, and crestal bone loss or dehiscence which increases the effective implant length[109, 142, 146]. Portman and Glauser (2006) [147] found that the initial decrease in ISQ was more pronounced for implants placed in soft bone or in areas with bone defects. It was speculated that splinting of the implants reduces micromotion and, therefore, may limit changes in stability during the early healing phase.

In contrast, many studies have shown a consistent increase in RF value over time for immediately-loaded implants and this may partly be due to differences in design. Cornelini et al (2004) [110] conducted a prospective clinical study of 30 SLA (ITI) implants placed in the posterior mandible with a minimum ISQ of 62 and restored immediately with single crowns. ISQ increased from baseline (70.6) to 6 months (71.7) to 12 months (76.7). In 2003, Payne et al[148] used RFA to monitor stability of two types of implants placed in the anterior mandible to support overdentures, which were loaded after 2 weeks. Patients were randomly assigned to receive ITI or Southern sand-blasted acid-etched implants (Southern Implants Ltd, Irene, South Africa). RF was measured at 0, 6, 12, and 52 weeks. ISQ was higher for the Southern implants than for ITI implants at every time point. The mean initial and 1-year values for ITI implants were 61.9 and 62.3, compared with 79.3 and 73.4 for Southern implants. The Southern group experienced a drop in ISQ values from surgery until 6 weeks but the ITI implants showed no such decrease. There was no further decrease in RF values from 6 to 52 weeks. The differences between groups were attributed to differences in implant design and placement protocol, as well as the placement of Southern implants in denser bone. It was suggested that the initially higher ISQ value and the drop from baseline to 6 weeks for the Southern implants was due to their self-tapping design. The protocol for ITI implants included pre-tapping, which likely resulted in less outward pressure and subsequent relaxation of the surrounding bone. Sites with type 3 bone had significant increases in ISQ from 12 to 52 weeks and eventually the values were similar to those with type 2 bone.

Immediate/early loading of 53 tapered Nobel Biocare implants was assessed clinically and radiographically over the course of 1 year[149]. Single tooth replacements were loaded on the same day as implant placement, and bridges were loaded within 16 days. The mean ISQ values at baseline, 3, 6, and 12 months were 63.3, 64.3, 65.0, and 66.8. The increase from baseline to 1 year was statistically significant.

Several studies have compared immediate or early loading with conventional loading or unloaded controls, and shown no statistically significant difference in ISQ. These results have been obtained with animal studies[150], as well as clinical studies using ITI implants[90], SwissPlus (Zimmer) implants[151], and TiUnite (Nobel Biocare) implants[108, 152-156].

When deciding whether to immediately load an implant, many studies have used a minimum of 60 ISQ units as a key criterion[7, 109, 146, 157-161]. A few studies have recommended slightly higher values, with Cornelini et al (2006) [162] using 62 ISQ units, in addition to a lack of infection of adjacent teeth, a bilaterally-stable occlusion, and placement of implants of minimum dimensions, and Bornstein et al (2009) [113] using 65 ISQ units with repetitive measurements at 3-week intervals until at least 65 is obtained. Balshi et al (2005) [31] commented that the previously recommended minimum value of 60 for immediate loading may need to be altered depending on the location of implant placement and on the bone type. In this report, successful osseointegration was found for 97% of implants with an initial primary stability of only 47-59.

In contrast, Shiigai et al (2009) [163] conducted a pilot study to assess the efficacy of using pre-selected sets of ISQ values to predict adequate stability for immediate or early loading and recommended a minimum ISQ of 70 – a higher value than other investigators. Twenty patients had mandibular implants loaded immediately (n=10 implants), at 6 weeks (early; n=25), or after 12 weeks (delayed; n=6). For immediate loading, the implants needed to be at least 10mm in length, placed in moderately-high to high density bone, have an insertion torque of at least 45Ncm and an ISQ value of at least 70. For early loading, the implants needed to be at least 10m in length, placed in moderately low to high density bone, have an insertion torque of at least 30-45Ncm and an ISQ value of 40-70. A delayed loading protocol was used if these criteria were not met. All of the implants survived to 12 weeks, at which time the immediately-loaded ISQ was 76.6 and the early-loaded ISQ was 74.2. There was a slight decrease in the ISQ for most of the immediately-loaded implants by week 1, followed by an increase by week 6, and stabilization or an increase at 12 weeks. In contrast, the ISQ of most early-loaded implants remained stable or increased for the first 3 weeks, then 68% increased at week 6 and stabilized or continued to increase until week 12.

2.4.3 Sinus augmentation

Lundgren et al (2004) [164] used RFA (Osstell), in addition to clinical and CT exams, to evaluate healing after sinus membrane elevation with simultaneous implant placement, but without grafting material. Ten patients were treated with 19 TiUnite Brånemark implants and the mean ISQs at placement, abutment surgery, and after 1 year of loading were 65, 66, and 64 respectively. The high stability values, and new bone formation visible on CT scans, support the use of simultaneous implants and sinus elevation procedures, without additional grafts.

Lai et al (2007) [165] used RFA to monitor the stability changes of 42 ITI implants placed in conjunction with osteotome sinus floor elevation without bone grafting. The success rate was 95.2%, with the 40 successful implants having high primary stability. The implants that failed had ISQ values (Osstell) of 69 and 70 at placement and 58 and 62 at 2 weeks. All implants had a baseline ISQ over 66 (mean 69.1). The mean ISQ then decreased to 57.1 by 4 weeks and increased to 64.2 by 6 weeks and to 70.1 by 20 weeks. There was no significant difference between type 3 and 4 bone at any time point, other than 8 weeks, when the mean ISQ in type 3 bone was 66.3 versus 65.5 in type 4 bone. Although greater stability is generally anticipated with denser bone, the lack of difference found in this study may be due to lateral compression of the bone by osteotomes, which increases the trabecular density.

RFA (Osstell) was again used to evaluate the clinical outcome of simultaneous implant placement (n=62 implants) and endoscope-guided sinus elevation without graft material[166]. The overall success rate at 12 weeks was 94% and the ISQ values indicated good stability. The values at surgery ranged from 54-65, with a mean of 60 and those at 4- and 12-weeks ranged from 46 to 89, with a mean of 57.9.

Palma et al (2006) [167] conducted an experimental study in non-human primates to evaluate the outcome of simultaneous sinus elevation and implant placement with or without autogenous bone grafting. The maxillary premolars and first molar were extracted bilaterally and sinus elevation surgery was performed 4 months later, at the same time as placement of two implants (one turned and one oxidized) on each side. The left sinus received an autogenous tibial bone graft and the right sinus served as an un-grafted control. In the grafted group, the mean ISQs at placement/6 months were 68.0/67.6 for turned implants, and 68.0/65.0 for oxidized implants. In the un-grafted group, the corresponding values were 67.0/64.0 for turned implants and 63.2/65.7 for oxidized implants. No statistically significant histological or stability differences were noted between the grafted and un-grafted sites but oxidized implants showed higher BIC and more bone within the implant threads.

Degidi et al (2007) [168] compared 63 XiVE (Dentsply-Friadent) implants placed in previously sinus-grafted sites (after 6 months of healing) with 17 implants placed in healed bone. The graft material consisted of 50% autogenous bone and 50% deproteinized bovine xenograft material. In general, grafted sites had high ISQ values but the difference between the grafted (62.1) and un-grafted (61.4) ISQs was not statistically significant. One possible explanation for this is the relatively greater importance of the crestal third of the implant site[166].

2.4.4 Guided bone regeneration

In a study evaluating the use of non-absorbable membranes for onlay bone grafting in rabbits, Rasmusson et al (1999) [169] used RFA to evaluate stability of implants placed in grafted areas. The animals were followed for up to 24 weeks, with histological and histomorphometrical evaluation at various time points. RFA showed that there was no statistically significant difference in stability between the groups at any time point (0, 8, 16, and 24 weeks). The RF values increased from approximately 8600 Hz at time of implant placement to over 11000 Hz by 8 weeks, at which time there was no statistically significant difference between the groups with and without the membrane despite a greater bone-implant contact at the membrane sites. It was suggested that this could be due to immaturity of the bone or to comparing 3 sacrificed animals with RF values from a separate 6 animals. By 24 weeks, the bone height was similar between the groups.

Kramer et al (2005) [78] used serial ISQ values to monitor the stability of implants placed in patients who had previously been treated with free fibula grafts. Sixteen patients received 51 implants 3 months after the bone grafting procedure. ISQ values were obtained at implant placement, implant exposure, and 1 year and showed a significant increase in ISQ over the 12 month follow-up period. The authors concluded that implants placed in areas treated with a fibula graft had reliable results. Brechter et al[170] also found an increase in stability after 12 months of loading of implants placed in grafted sites, including sinus elevation without graft material, sinus elevation with autogenous bone harvested from the ramus, autogenous onlay bone grafting from the iliac crest, autogenous interpositional bone grafting, zygomatic implants, and vertical distraction osteogenesis.

Sjöström et al (2005) [6] used RFA to show that implants placed in grafted maxillary bone after 6 months of healing achieve similar stability as those placed in native bone. Patients received either autogenous onlay grafts (n=24) or interpositional grafts with a Le Fort I osteotomy (n=5), followed by 6-8 months of healing and placement of a total of 222 Standard or Mark II Brånemark implants. For comparison, there was a control group of 10 non-grafted patients with 75 Brånemark implants. Implants placed in grafted bone had average ISQ values of 61.5 at implant placement, 60.2 at abutment connection, and 62.5 after 6 months of loading. The corresponding values for the control implants were 58.5, 60.9, and 63.0. There were no statistically significant differences between the groups but the tendency towards higher initial stability in the grafted group was attributed to placement of the implants in sites with a smaller final preparation diameter (2.85mm versus 3.00mm for implants 3.75mm in diameter). RF values increased with time in all groups with a tendency towards higher stability for interpositional grafts, likely due to placement of implants in the residual maxilla versus in grafted bone with the onlay technique.

Özkan et al (2007) [5] performed a clinical pilot study to compare the stability of implants placed in posterior mandibles, some of which had received autogenous symphyseal grafts 4 months prior to implant placement. Eight grafted patients received 17 implants and 7 non-grafted patients received 18 implants (control). After 1 month of healing, fabrication of fixed partial dentures was initiated. The mean ISQ values of implants placed in grafted sites were 63.0, 64.3, 68.4, and 70.3, at baseline, 1 and 4 months post-operatively, and 12 months post-loading, respectively. The corresponding mean values for implants placed in non-grafted sites were 65.3, 64.1, 68.6, and 70.1. The change in ISQ value from baseline to 1-month was insignificant in both groups but the increases at other time points were significant. There were no statistically significant differences in ISQ values between the grafted and non-grafted groups at any of the time points, indicating that high implant stability can be achieved for implants placed in grafted sites. In a separate study, 16 patients received autogenous bone grafting, followed by placement of 42 SLA (ITI) implants in the anterior maxilla, after 12 weeks of healing[4]. Comparison was made with 22 patients with 50 implants placed in non-grafted sites. ISQ values taken at 0, 4, 12, and 52 weeks showed no significant differences between groups.

The primary and secondary stability of implants, placed in either osseodistraction-generated (n=32) or native (n=39) bone, was assessed using the Osstell Mentor[171]. At the time of placement, the mean ISQ values for osseodistraction and native implants were 73.0 and 76.8, respectively. The corresponding values after 6 weeks were 77.2 and 79.7. Although both groups demonstrated good stability at both time points, the values were higher for implants placed in native bone.

2.4.5 Predictive value of RFA

Implants can fail for a variety of reasons, mostly related to the design of the particular implant, surgical placement technique, adverse host response or excessive loading forces[13, 18]. Glauser et al (2004) [146] evaluated immediate or early loading of implants in 23 patients and found a failure rate of 11.1%, with implants lost in 6 patients. RFA was able to detect failing implants earlier than clinical assessment, since the ISQ decreased continuously until failure. Low RF values at 1 and 2 months were indicative of implants at risk of failure. Since this was a blinded study, it was not possible to use the ISQ values to dictate reduction of loading forces in failing implants. In a separate study of 122 implants in 31 patients[132], the ISQ values of 2 implants that did not integrate showed a gradual decrease and a final reading around 40 ISQ. The drop in ISQ was evident prior to detection of clinical mobility. Nkenke et al (2005) [47] also found that the pattern of implant failures was reflected in decreasing RF values. In this study, there was a high rate of failure (46 out of 108 implants) for XiVE implants placed in minipigs. Vanden Bogaerde et al[172] observed a decrease in ISQ from 67 at baseline to 53 at 6 weeks, when there were signs of failure.

Payne et al (2004) [173] observed that the ISQ of failed implants was lower than that of surviving implants and ranged from 36-50. A lower ISQ for failing or failed implants has also been found in several other studies. Thor et al (2005) [174] found a large decrease in ISQ for one failing Astra Tech implant (from 64 at implant placement to 40 at abutment connection). Degidi et al (2006) [159] obtained a mean ISQ value of 43 for 3 failing implants, compared to about 60 for surviving implants. Horwitz et al (2007) [102] observed failure of 12 implants, out of a total of 74 that were placed in 19 patients. Most (10) of the failures were in the maxilla and the mean ISQ for implants that failed was 57.5. Turkyilmaz et al (2008) [92] also found that the mean ISQ for successful implants was significantly higher than for failed implants (67.1 versus 46.5).

Balleri et al (2002) [131] presented a pilot study using Osstell for 45 implants in 14 partially edentulous patients after 1 year of loading. At one year, ISQ values ranged from 57-82 (mean 69) and all implants were clinically stable. It was therefore concluded that an ISQ value falling in this range represents good implant stability and osseointegration for partially edentulous patients.

Sjöström et al (2005) [6] found lower RF values for implants, which were rotationally mobile at placement. Overall implant survival was 92% at the 1-year follow-up. Failed implants tended to have lower RF values, compared to successful implants. The mean initial ISQ for implants that failed was 54.6 and that for mobile implants was 52.8. The mean initial ISQ values for successful implants was 62.0 and that for stable implants was 62.3. In 2007, a 3-year follow-up[175] was reported, with implant survival of 90%. The mean ISQ value after 3 years was 61.8, which is similar to that at baseline (61.9). Successful implants had a mean initial ISQ value of 62.6, whereas implants that failed had a mean initial ISQ of only 54.9, representing a statistically significant difference. The authors suggested that the initial ISQ may be useful in predicting future failure of implants, particularly if several measurements are available. The value of a single ISQ measurement in predicting failure, however, is limited.

Al-Nawas et al[48] observed the loss of 11 implants (6 during healing and 5 during loading), from a total of 160 placed in dogs. ISQ values at time of fixture placement were significantly higher for successful implants. When an initial stability threshold of 65.5 was used, a sensitivity (the ability to correctly identify mobility) of 83% and specificity (the ability to correctly identify stability) of 61%, for prediction of future implant loss, was obtained. If the ISQ at the time of loading was used instead of the initial value, no statistically significant difference was found between successful and unsuccessful implants. Nedir et al[33] also investigated a threshold ISQ value, which could predict osseointegration. Once a threshold ISQ to indicate stability was proposed, it was used to calculate the sensitivity, the specificity, the positive predictive value (PPV, the likelihood that an ISQ below the threshold corresponds to a mobile implant), and the negative predictive value (NPV, the likelihood that an ISQ value above the threshold corresponds to a stable implant). At the time of implant placement, ISQ values of 106 implants ranged from 42-72. Two implants experienced mobility and were removed; the ISQ values of these implants were 43 and 46. Since no implants with a higher initial ISQ were mobile, a threshold of 47 was selected to represent a stable implant. Using this cut-off value, the sensitivity was 1, specificity 0.973, PPV 0.087, and NPV 1. A PPV of 0.087 means that only 8.7% of the implants, indicated to be mobile based on an ISQ of <47, were actually mobile. Nedir et al concluded that the ISQ values were not reliable to accurately identify implant mobility. The ISQ, however, was found to be very reliable in identifying stable implants. The sensitivity of 1 meant that all stable implants were correctly identified. It has been suggested that the inability of RFA to consistently identify mobile implants is due to the extremely low stiffness of mobile implants, which prevents the device from detecting the first resonance frequency[8]. Instead, the second value may be registered which provides a falsely elevated RF value[8].

Nedir et al [33] found delayed-loaded implants with an initial ISQ over 49 were osseointegrated at one year. The value for immediately loaded implants was higher, at 54. Clinically, this translates to an expectation of osseointegration above these ISQ values. It is logical that the value for immediate loading is higher, since these implants are subject to higher stresses early in the healing process. The clinical implications of the findings are that an initial ISQ of ≥49 in a delayed loading protocol is likely to predict osseointegration at 1 year. If the implant is to be immediately loaded, an initial ISQ of ≥54 predicts osseointegration. Values less than these thresholds do not necessarily mean that the implant will fail but do indicate a higher risk situation which may benefit from rigorous follow-up and a reduction in loading forces. Scarano et al (2007) [35] measured the ISQ (Osstell) of 37 implants that were removed due to failure. The mean ISQ for these failed implants was 37, and data suggested that any ISQ value less than 40 is associated with irretrievability.

Using the mean ISQ of surviving osseointegrated implants, guidelines were provided with a range of expected implant stability values for immediately loaded implants[31]. A safety margin of 1 standard deviation was included. For implants placed in the anterior mandible, ISQ values were as high as 86±2 for males with type 1 bone and as low as 74±6 for females with type 3 bone. In the posterior mandible, the values ranged from 73±6 for females with type 2 bone to 85±2 for males with type 1 bone. For implants placed in the anterior maxilla, expected ISQ values were as high as 75±6 for males with type 2 bone and as low as 64±7 for females with type 4 bone. In the posterior maxilla, the values ranged from 64±7 for females with type 3 or 4 bone to 72±6 for males with type 2 bone. It is clear that higher values were found for males and for denser bone types. The authors caution that these values will not apply to all implants in all clinical situations. They do not mean that implants placed at lower values will not survive if immediately loaded and do not guarantee that implants placed at or above these values will be successful.

A threshold of 65 was suggested by Ramakrishna and Nayar (2007) [137] as the ISQ above which few failures should be expected. Setting a value below which failure is more likely is difficult. ISQ values tend to be between 50 and 60 for maxillary (softer) bone and between 60 and 80 in mandibular (denser) bone. A value of 45 was suggested as a threshold below which measures to increase stability should be considered. A temporary increase in primary stability value can be obtained by using thinner drills and wider or tapered implants. This increases the lateral compression of the bone, resulting in an increased ISQ value at the time of implant placement. However, this may be followed by a decreased ISQ value as the bone remodels. This modified surgical protocol may be beneficial in softer bone. In order to improve secondary stability, extending the healing period to 9 or 12 months was recommended. If a decreased ISQ value is obtained, a radiograph is necessary to determine whether the change is due to marginal bone loss or demineralization of the bone surrounding the implant.

Karl et al (2008) [57] measured ISQ values (Osstell Mentor) of 385 ITI implants at placement and after a healing period of 6 (mandible) to 12 (maxilla) weeks. At fixture placement, ISQ values ranged from 39 to 86 and after healing from 35 to 89 – this large variation indicates that it is difficult to identify a standard, which would define a successful implant. Further, the difference between the arches, and for anterior versus posterior, means that comparisons should only be made within the same region.

Valderrama et al (2007) [29] found an association between implant rotation and decreased ISQ. For 8 implants that rotated, the ISQ decreased by an average of 11 for magnetic RFA and 6 for electronic RFA, followed by an increase over the next 2-3 weeks. Marginal bone loss was noted around one implant and the magnetic RFA detected this change as a decrease in the ISQ. It was suggested that lower initial ISQ values indicate implants that are more susceptible to failure and may benefit from a prolonged period of healing. The authors discuss the possibility that repeated application of the transducer and multiple RF readings may have contributed to the rotational movement found in these implants.

In a longitudinal study[91] of 32 patients who received Straumann Standard Plus SLA implants, all ISQ readings taken at the time of surgery indicated adequate stability. All implants osseointegrated and showed clinical stability at weeks 1, 2, 3, 4, 5, 6, 8, and 12. The authors describe any ISQ reading above 55 as indicating clinically relevant stability but discuss the lack of a defined ISQ value, above which stability of the implant is reliable. Han et al (2010) [114] placed 25 Straumann implants in 23 patients. All implants were considered clinically successful. At the time of implant placement, ISQ values ranged from 64-81 and over all follow-up periods, the ISQ ranged from 55-84. As such, it was suggested that ISQ values falling in the range 55-84 likely represent homeostasis and stability of implants during the healing phase. Huwiler et al[61] found the normative range for ISQ values of Straumann SLA implants to be 57-70.

Implant stability was determined by the Osstell Mentor for 542 SLA (Straumann) implants, at implant placement and at restoration (2-4 months) [176]. The implants were divided based on an ISQ value above or below 60. There was no significant association between the baseline ISQ and implant survival but there was a significant association between the ISQ at restoration and implant survival. There were no failures when the secondary stability measurement was >60 but, for the 21 implants with an ISQ ≤60, there were 4 failures (19%). This study showed that primary stability might not be a prerequisite for long-term implant survival. Veltri et al[111] found that osseointegrated Astra Tech TiO_2 implants placed in the maxilla have ISQ values in the range of 53-76 after 1 year of loading and an ISQ value >50 at second-stage surgery likely indicates implants that will maintain their stability for at least a 3-year period.

Huwiler et al (2007) [61] found no predictive value of ISQ for losing stability (failing). One Straumann SLA implant lost stability at 3 weeks and had a drop in ISQ value from 68 at 2 weeks to 45 at 3 weeks but this decrease did not occur until after the failure was detected clinically. Östman et al (2008) [7] also found that implant failure was not correlated with primary stability and the initial ISQ values for the 4 implants that failed were 71, 66, 65, and 82. Similarly, Sennerby et al (2010) [89] found initial ISQs of 3 failed implants to be 72, 77, and 63. These implants, however, did show a decrease in ISQ from initial placement to abutment connection. Koka[177] reviewed the performance of RFA and challenged its use as a prognostic or diagnostic tool in clinical practice. Koka emphasizes that there is no information demonstrating that RFA is superior to subjective information obtained at the time of implant placement by an experienced surgeon.

In considering the literature, Sennerby and Meredith[8] state that ISQ values of 65-75 and 55-65 are likely to represent adequate stability for Brånemark and Straumann implants, respectively. Values below 55 for Brånemark or 45 for Straumann should be considered as a warning of reduced or inadequate implant stability. If these low values are detected at placement, extension of the healing period is recommended. For lower values obtained after loading, a period of unloaded healing is advised to regain stability, in addition to radiographic examination to evaluate the marginal bone level.

3. OBJECTIVES

A retrospective chart review was performed to assess the stability of implants in a variety of clinical situations, including placement at sites with a history of bone augmentation using bone allograft.

The following ***hypotheses*** were tested:

1. Implants placed in sites grafted with bone allograft or other bone materials will have similar stability to those of implants placed in native, healed bone.
2. Implant stability will vary based on the implant dimensions (length, width, and surface area).
3. Implants with bone loss or bony dehiscences will have lower stability values than implants surrounded entirely by bone.

4. MATERIALS AND METHODS

A chart review was performed of 286 implants placed in 149 patients from July 2009 to September 2011, at two centres in Vancouver, British Columbia. Human ethics approval was obtained from the Clinical Research Ethics Board, University of British Columbia Office of Research Services. Implants were placed in partially dentate and edentulous patients, in maxillary and mandibular arches, using either immediate or conventional placement. Implants were placed in both native bone, as well as sites previously or simultaneously augmented with guided bone regeneration or sinus augmentation.

The Osstell ISQ device (Gothenburg, Sweden) was used to measure implant stability (RFA), by emitting magnetic pulses that cause a SmartPeg attached to the implant to resonate according to the stability of the implant. RFA measurements were taken in triplicate from the buccal, lingual, mesial and distal and recorded in Implant Stability Quotient (ISQ) units ranging from 1-100, with higher values indicating higher implant stability. All included implants had measurements taken after a period of initial healing and prior to functional loading. Measurements were also obtained at the time of implant placement if the patient was treated at the University of British Columbia and had a minimum insertion torque value of 15Ncm. This torque value was selected because attachment of the SmartPeg to finger tightness was found to lead to rotation of the implant at lower torque values.

Inclusion criteria:

1. Patients who had at least one implant placed either in a private periodontal practice or in the UBC graduate periodontics clinic.
2. Availability of ISQ values taken after a period of initial healing. Analyses included implants which subsequently were removed due to failure.

Patient demographic information and clinical data concerning implant placement and bone augmentation procedures were collected and entered into a computer database (Microsoft Excel 2008; Microsoft Corporation, Redmond, WA). Implants were considered to have failed if they were lost or removed due to mobility, unresolved infection or clinical symptoms, or if they had advanced, untreatable bone loss. Failure of the implant did not preclude inclusion for statistical analysis. ISQ measurements were obtained prior to implant removal.

Variables identified as likely to affect implant stability and ISQ value included patient-related factors (age, gender, smoking status, and diabetes), RFA-related factors (direction of measurement, repeatability of measurements), anatomic site-related factors (arch, site, previous or simultaneous bone augmentation, and presence of a dehiscence at implant placement), implant design properties (implant type, length, width, and surface area), implant placement-related factors (insertion torque, bone density, and number of implants), timing of placement (immediate versus delayed), and the level of training of the surgeon.

Smoking status and diabetic control were determined based on information obtained from the medical history questionnaire. Immediate implant placement referred to placement of the implant immediately following and at the same appointment as extraction of the tooth. Bone density was classified as soft, medium, and dense, and was determined at the time of implant placement at the discretion of the surgeon. Patients were provided with a variety of provisional restorations after implant placement and until loading of the implants.

Statistical analysis was performed using the PASW statistics program (PASW, Chicago, IL, version 18.0) and included ANOVA with post-hoc Bonferroni adjustment, T test, and Spearman's and Pearson's correlation tests. Most data was analyzed at the implant-level. Patient-level data included the impact of age, gender, diabetes, smoking, and number of implants placed in the patient, on the ISQ value.

Box plots were selected to show results, in order to display the distribution of data. In this representation, the central rectangle displays a span of the first quartile to the third quartile – this is referred to as the interquartile range (IQR) and includes 75% of the data. Within the rectangle, the band indicates the median. The lines extending above and below the rectangle indicate the range of data, except if there are data points that lie significantly outside the other results - these are referred to as outliers and are displayed as individual data points. Outliers are defined as results lying either above or below the rectangle by more than 3 IQR.

For the majority of the analyses, ISQ measurements from the buccal, lingual, mesial, and distal were combined to provide one mean value per implant. Variables that were analyzed using only the buccal-lingual ISQ measurements included lateral ridge augmentation and the presence of a buccal dehiscence at implant placement. The majority of the records were lacking ISQ measurements at implant placement, therefore it was decided to perform statistical analysis primarily on the follow-up ISQ measurements taken at second stage. In most cases, the implant stability was not followed or reported after functional loading. The p-value of 0.05 was considered to be statistically significant.

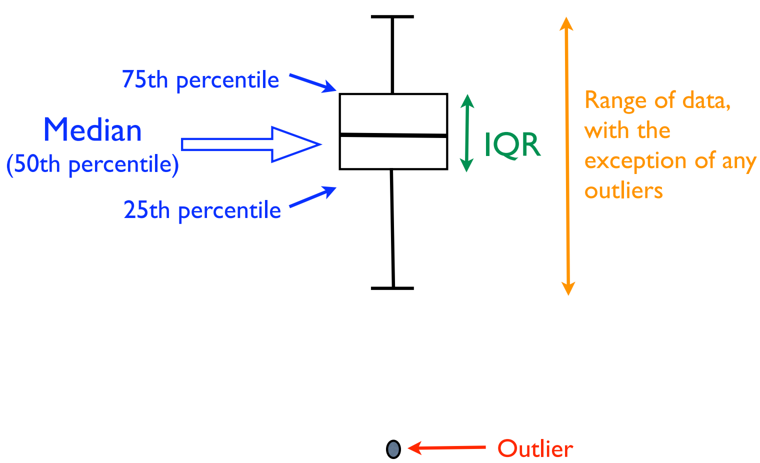


Illustration 1. Box plot representations

5. RESULTS

5.1 Population and Implant Distribution

The patient population included 149 patients, comprised of 43.6% males and 56.4% females, aged 54 ± 15 years. A total of 286 implants were placed at two centres in Vancouver, British Columbia: a private periodontal practice (n=231) and a university Periodontics clinic (n=55). The following types of implants were placed: Nobel Replace Tapered Groovy (n=85), Nobel Replace Straight Groovy (n=12), Nobel Replace Select Straight (n=3), Nobel Replace Select Tapered (n=9), Nobel Active (n=70), Nobel Conical Connection (n=1), Straumann BL SLA (n=31), Straumann BL SLActive (n=11), Straumann Roxolid (n=5), Straumann SP SLA (n=10), Straumann SP SLActive (n=8), and Astra Straight (n=41).

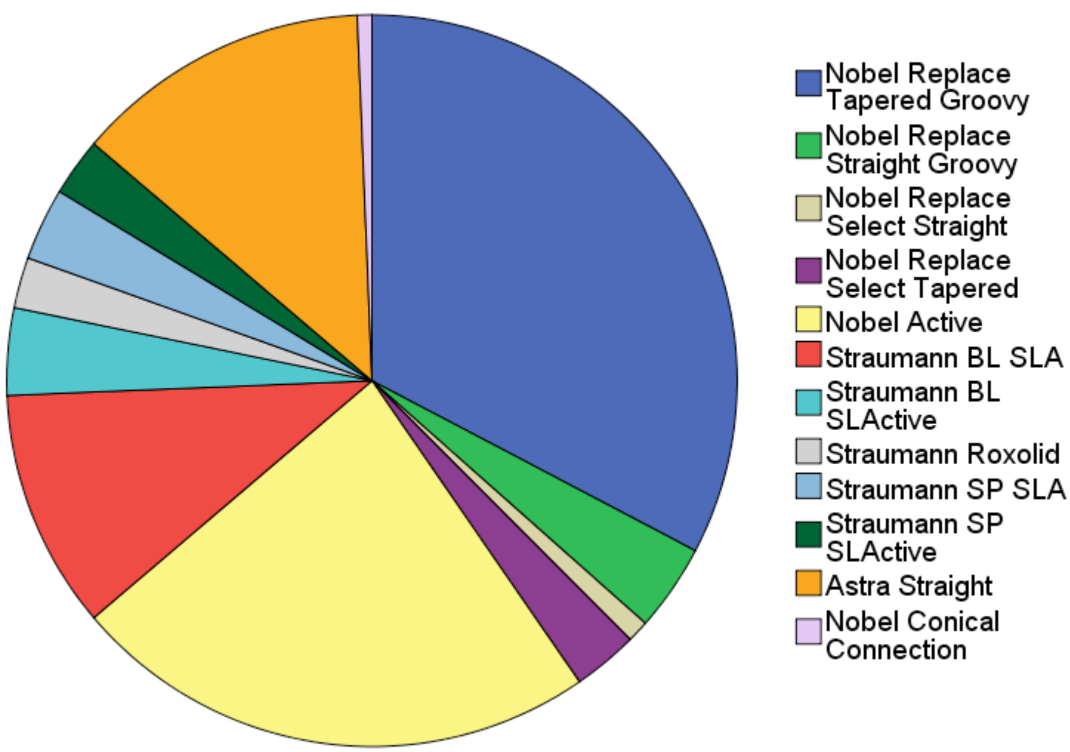


Figure 1. Distribution of implants

A total of 3 implants failed to osseointegrate and were removed, resulting in an overall survival rate of 98.9%. Additionally, of the 55 implants placed at the University of British Columbia Periodontics clinic, 3 (5.5%) were treated for peri-implant bone loss and were re-submerged for additional healing. No data was available for implants treated for peri-implant bone loss at the private periodontal clinic.

5.2 Osstell-Related Factors

5.2.1 Orientation of transducer

Measurements were taken in triplicate from each of the buccal, lingual, mesial, and distal of each implant and the highest value for each implant was recorded. The mean ISQ was 77.36±6.59 from the buccal (range 52-90), 78.00±6.53 from the lingual (range 52-93), 79.02± 5.84 from the mesial (range 48-89), and 79.01± 5.80 from the distal (range 52-89). Measurements taken from the buccal and lingual were not significantly different (p=0.84). Similarly, measurements taken from the mesial, distal, and lingual did not differ significantly (p=>0.30). A statistically significant (p=0.004) difference, however, was found for measurements taken from the buccal, compared with both the mesial and distal orientations. A significant difference (p=<0.001) was also found when the buccal and lingual directions were combined and compared with a combination of mesial and distal measurements. However, the mean difference was clinically quite small (1.33 ± 2.96).

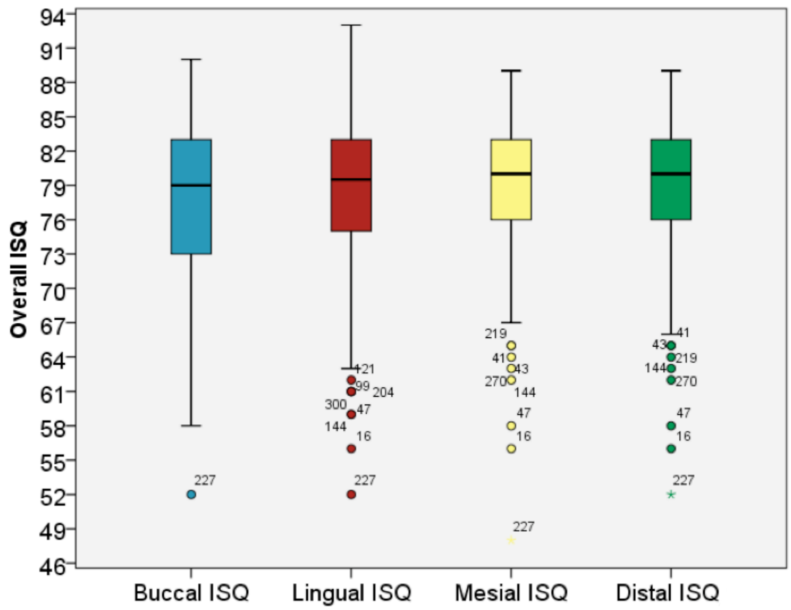


Figure 2. ISQ values for measurements taken from the buccal, lingual, mesial, and distal

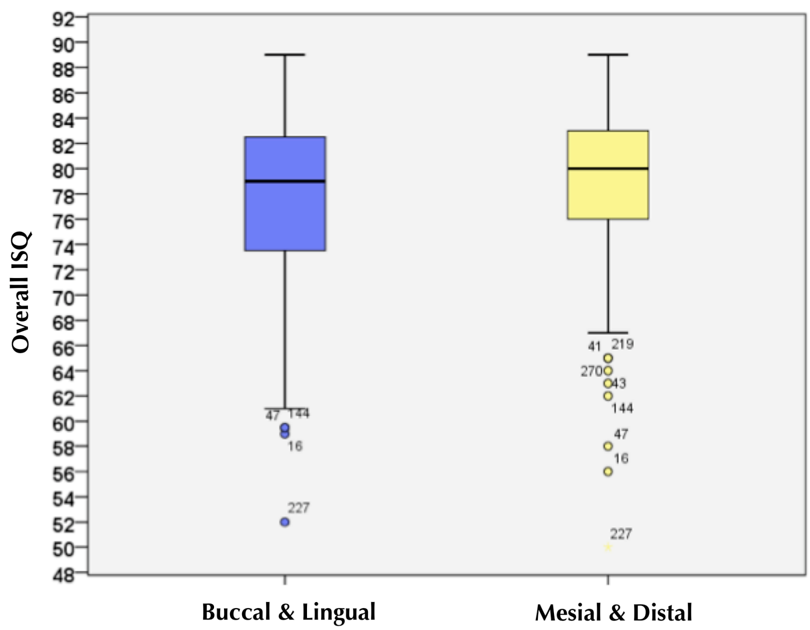


Figure 3. ISQ values for measurements taken from the buccal/lingual and mesial/distal

5.2.2 Repeatability of measurements

Triplicate measurements were taken for 24 implants at surgical placement and 48 implants at second surgery. All repeated measurements were highly correlated, with a range of 0.753 to 0.978. Specifically, for buccal measurements taken at implant placement and exposure, the correlation ranges were 0.887-0957 and 0.753-0.946, respectively. For lingual measurements, the ranges were 0.956-0.978 and 0.783-0.954. For mesial measurements, the ranges were 0.922-0.972 and 0.936-0.974. For distal measurements, the ranges were 0.908-0.974 and 0.916-0.956.

5.3 Patient-Related Factors

5.3.1 Patient age

The study population was divided into 3 age groups: those younger than 45 years (n=36), those aged 45-64 (n=78), and those aged 65 years or older (n=34). The mean ISQ for the youngest age group was 77.30±6.68, compared with 79.37±4.95 for the middle age group, and 78.73±4.06 for the oldest age group. Although the youngest patients tended to have lower stability values, no statistical significance was found when comparing these age groups. The mean difference between the youngest age group and the middle age group was 2.07 ISQ units (p=0.156). The mean difference between the youngest and oldest age groups was 1.43 ISQ units (p=0.764), and that between the middle and oldest age groups was 0.637 (p=1.00).

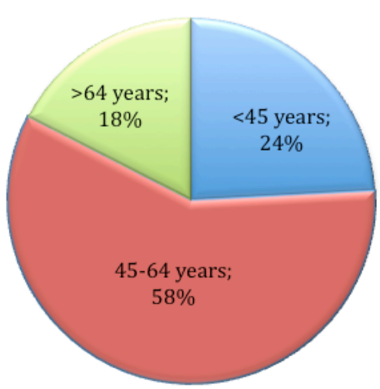
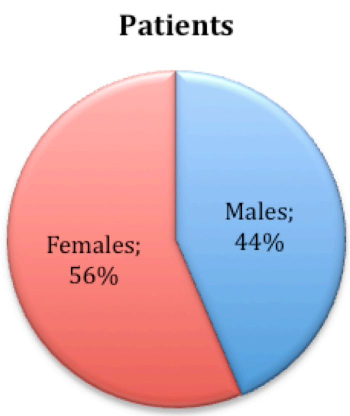


Figure 4. Distribution of age groups

5.3.2 Patient gender

Of the 149 patients, 84 were women (56.4%) and 65 were men (43.6%) and these groups received 149 (52.1%) and 137 (47.9%) implants, respectively. For gender comparison, the data was evaluated at the patient level, rather than the implant level. The mean ISQ for females was 78.44 ± 5.33 and that for males was 79.03 ± 5.21. The difference in ISQ between implants placed in women and men was not statistically significant, with a mean difference of 0.59 units (p=0.502).



Figures 5 Distribution of patients according to gender

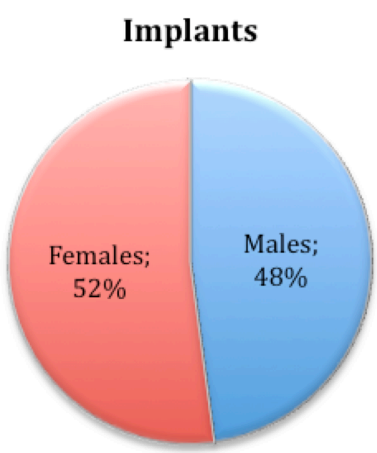


Figure 6. Distribution of implants according to gender

5.3.3 Diabetic status

There were no cases of Type 1 diabetes mellitus but 9 patients (6.0%) were being treated for Type 2 diabetes mellitus. The mean ISQ for diabetic patients (n=9) was 80.26 ± 4.65, and that for non-diabetic patients (n=140) was 78.60 ± 5.31. The difference between the groups did not reach statistical significance (p=0.33).

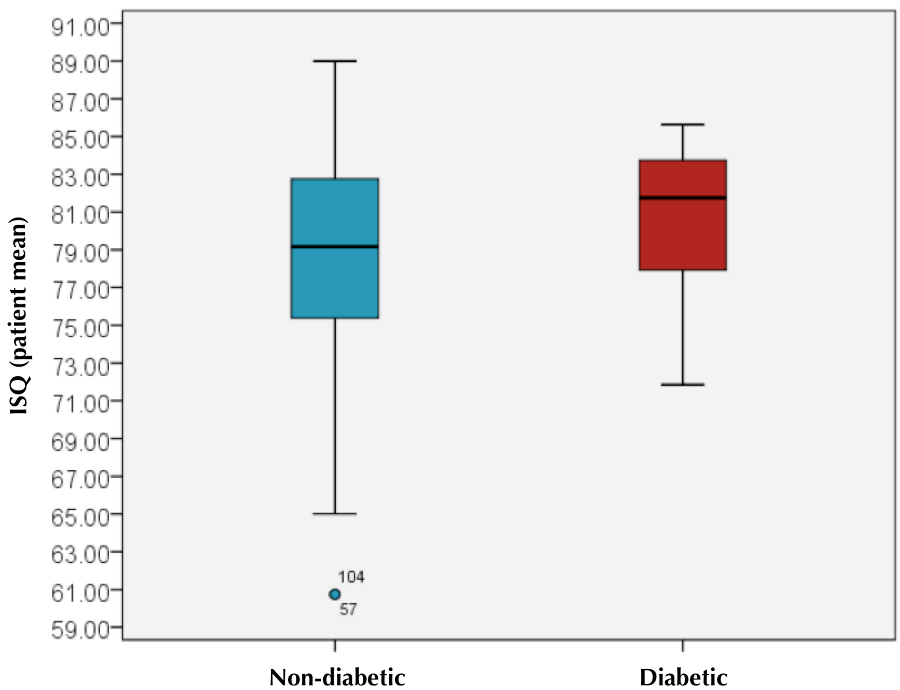


Figure 7. ISQ depending on diabetic status of patient (patient-level analysis)

5.3.4 Smoking status

Smokers constituted 6.0% (n=9) and former smokers 20.1% (n=30) of the population. Pack years of smoking ranged from 1 to 60. Half of the smokers and ex-smokers had a cumulative pack year history between 10 and 20 years, while 18.8% had a history of 5 or fewer years, and 31.2% had a history of 30 or more years. The mean ISQ in never-smokers was 79.04 ± 5.22, compared with 77.99 ± 5.16 in former-smokers, and 76.87 ± 6.24 in current smokers. No statistically significant difference was found between current or former smokers and non-smokers; however, a greater proportion of those individuals with stability values consistently lower than average were heavier smokers or had a history of heavy smoking. The mean difference between smokers and never-smokers was 2.17 (p=0.707), that between smokers and former-smokers was 1.12 (p=1.000), and that between never-smokers and former-smokers was 1.05 (p=1.000).

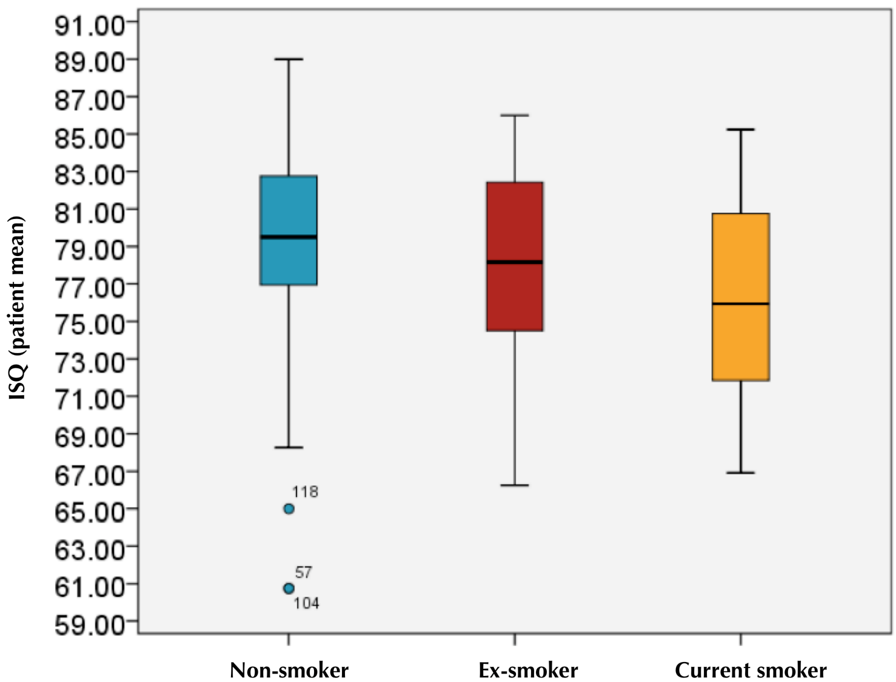


Figure 8. ISQ depending on smoking status of patient (patient-level analysis)

5.4 Implant Design-Related Factors

5.4.1 Implant system

Although there was some variation in stability values between implant systems, no consistent trends were noted. Nobel Replace Conical Connection implants were not included, as the number placed (n=1) was too low to perform statistical analysis.

	Number placed (% of total)	Mean ISQ value
Nobel Replace Tapered Groovy	85 (29.7)	79.87±6.09
Nobel Replace Straight Groovy	12 (4.2)	81.04±5.20
Nobel Replace Select Straight	3 (1.1)	81.42±4.16
Nobel Replace Select Tapered	9 (3.2)	78.01±4.52
Nobel Active	70 (24.5)	75.42±4.59
Straumann BL SLA	31 (10.8)	77.06±5.99
Straumann BL SLActive	11 (3.8)	79.52±6.49
Straumann Roxolid	5 (1.7)	75.60±4.93
Straumann SP SLA	10 (3.5)	79.12±4.13
Straumann SP SLActive	8 (2.8)	79.66±5.33
Astra Straight	41 (14.3)	79.73±6.53

Table 1. Distribution and mean ISQ for types of implants placed

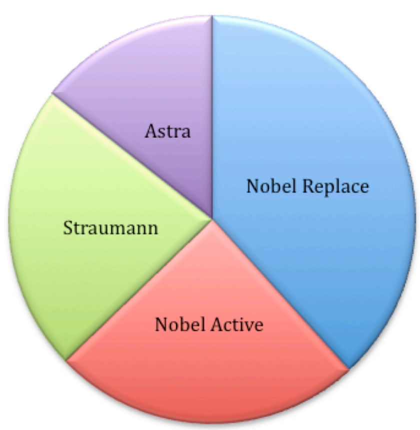


Figure 9. Distribution of implants according to implant system

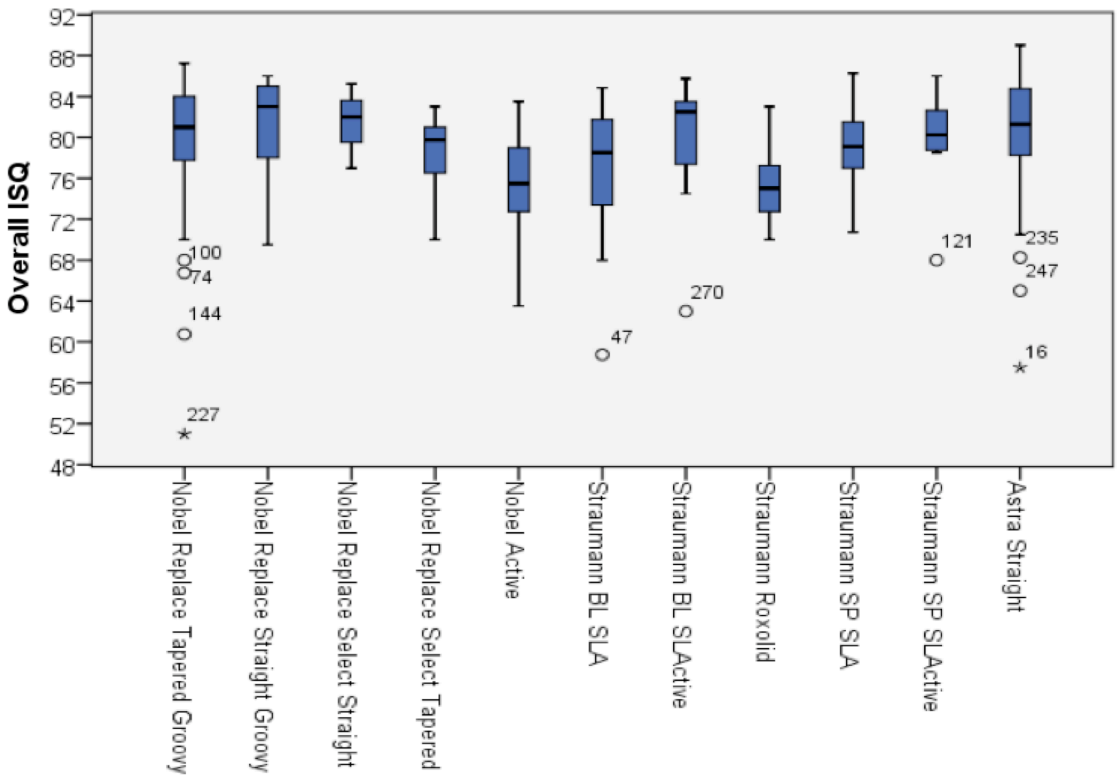


Figure 10. ISQ values for each implant type placed

A total of 180 Nobel Biocare implants were placed, with a mean ISQ of 78.16±5.77. The mean ISQ values of Straumann (n=65) and Astra (n=41) implants were 78.00±5.68 and 79.73±6.53, respectively. No statistically significant differences were found between any of the groups.

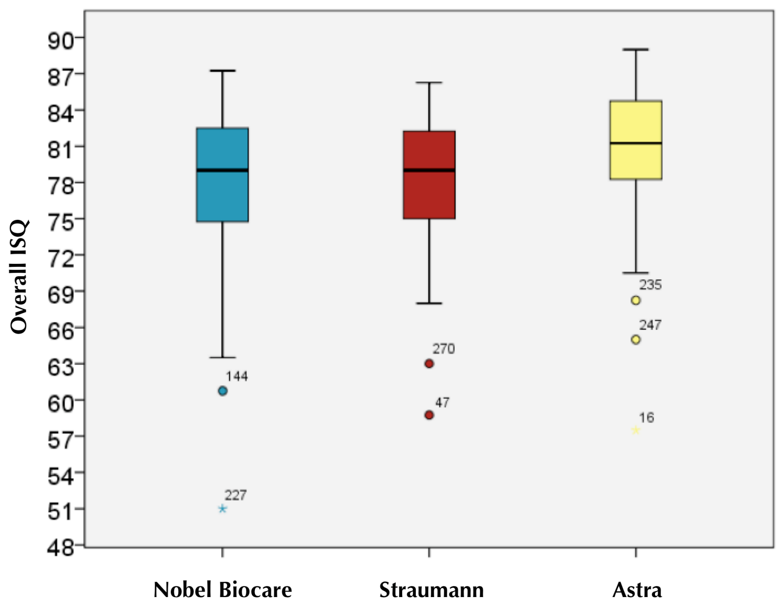


Figure 11. Mean ISQ values for Nobel Biocare, Straumann, and Astra Tech implants

The mean ISQ of Straumann tissue-level implants (n=18) was 79.36±4.56 and that for Straumann bone level implants (n=42) was 77.71±6.14. The difference between the groups was not statistically significant.

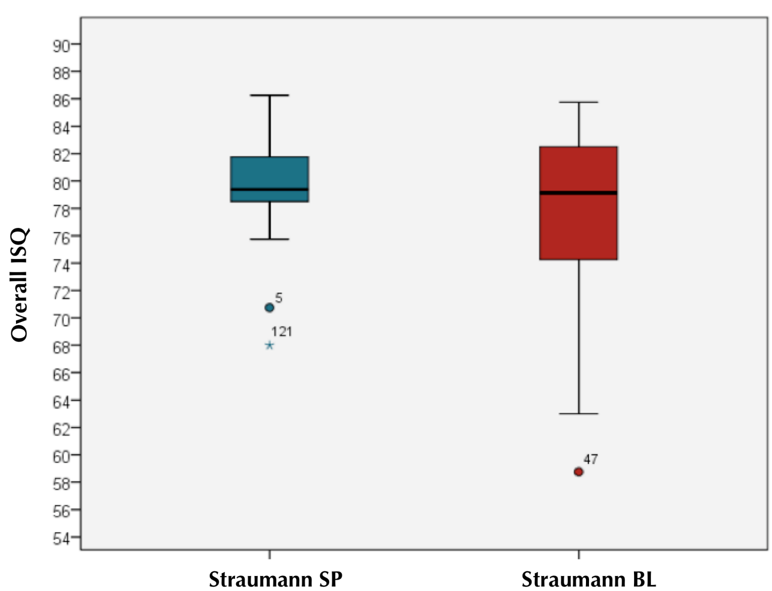


Figure 12. Mean ISQ values for Straumann SP and Straumann BL implants

5.4.2 Implant dimensions - length

Implants were divided into 3 length groups: ≤9mm (short), 10-12mm (regular length), and ≥13mm (long). Of the 286 implants, 43 (15.0%) were short, 150 (52.5%) were regular length, and 93 (32.5%) were long. Shorter implants were found to have significantly higher ISQ values than both regular length implants (p=0.01), and long implants (p=<0.001). No significant difference was found between regular length implants and long implants (p= 0.11).

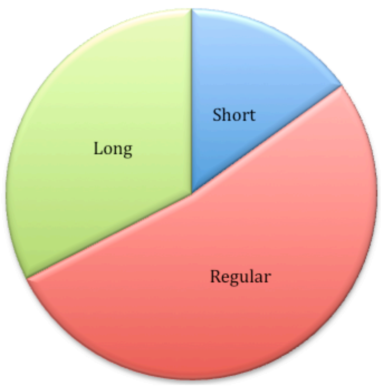


Figure 13. Distribution of implants according to implant length

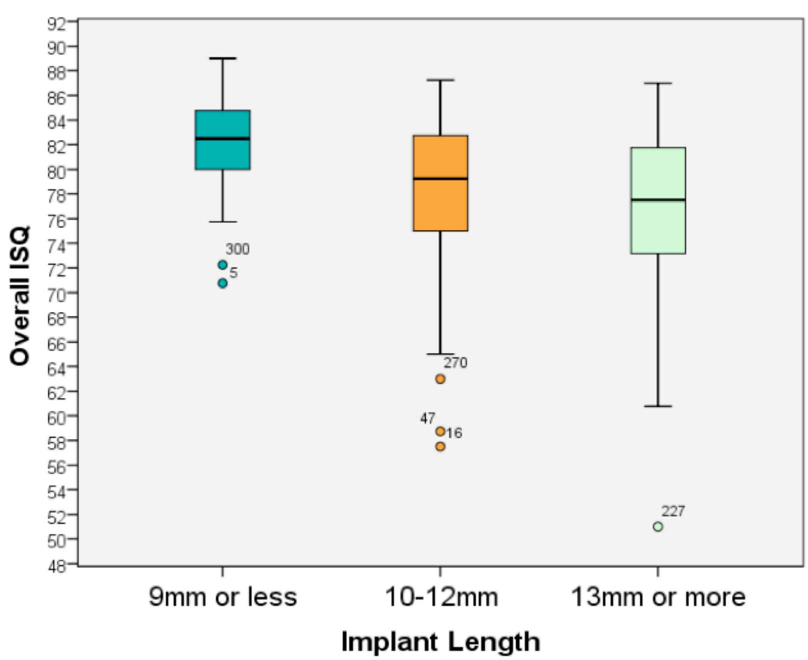


Figure 14. ISQ of implants based on length

When implant length was considered in the maxilla in isolation, no statistically significant differences were detected. The mean difference between short and regular length implants was 2.54 ± 1.95 ISQ units (p=0.59) and that between short and long implants was 2.63 ± 1.95 ISQ units (p=0.68). The difference between regular length and long implants was negligible (0.18 ± 0.96 ISQ units, p=1.0).

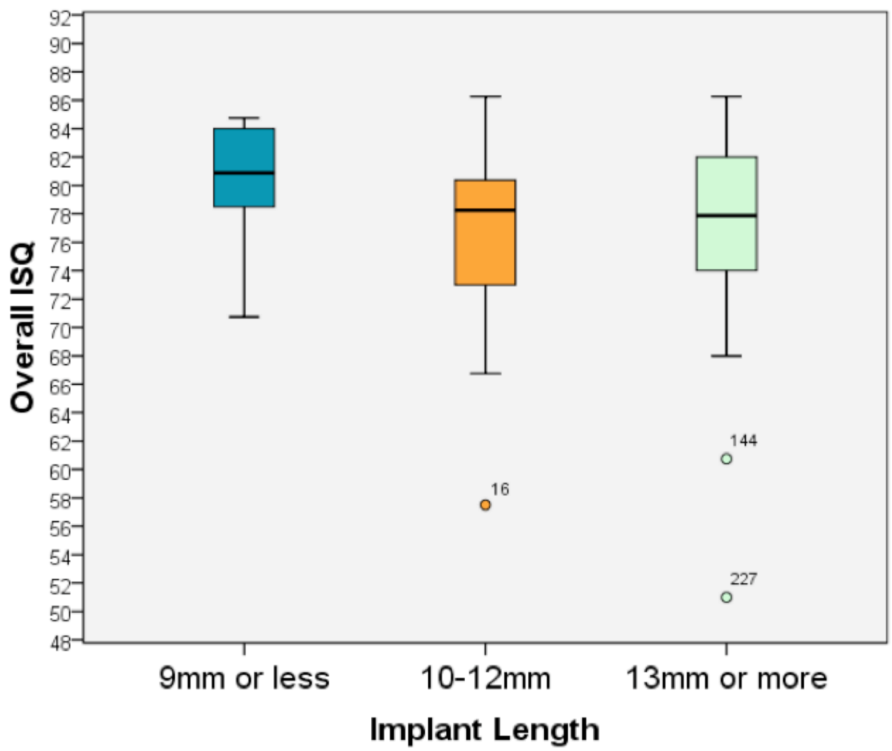


Figure 15. ISQ of maxillary implants based on length

In contrast, statistically significant differences were found between mandibular implants of different lengths. The mean difference between short and regular length implants was 3.27 ± 1.10 ISQ units (p=0.01). The difference between short and long implants was even greater at 7.86 ± 1.52 ISQ units (p=<0.001), as was the difference between regular length and long implants (mean difference 4.59 ± 1.35 ISQ units, p=<0.001).

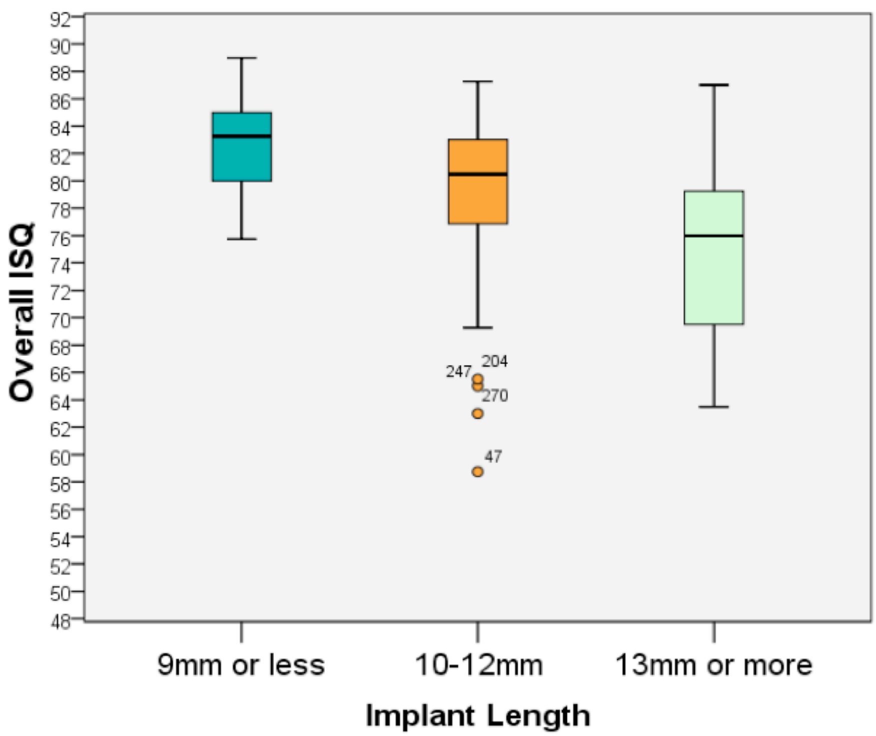


Figure 16. ISQ of mandibular implants based on length

Short implants (<10mm in length) were isolated and analyzed by comparing those in the anterior and posterior, as well as those in the maxilla and mandible. There were 10 short implants placed in the maxilla and 33 placed in the mandible. The mean ISQ in the maxilla was 79.60 ± 4.78 and that in the mandible was 82.69 ± 2.91. The mean mandibular ISQ value was 3.09 units higher than the maxilla and this was statistically significant (p=0.016).

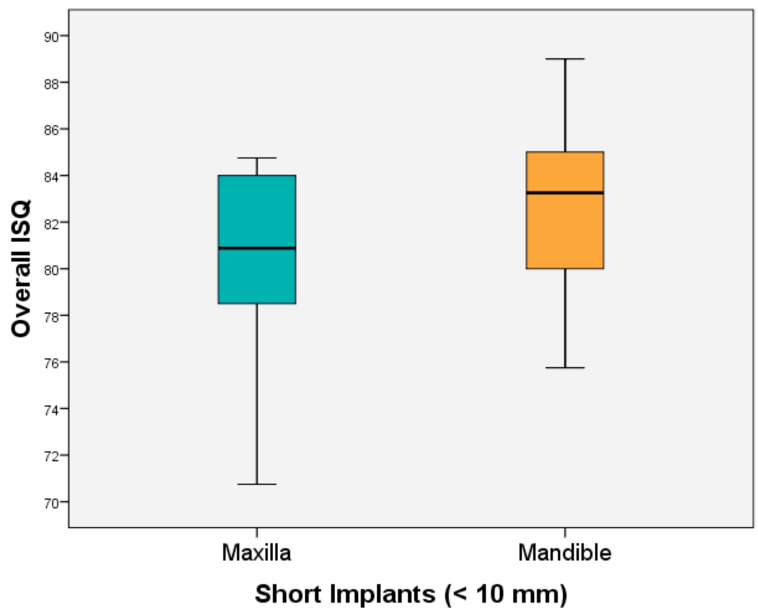


Figure 17. ISQ of short implants (<10mm) placed in the maxilla and mandible

There were 7 short implants placed in the incisor and canine sites (defined as anterior) and 36 placed in the premolar and molar sites (defined as posterior). The respective means for these groups were 82.75 ± 2.70 and 81.81 ± 3.78. The mean difference between the groups was 0.93 ISQ units and was not significant (p=0.54).

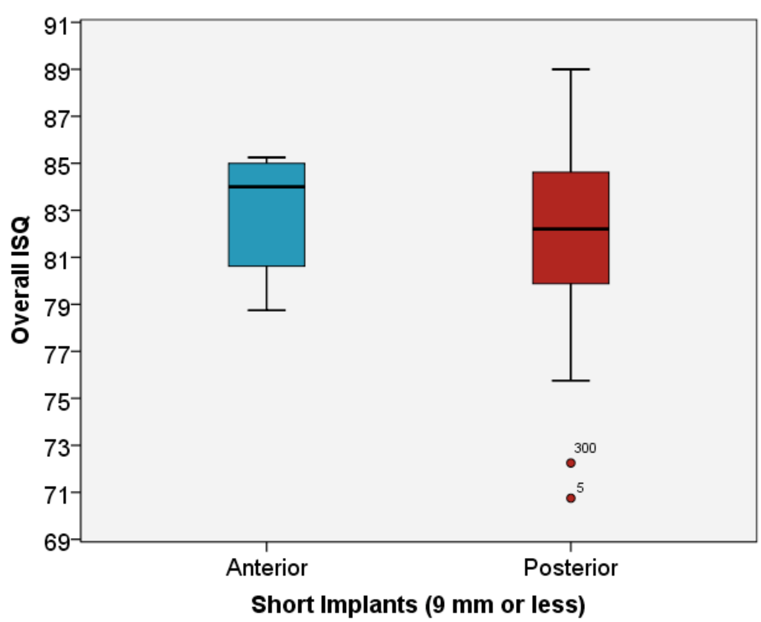


Figure 18. Mean ISQ of short implants placed in anterior or posterior sites

5.4.3 Implant dimensions - diameter

Implant body diameter was divided into 3 groups based on average dimensions of the various implant systems studied; these included <4.0mm for narrow (56 implants, 19.6%), 4-4.3mm for regular width (148 implants, 51.7%), and >4.3mm for wide (82 implants, 28.7%). A statistically significant difference was found between narrow and regular width implants and between narrow and wide implants (p=<0.001), but no significant difference was found between regular width and wide implants (p=0.67). The mean stability of narrow implants was 6.76 ± 0.81 ISQ units lower than regular width implants and 7.6 ± 0.90 ISQ units lower than wide implants. The mean ISQ of wide implants was slightly greater than regular width implants (0.87 ± 0.71 units).

When only maxillary implants were considered, there was a statistically significant difference between narrow implants and regular or wide implants (p=<0.001), but not between regular and wide implants (p=1.00). The mean difference in ISQ between narrow and regular width implants was 5.68 ± 1.04, while that between narrow and wide implants was 5.55 ± 1.21, and that between regular and wide implants was 0.13 ± 1.04. Similar findings were obtained when only mandibular implants were considered. A statistically significantly (p= <0.001) lower mean ISQ was obtained for narrow implants compared with both regular width (mean difference 8.37 ± 1.28), and wide (mean difference 9.96 ± 1.36) implants. The difference was not significant between regular width and wide implants (1.59 ± 0.94 units, p=0.28).

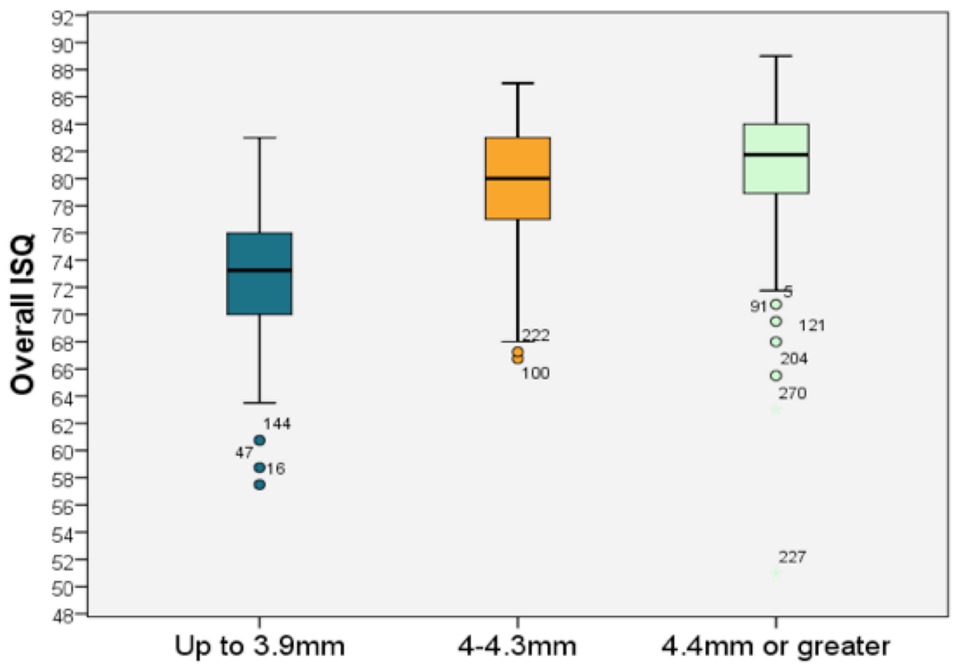


Figure 19. ISQ according to implant diameter

Figure 20: Distribution of implants according to diameter

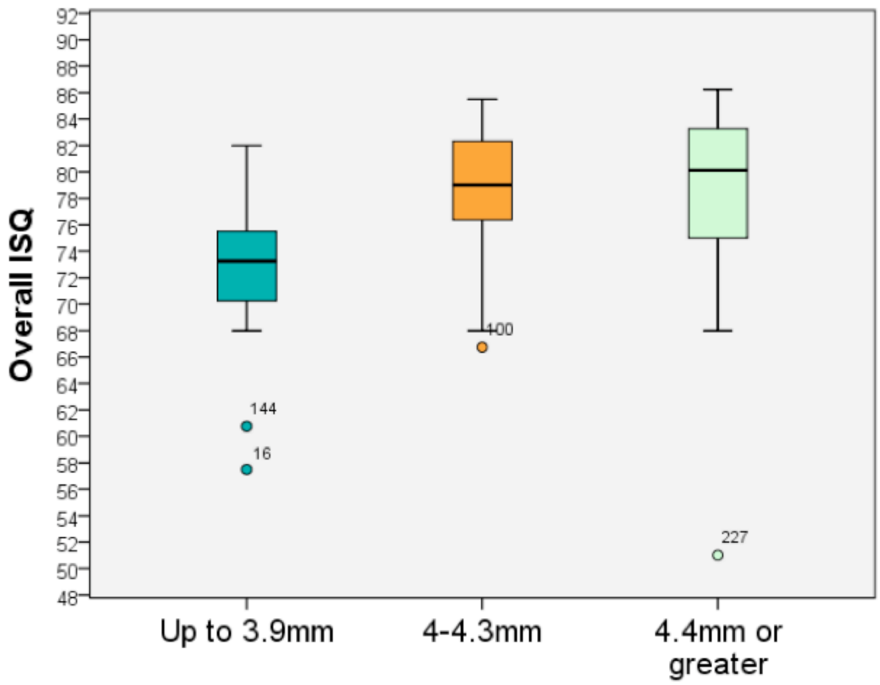


Figure 21: Maxillary ISQ values according to implant diameter

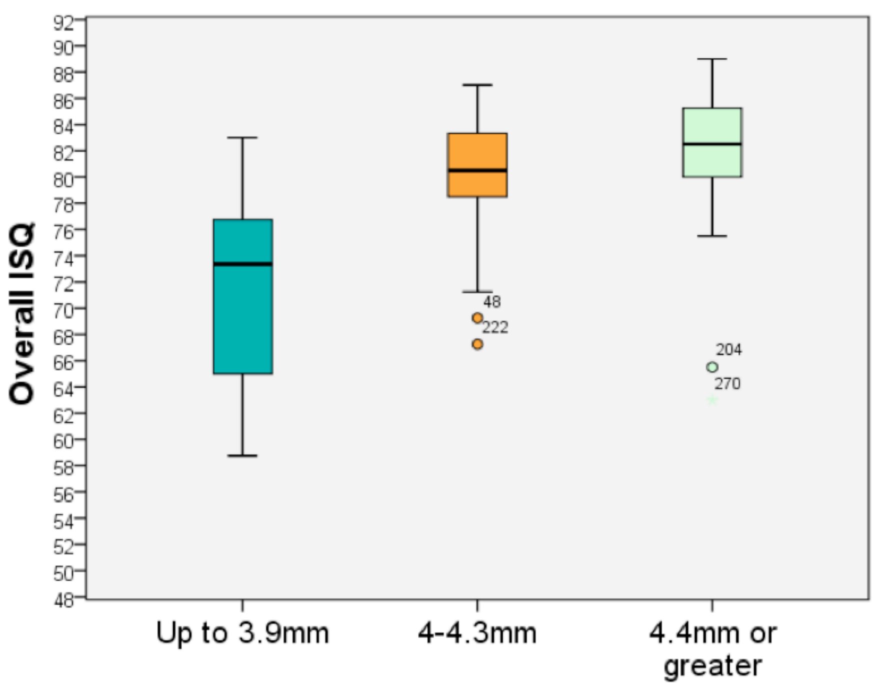


Figure 22: Mandibular ISQ according to implant diameter

Data were available for 179 Nobel Biocare implants. The mean ISQ for Nobel Active implants (n=70) was 75.42±4.59 and that for other Nobel Biocare implants (n=109) was 79.89±5.82. The mean difference between these types of implants was 4.47 and this was highly statistically significant (p=0.000).

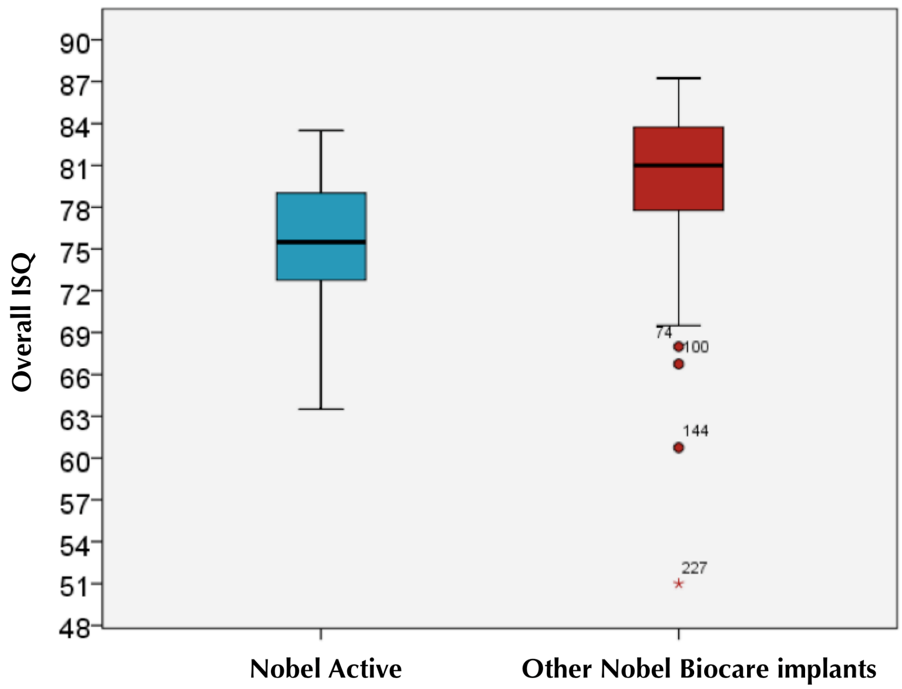


Figure 23. Mean ISQ for Nobel Active implants, compared with all other Nobel Biocare implants

5.4.4 Implant dimensions - surface area

Surface areas were available for the Nobel implants and ranged from 133 to 295mm^2. A positive correlation was found between surface area and ISQ but the value was very low (Pearson correlation coefficient 0.172, P-0.027). The scatter plot shows that there are no consistent patterns.

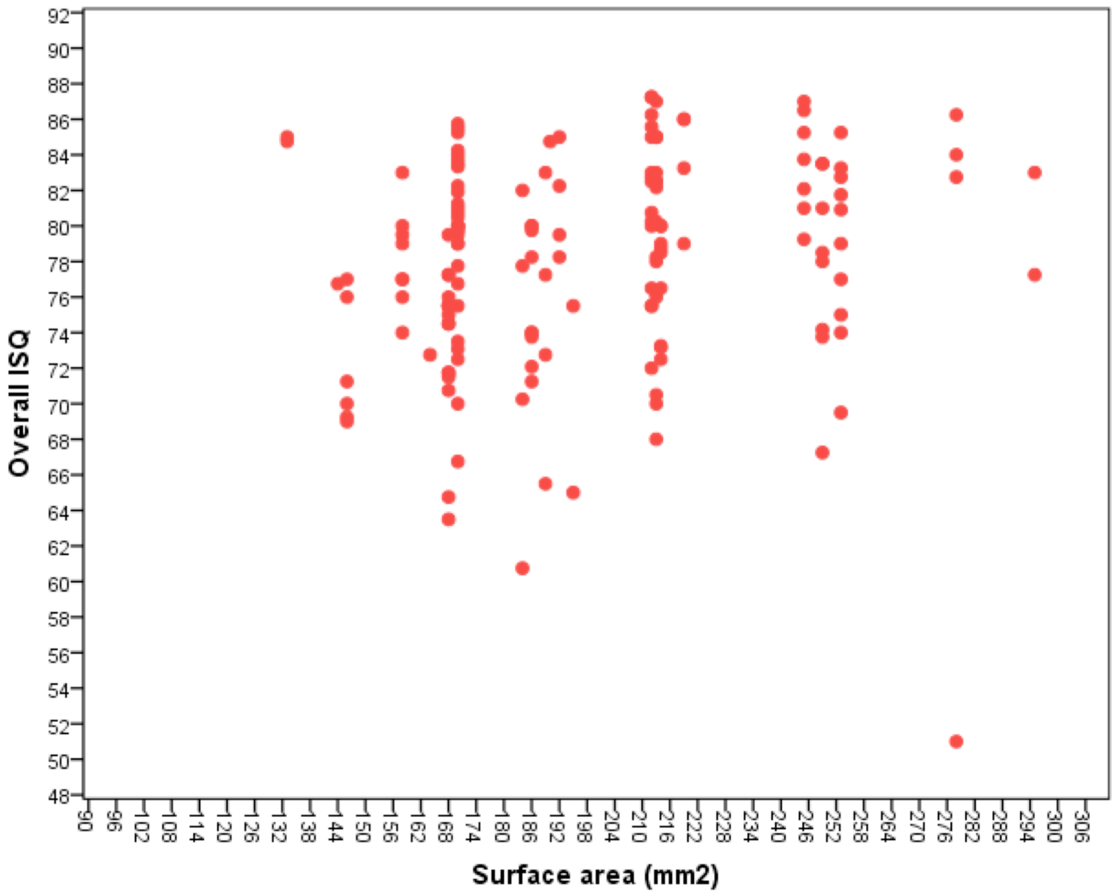


Figure 24: ISQ according to implant surface area (Nobel Biocare implants only)

5.5 Implant Placement-Related Factors

5.5.1 Insertion torque value

Implants were classified into five groups, based on the insertion torque value (Ncm) obtained at surgery, when available. The groupings were: 0-10 (n=5), 11-20 (n=45), 21-30 (n=68), 31-40 (n=104), and >40 Ncm (n=51). Insertion torque values were not available for 39 implants (12.5%). No statistically significant difference was found in ISQ between groups at second surgery (p= >0.20 for all comparisons). Additionally, both ISQ taken at the time of implant placement and insertion torque were available for 58 implants but the relationship between the two was completely insignificant (p=1.00).

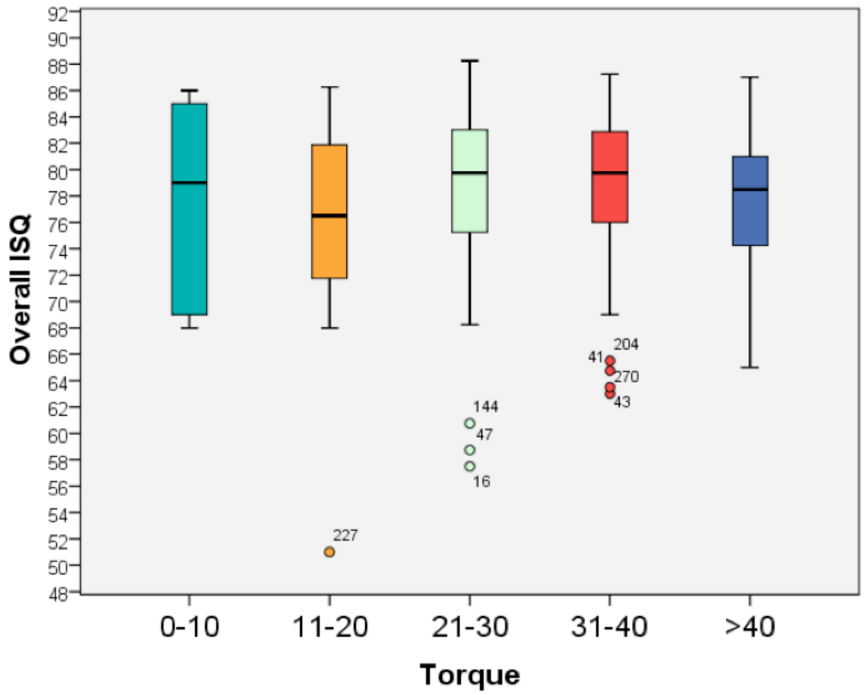


Figure 25: Second stage ISQ of implants based on insertion torque (Ncm)

5.5.2 Bone density

A tactile assessment of bone density was available for 151 implants. A statistically significant difference in ISQ was found for implants placed in soft (n=22), medium (n=99) and dense (n=30) bone. The mean ISQ for implants placed in dense bone was 77.60±6.18 and that of implants placed in medium bone was 77.82±5.52. In comparison, the mean ISQ for implants placed in soft bone was only 73.75±7.87, which was statistically significantly lower than the value for implants placed in bone of medium density (p=0.014). The differences between soft and dense bone (p=0.074) and between medium and dense bone (p=1.00) did not reach statistical significance. ISQ measured at implant placement and bone density were available for 36 implants and the relationship between the two was not statistically significant (p=1.00).

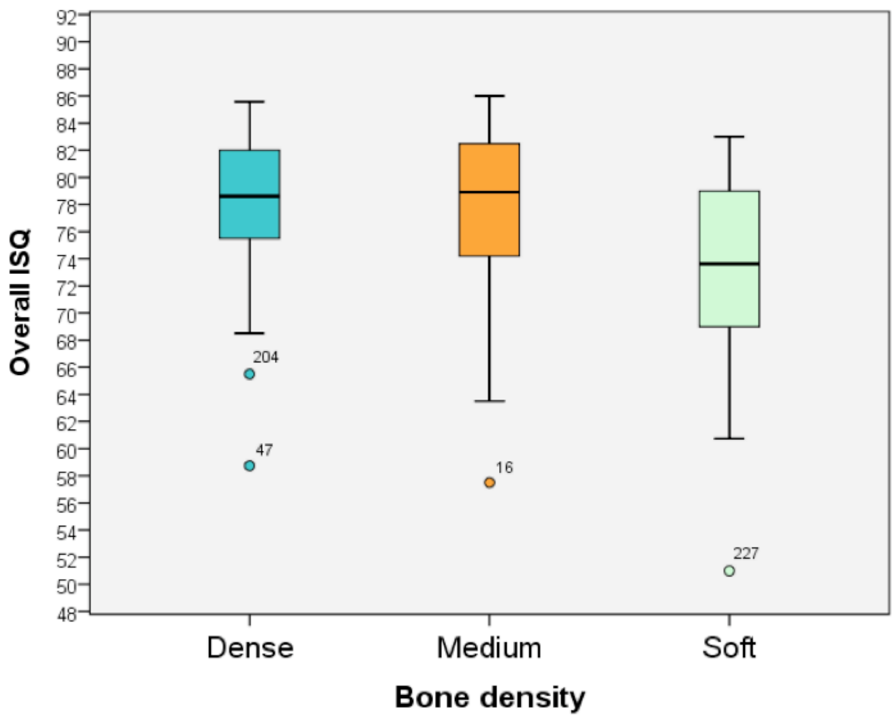


Figure 26. ISQ of implants based on bone density

5.5.3 Number of implants

Patients in this study population received between 1 and 14 implants, with 53.7% receiving only 1 implant, 25.5% receiving 2 implants, and 11.4% receiving 3 implants. Most patients had 4 or fewer implants but 5.4% had 4 or more implants. A slightly lower ISQ value was observed in patients who had more implants. The mean ISQ obtained for the 135 patients receiving between 1 and 3 implants was 78.97 ± 5.24, compared with 76.12 ± 4.94 for the 14 patients receiving between 4 and 14 implants. The difference between the two groups bordered on statistical significance (p=0.054).

5.6 Anatomic Site-Related Factors

5.6.1 Arch

Implants were placed in all regions of both jaws, with 54% in the maxilla and 46% in the mandible. The mean ISQ for implants placed in the mandible was 79.57 ± 5.76 and that for implants placed in the maxilla was 77.22 ± 5.79. A significantly higher mean ISQ was obtained for implants placed in the mandible, compared with implants placed in the maxilla (p=<0.001)

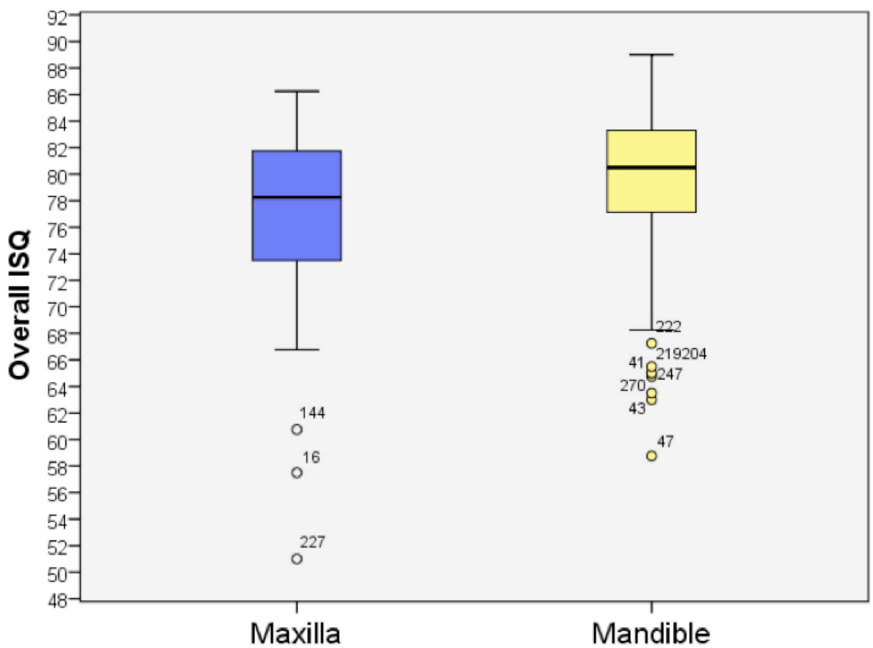


Figure 27. ISQ according to arch (maxilla or mandible)

5.6.2 Location in arch

Implant sites included 74 incisors, 24 canines, 81 premolars, and 107 molars. ISQ values for incisors were lower than the values for canines but the difference was not statistically significant (p=0.487). Incisors did, however, have a significantly lower mean ISQ than premolars (p=0.01) and molars (p=<0.001).

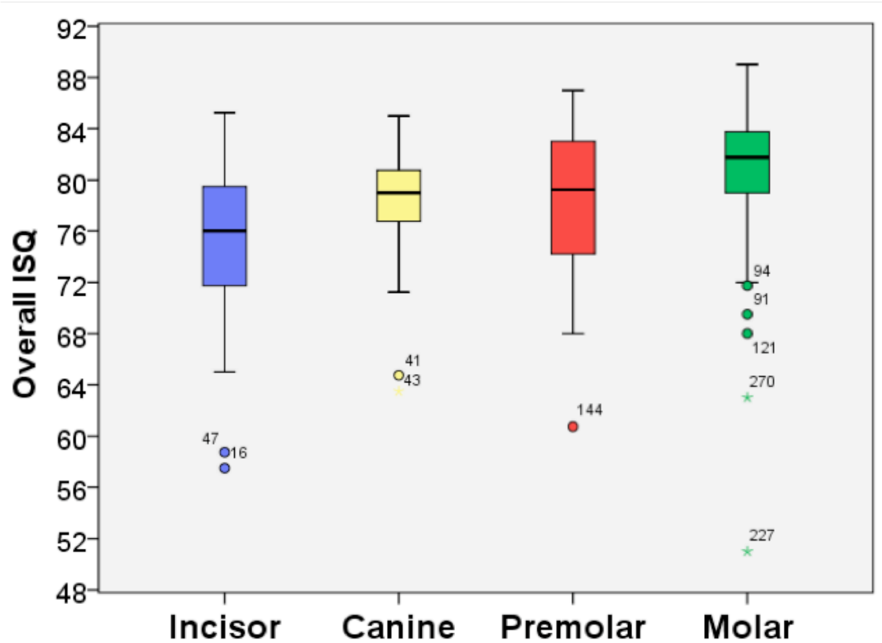


Figure 28. ISQ according to implant site

Data were also analyzed based on site within each arch. In the maxilla, there was no statistically significant difference in ISQ value based on the site (p=0.079). In the mandible, however, a significant difference was seen between incisors and premolars (p=<0.001, mean difference 6.51 ISQ units), between incisors and molars (p=<0.001, mean difference 8.81 ISQ units), and between canines and molars (p=0.005, mean difference 5.18 ISQ units).

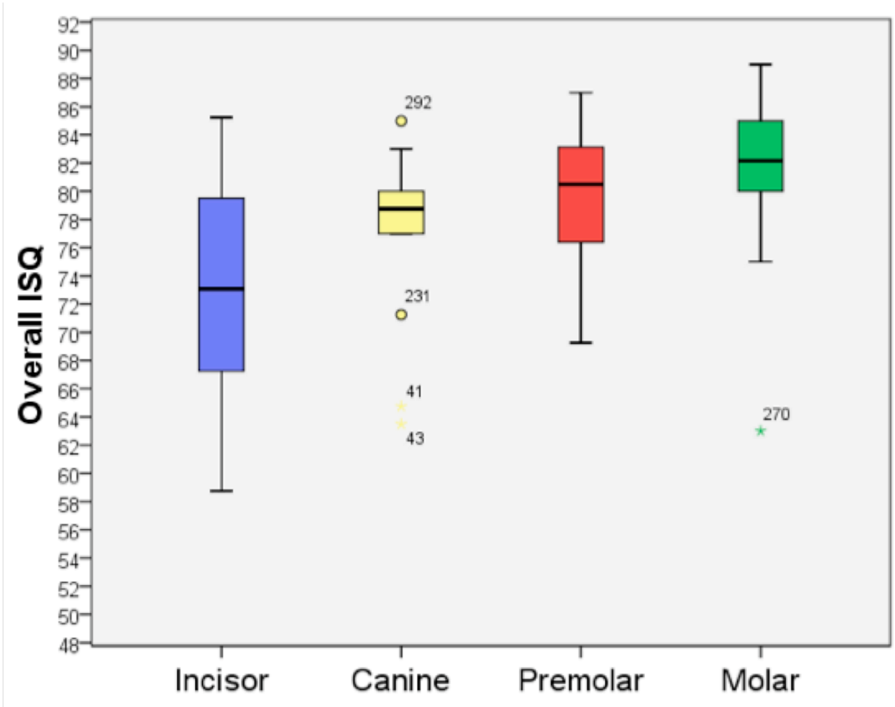


Figure 29. ISQ according to implant site in the mandible only

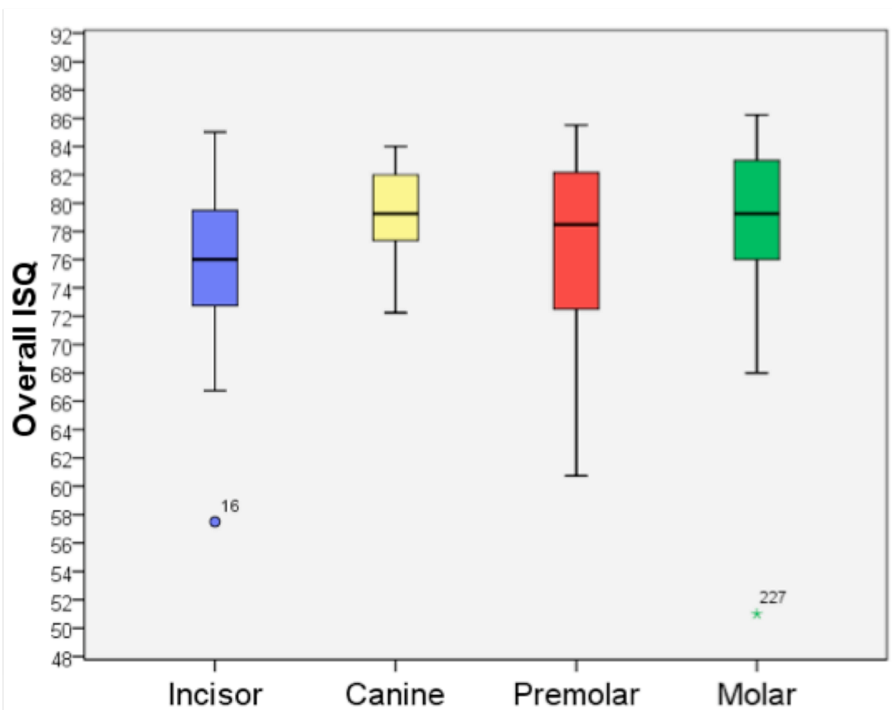


Figure 30. ISQ according to implant site in the maxilla only

Further comparison of arch site was done comparing maxilla and mandible. There were 57 maxillary incisor implants (mean ISQ 75.95 ± 5.11) and 17 mandibular incisor implants (mean ISQ 73.11 ± 7.53). The difference between arches was not statistically significant (p=0.16, mean difference 2.84 ISQ units). There were 11 maxillary canine implants (mean 79.14 ± 3.85) and 13 mandibular canine implants (mean 76.73 ± 6.46). The difference between arches was not significant for canines either (p=0.27, mean difference 2.41 ISQ units). There were 42 maxillary premolar implants (mean 77.21 ± 6.10) and 39 mandibular premolar implants (mean 79.62 ± 4.48). The difference between maxilla and mandible was statistically significant but clinically small (p=0.045, mean difference 2.41 ISQ units). There were 45 maxillary molar implants (mean 78.67 ± 6.35) and 62 mandibular molar implants (mean 81.91 ± 4.05). The molars accounted for the largest difference between the maxilla and mandible, with a significant (p=0.004) mean difference of 3.24 ISQ units.

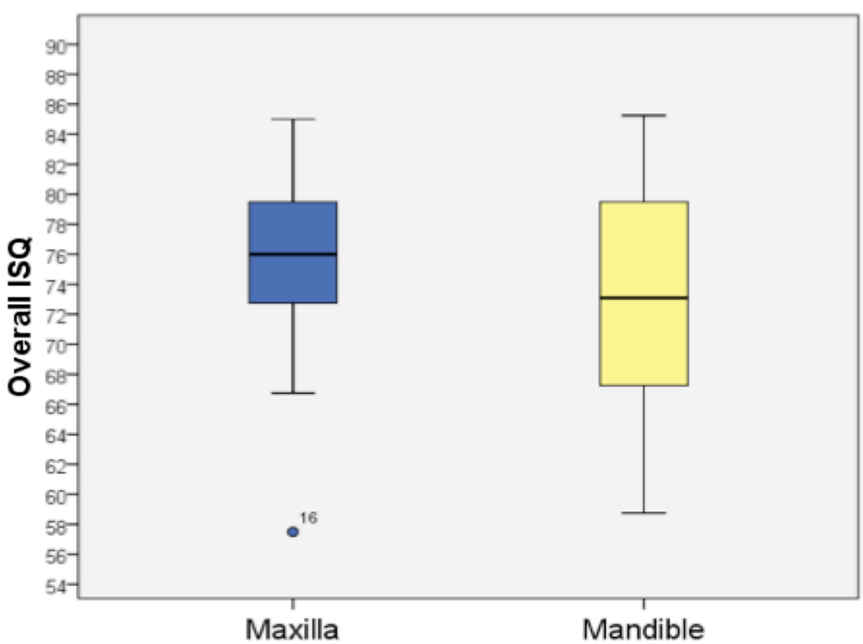


Figure 31. ISQ value for incisor implants placed in the maxilla and mandible

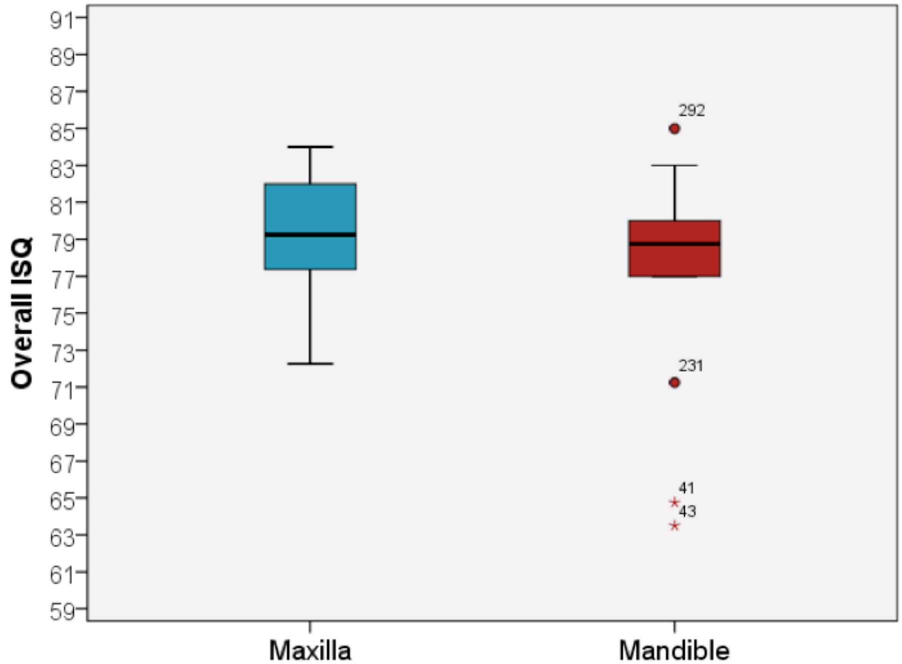


Figure 32. ISQ value for canine implants placed in the maxilla and mandible

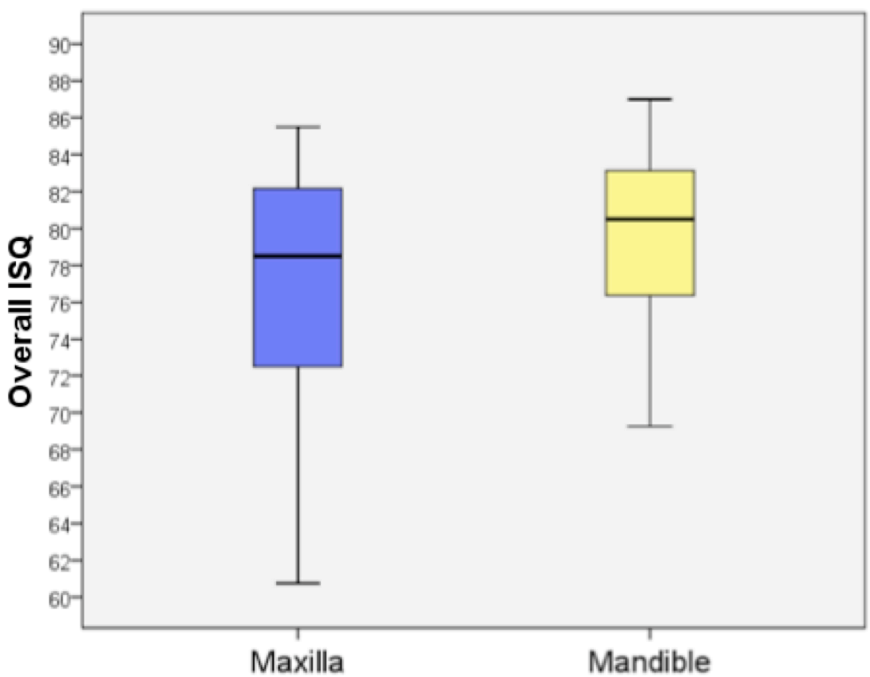


Figure 33. ISQ value for premolar implants placed in the maxilla and mandible

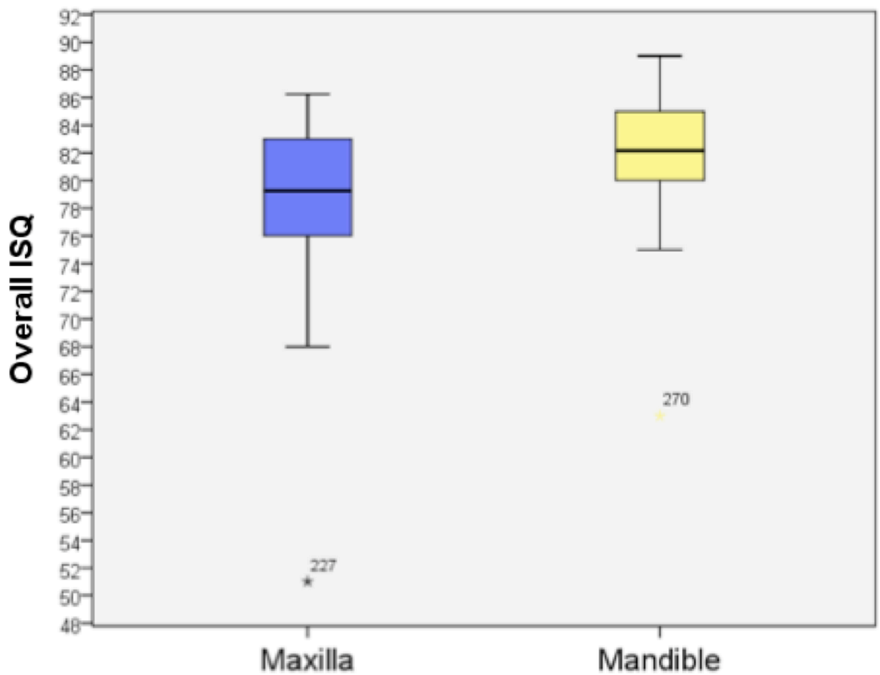


Figure 34. ISQ value for molar implants placed in the maxilla and mandible

5.7 Bone Grafting-Related Factors

A total of 110 implants were placed at sites that were not treated with any type of bone grafting, with a mean ISQ of 78.81±6.46. The mean ISQ for the 176 implants placed after any type of grafting (LRA, socket preservation, or sinus lift) was 78.06±5.47. The difference between these groups did not reach statistical significance.

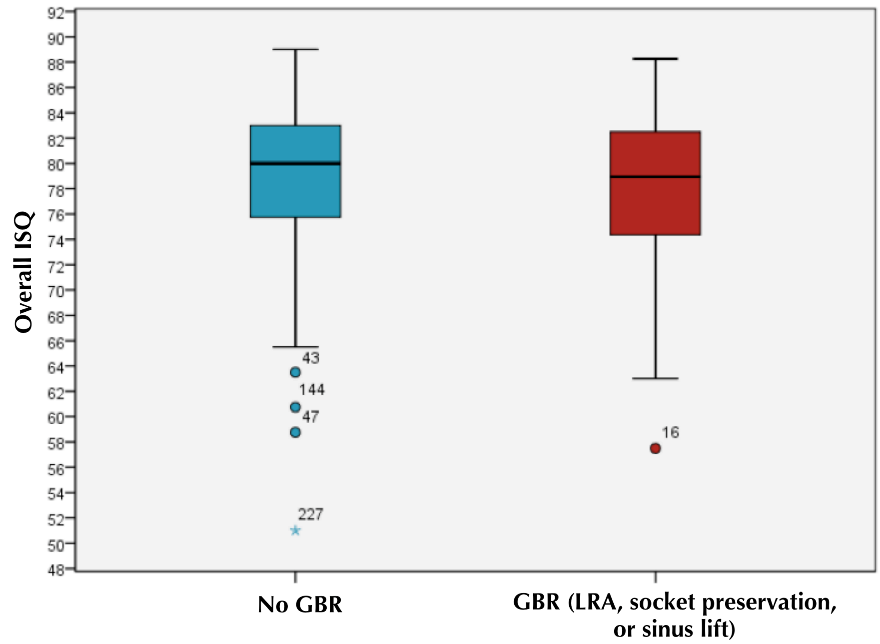


Figure 35. Mean ISQ of implants placed in native bone, compared to those placed at sites treated with guided bone regeneration

5.7.1 Lateral ridge augmentation

Of the assessed implants, 98 were placed at sites with lateral ridge augmentation (LRA) and 188 at sites without LRA (mean ISQ values 77.55 ± 5.64 and 78.76 ± 5.96, respectively). Overall, the ISQ values of implants which were placed at grafted or non-grafted sites did not differ significantly ($p=0.094$). There was also no statistically significant difference ($p=0.22$) in buccal ISQ between implants placed at sites treated with LRA (76.72 ± 6.01) and those placed at sites with native bone (77.69 ± 6.86).

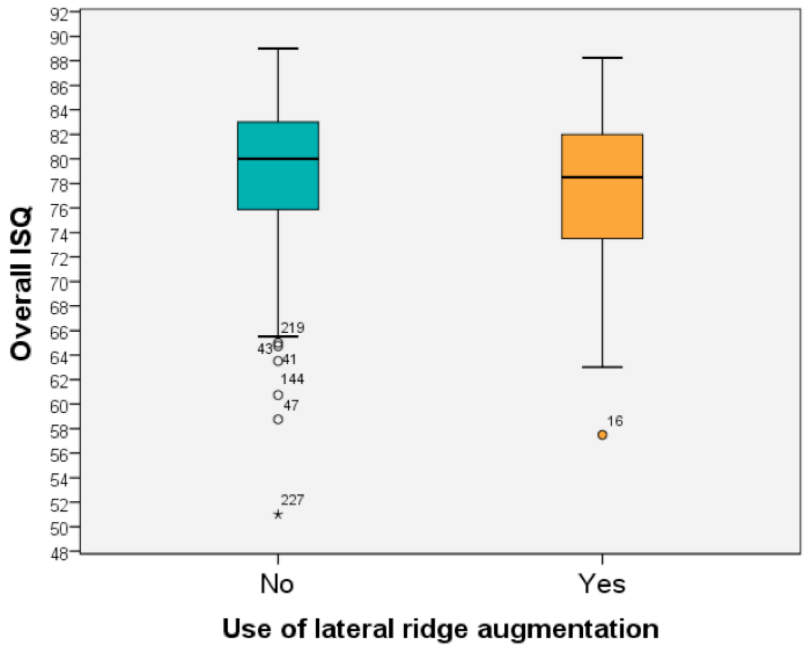


Figure 36. ISQ based on whether or not the site was treated with lateral ridge augmentation

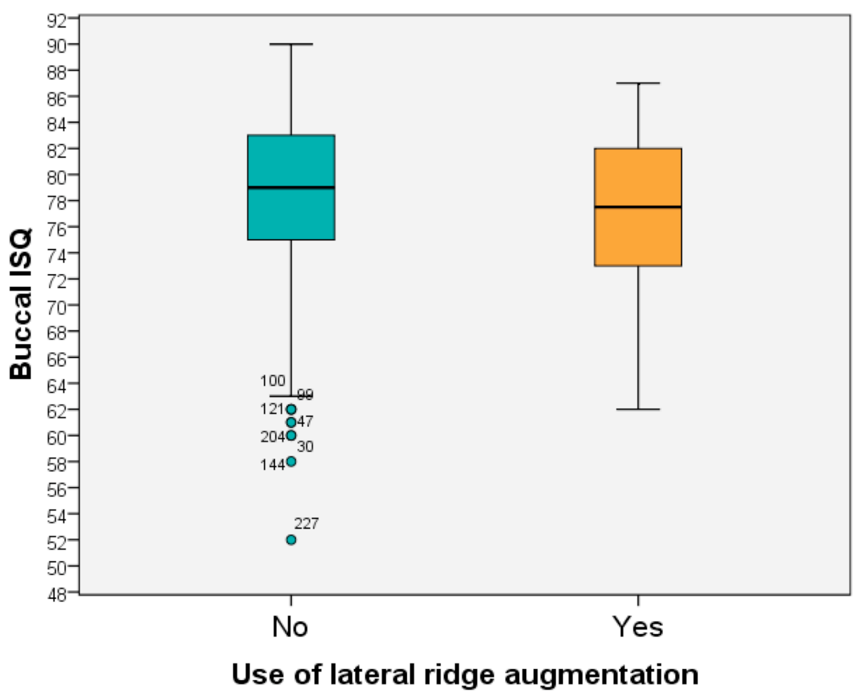


Figure 37. Buccal ISQ based on whether or not the site was treated with lateral ridge augmentation

Materials used for lateral ridge augmentation included autograft (n=12), allograft (n=64), and xenograft (n=22). The ISQ did not differ statistically significantly among most groups of implants placed in sites grafted with different LRA materials (no LRA 78.7±6.0; autograft 80.0±3.5; and allograft 78.0±5.8); however, the mean ISQ value for implants placed at sites treated with xenograft (75.2±5.2) was consistently lower than for other groups and significantly lower than for implants placed in sites with no LRA (p=0.042). When only the buccal ISQ value was considered for the various bone graft types, there were no statistically significant differences (p=>0.05 for all variables). Data regarding LRA and the ISQ at time of implant placement were available for 55 implants, all of which were placed in the university setting. The mean ISQ for implants placed in non-grafted bone (n=32) was 77.25±6.90. For grafted sites, the mean placement ISQ was 78.40±2.65 for autograft, 70.29±7.35 for allograft, and 76.32±4.65 for xenograft. The duration of healing from LRA to implant placement also did not appear to affect either the overall or the buccal ISQ value (p=>0.16 for all variables).

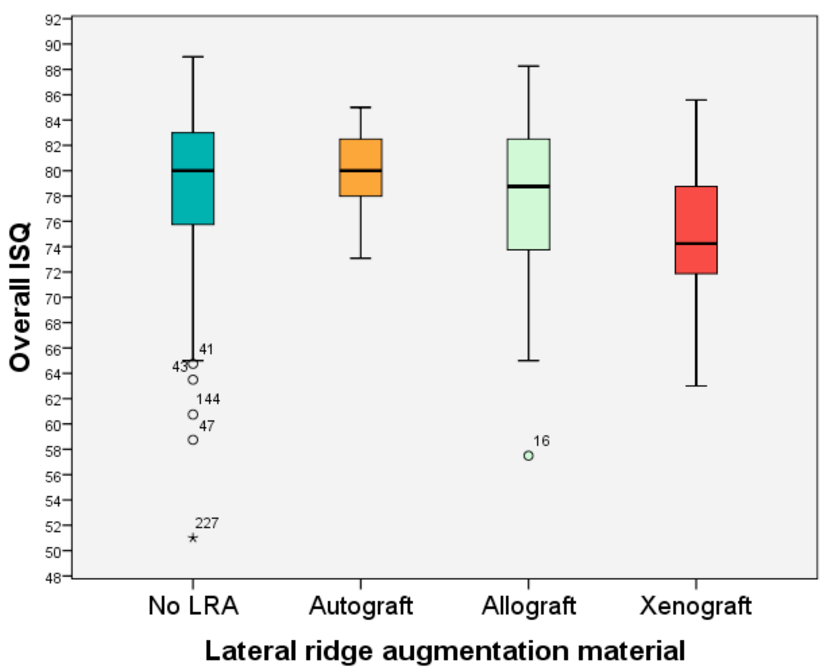


Figure 38. ISQ based on type of lateral ridge augmentation material used

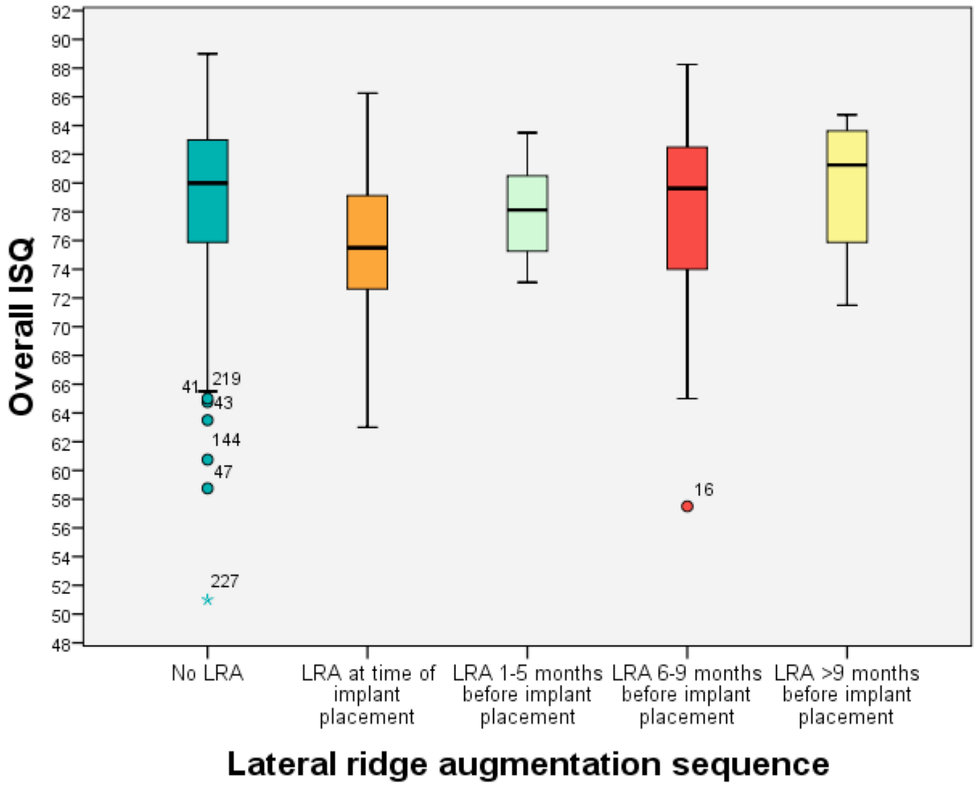


Figure 39. ISQ based on timing of lateral ridge augmentation

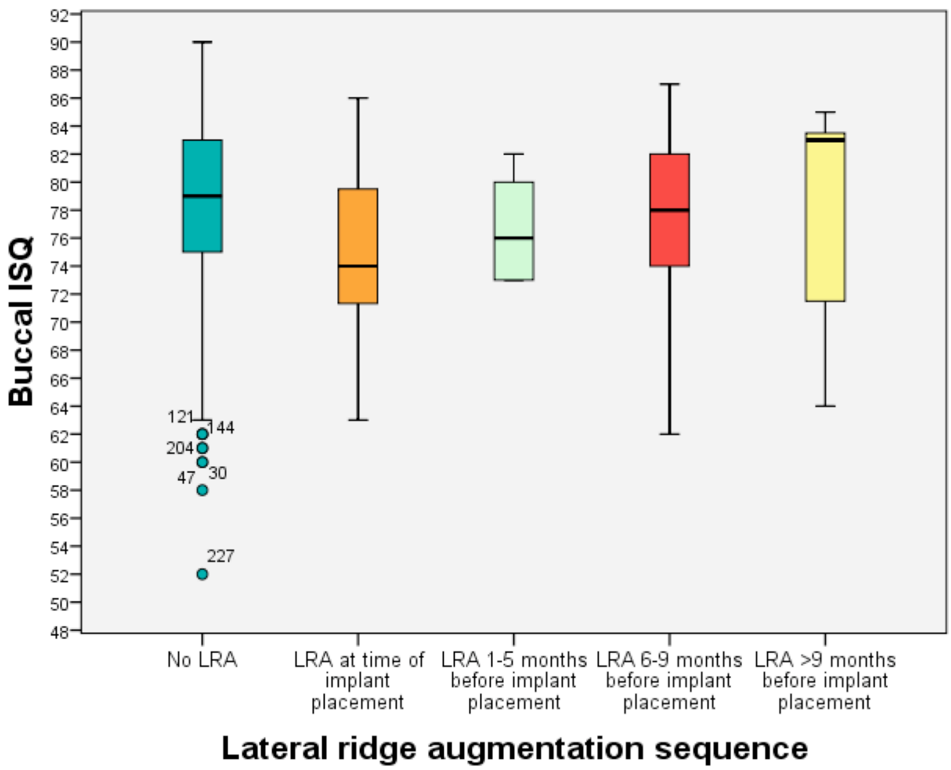


Figure 40. Buccal ISQ based on timing of lateral ridge augmentation

5.7.2 Socket preservation

No significant difference (p=0.835) was found in ISQ between implants placed in sites treated with socket preservation (n=53, mean 78.21 ± 5.21) and those not treated with socket preservation (n=232, mean 78.38 ± 6.03). Socket preservation was performed at 40 sites using allograft and 13 sites using xenograft and there were no significant differences in ISQ between these groups (p=>0.20 for all variables). Additionally, there was no significant effect whether the socket preservation was performed at the time of implant placement (for example, to fill in the gap between the implant surface and the alveolus during immediate implant placement), or if it was performed 1-5, 6-9, or >9 months prior to implant placement (p=>0.05 for all variables).

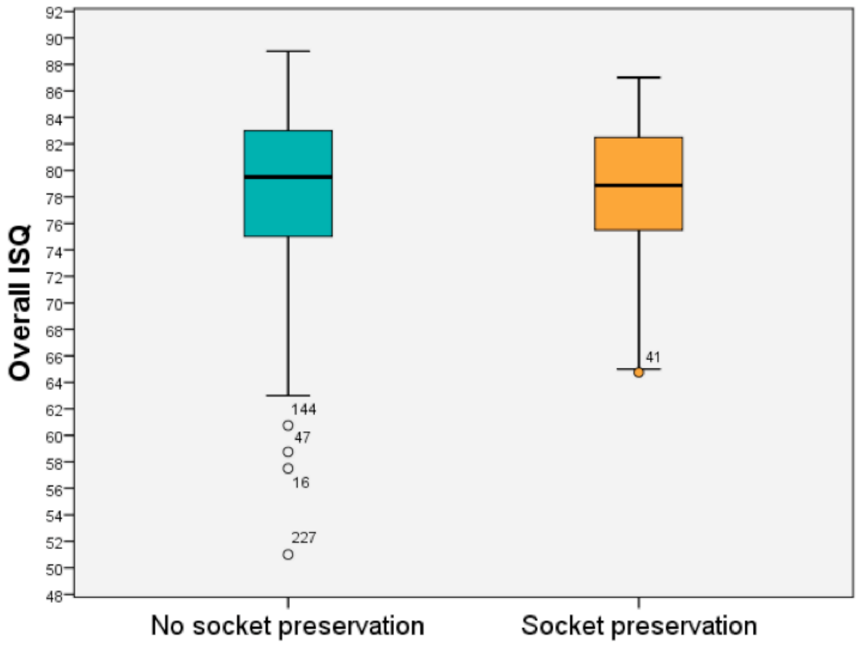


Figure 41. ISQ based on whether or not socket preservation was performed

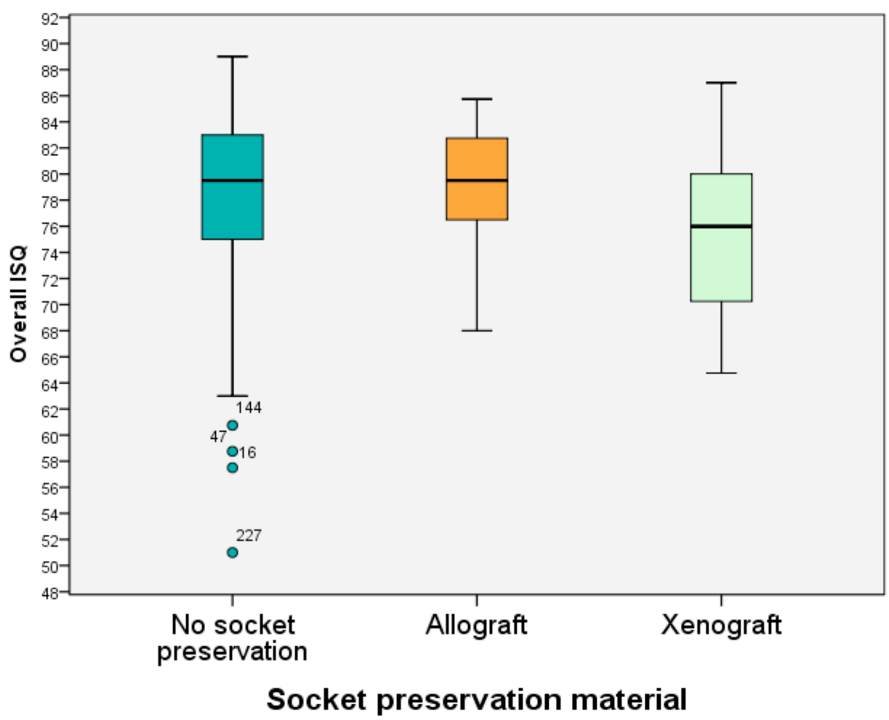


Figure 42. ISQ based on socket preservation material used

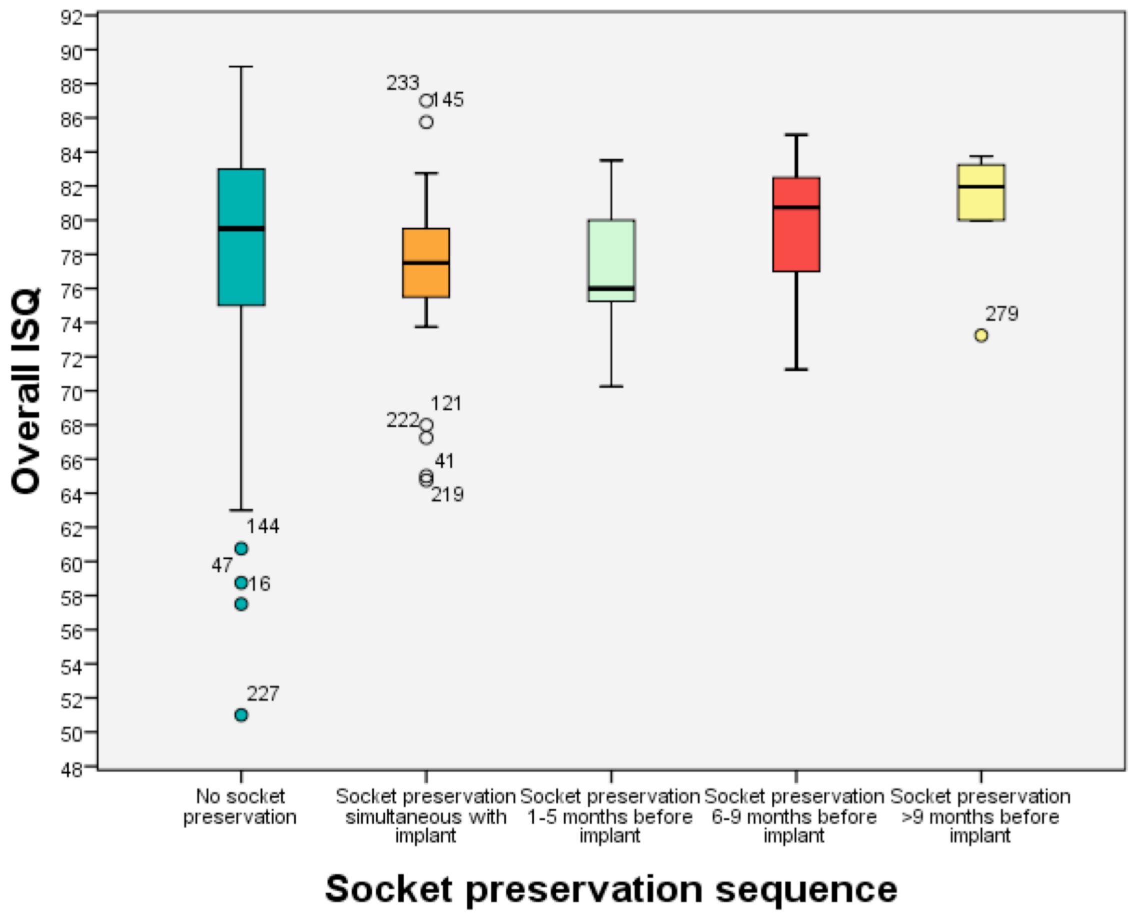


Figure 43. ISQ based on timing of socket preservation

5.7.3 Sinus lift

A total of 59 implants were placed at sites treated with sinus lifts. There was no significant difference in ISQ, whether or not the site had received sinus grafting (p=0.62). There were also similar results at sites treated with sinus lifts, regardless of the material used (no sinus lift 78.3±6.1; allograft 79.6±4.8; and xenograft 78.1±5.1). No statistical significance was reached (p=>0.1 for all comparisons). Implants placed simultaneously with sinus lifting (n=27) had similar ISQ values, compared with those placed both 1-9 (n=14) and >9 months later (n=18) (p=0.67).

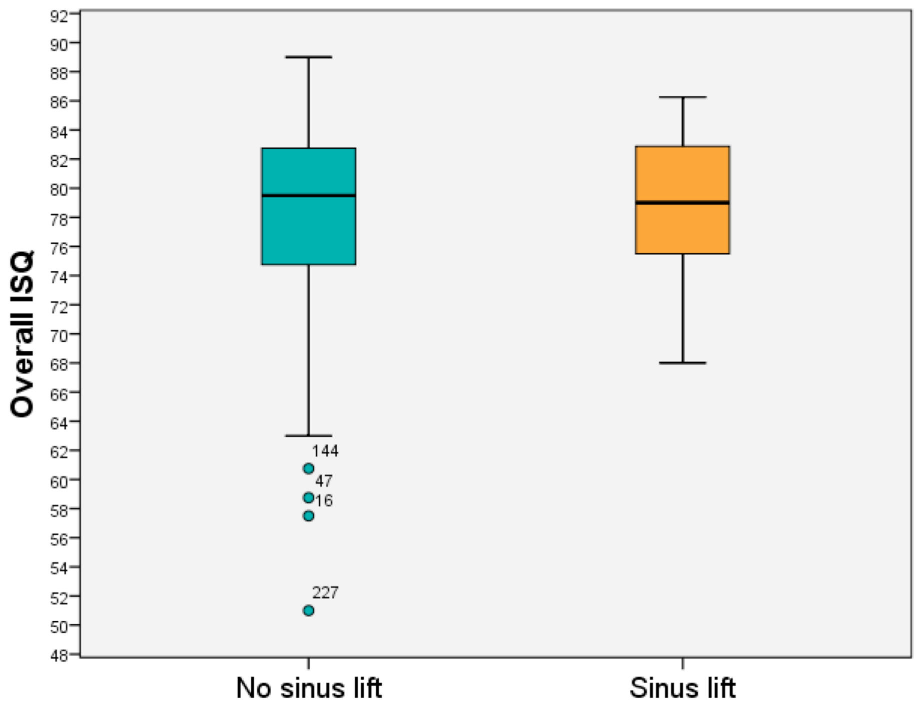


Figure 44. ISQ based on whether or not sinus lift was performed

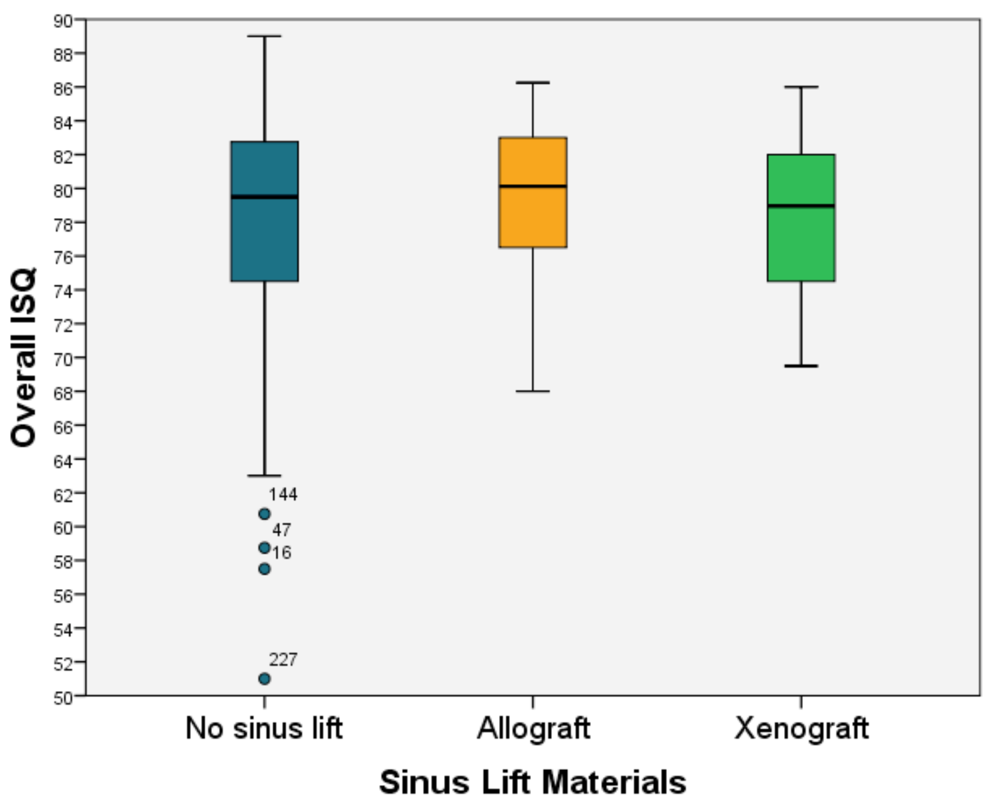


Figure 45. ISQ based on sinus graft material

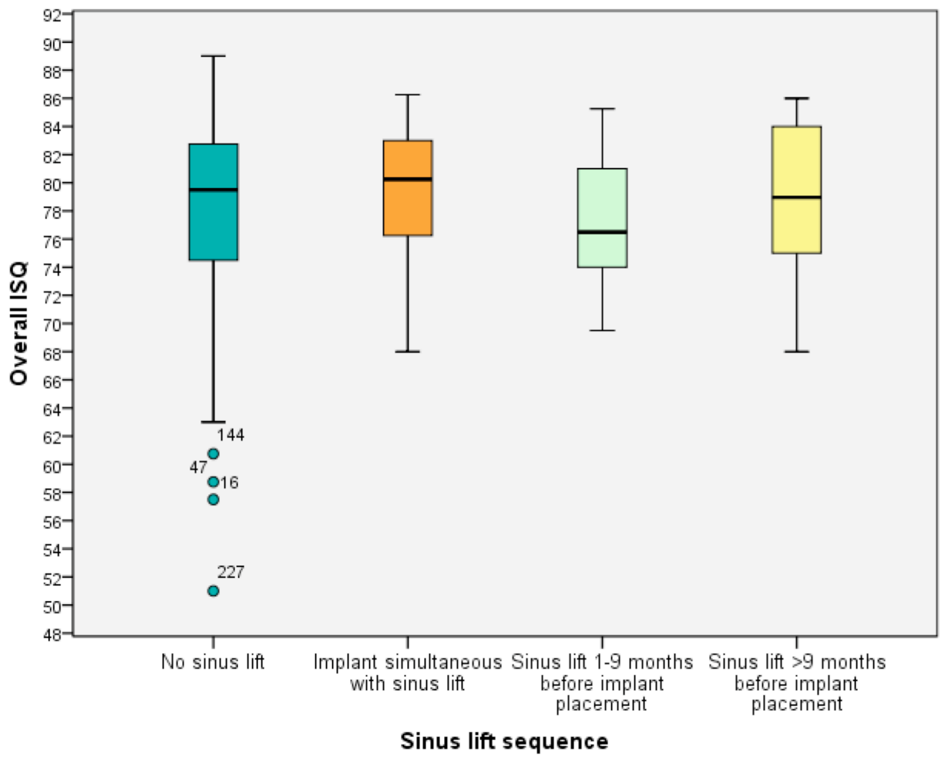


Figure 46. ISQ based on sinus graft timing

5.7.4 Presence of dehiscence at implant placement

If a dehiscence was present at the time of implant placement, it was measured and classified as either 0.5-2mm (n=23) or >2mm (n=9). There was no significant difference in overall ISQ value whether a dehiscence was present or between groups (p=1.00). Similarly, there was no significant difference when only the buccal ISQ was considered (p=1.00). Analysis of ISQ at the time of implant placement was not possible due to the small sample size.

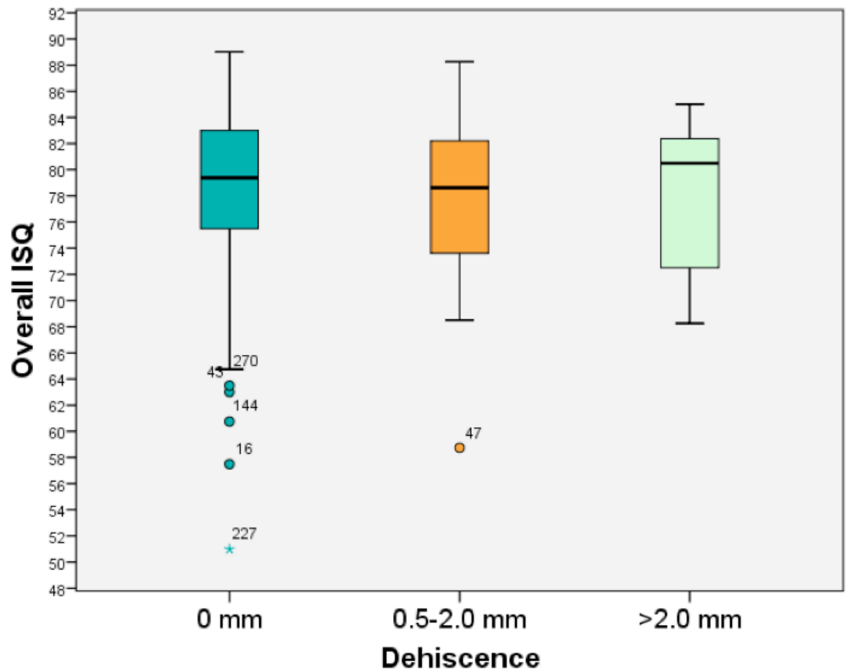


Figure 47. Overall ISQ based on presence and size of buccal dehiscence

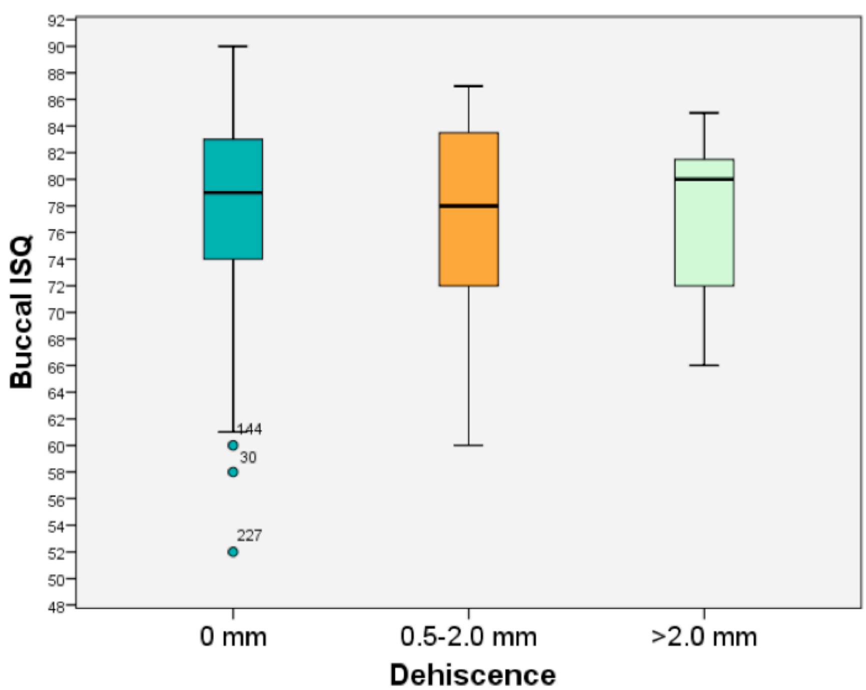


Figure 48. Buccal ISQ based on presence and size of buccal dehiscence

5.8 Factors Related to Timing of Implant Placement

5.8.1 Healing time

A significant correlation (p=0.004) was found between number of months of healing after implant placement and the ISQ, however the scatter plot demonstrated that there were no consistent trends

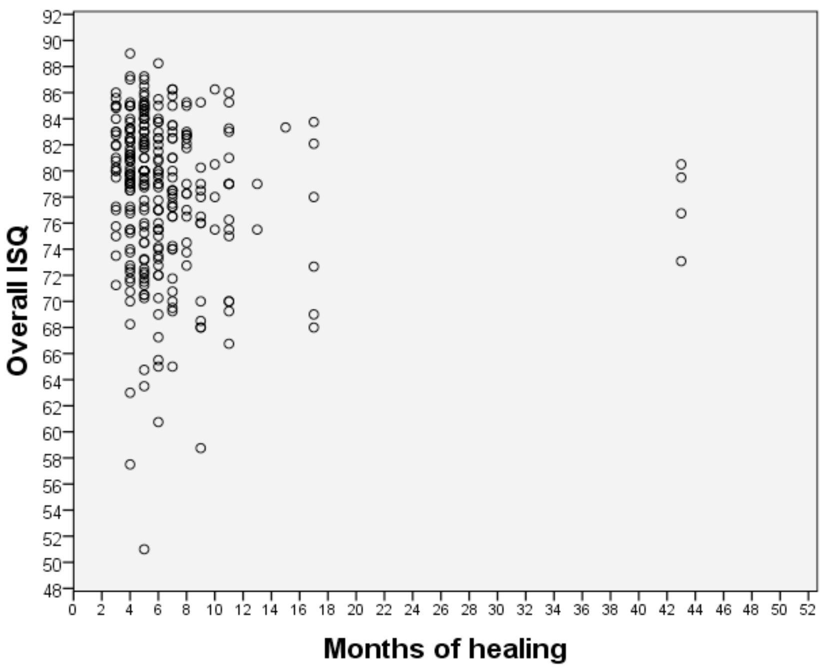


Figure 49. Scatter plot demonstrating no consistent pattern between the overall ISQ value and the months of implant healing prior to measurement of the ISQ.

5.8.2 Immediate placement

Immediately placed (n=40) and conventionally placed (n=246) implants were compared using the T test. A significant difference was found (p=0.008), with immediately placed implants having a lower mean ISQ (75.98 ± 5.91) than conventionally placed implants (78.73 ± 5.79). The mean difference between the groups was 2.75 ISQ units. Insufficient data was available on ISQ values taken at the time of implant placement.

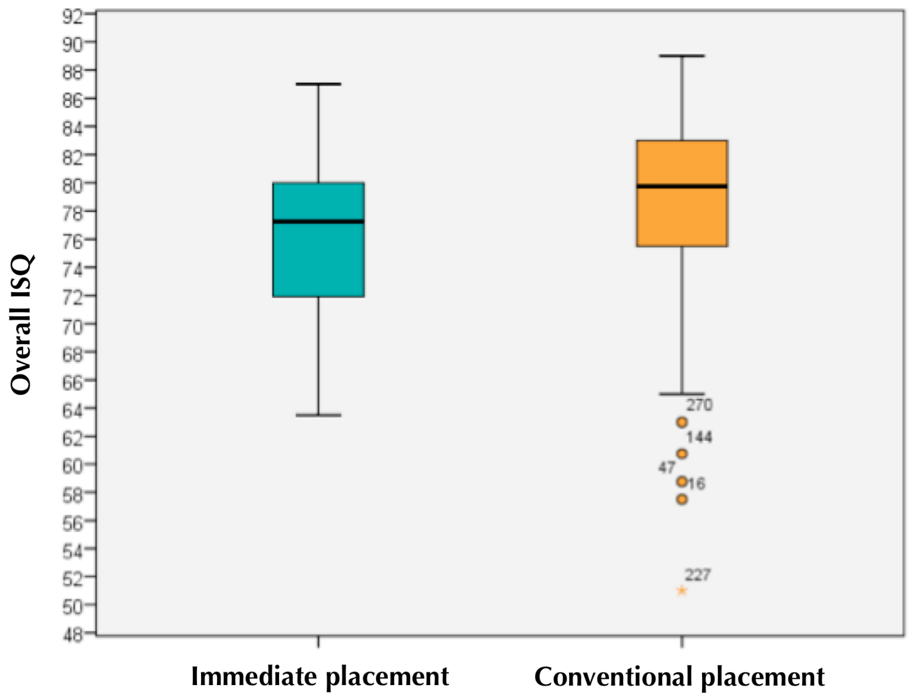


Figure 50. ISQ based on placement timing

5.8.3 Staging protocol

No statistically significant difference was found between implants which were placed with a one-stage or a two-stage (submerged) protocol. A total of 112 implants were placed in a one-stage manner, with a mean ISQ of 78.72 ± 5.92, compared with 174 two-stage implants with a mean ISQ of 78.11 ± 5.86.

ISQ measurements at the time of implant placement were available for 55 implants, 10 of which were placed with a one-stage protocol. The mean ISQ for this group was 78.66±3.61, compared with 75.98±6.88 for implants placed with a two-stage protocol. The difference between the groups did not reach statistical significance (P=0.093).

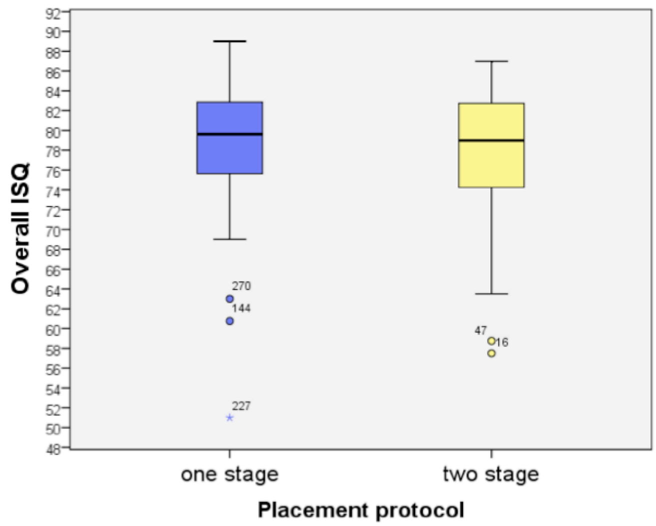


Figure 51. ISQ based on placement protocol

5.9 Level of Training of the Surgeon

Of the 286 implants, 231 were placed by experienced periodontists in private practice and 55 by graduate periodontics residents at the University of British Columbia (U.B.C.). This data was analyzed at the patient-level; 127 of the patients were treated by a periodontist and 22 were treated at U.B.C. The mean ISQ for implants placed by periodontists was 79.03 ± 5.22 and that for implants placed at U.B.C. was 76.83 ± 5.30. The mean difference was 2.20 ISQ units and did not reach statistical significance (p=0.083).

5.10 Linear Multiple Regression Coefficients

When controlled for gender, smoking (pack years, as a continuous variable), diabetes (presence/absence), number of implants, and surgeon (periodontist/resident), age remained a significant predictor of ISQ value (p=0.003). The remaining factors did not show statistical significance in this model: gender (p=0.499), smoking (p=0.078), diabetes (p=0.673), number of implants (0.062), and surgeon (p=0.078).

6. DISCUSSION

Measurement of implant stability is integral in evaluating the success of implants and deciding when to functionally load implants. Resonance frequency analysis, as used in this study, has the potential to provide an early indication of stability and allows repeated measurements over time to monitor changes. ISQ values were not consistently taken at implant placement, since most studies have shown that the initial ISQ has little bearing on the value obtained after a period of healing. It has been well-documented that initially high levels may decrease and initially low levels may increase in the early healing period, leading to similar ISQ values over time, regardless of the initial reading[6, 16, 24, 29, 31, 100]. The initial decrease in ISQ has been attributed to lateral compression during implant placement, leading to remodeling of the bone-implant interface post-insertion [109, 114]. Others, however, have found a steady increase in ISQ after placement[89, 91, 113], although this may be due to infrequent monitoring of ISQ in the early healing stages when the greatest change is expected. Cornelini et al (2004) [110] found that there was little change in ISQ if good primary stability was obtained. In the clinical setting in which the present study was conducted, the ISQ value was used to ensure sufficient stability had been reached to load the implant and to provide a baseline value for further follow-up. For these purposes, an additional measurement taken at the time of surgery would provide very little value, as it would not help in detecting early failure.

6.1 Osstell-Related Factors

6.1.1 Direction of measurement

The ISQ can be measured either perpendicular or parallel to the alveolar crest. The current study found that the buccal ISQ was not significantly different from the lingual or palatal ISQ, but that it was significantly lower than measurements taken from the mesial and distal. Several other studies have found lower ISQ values in a buccal-lingual orientation, compared with a mesial-distal orientation and this has been attributed to thinner bone on the buccal and lingual, compared to the interproximal areas[78, 79, 178]. It has been suggested that the difference between a parallel and perpendicular orientation to the alveolar crest may be up to 10 ISQ units[82]. It has also been shown that buccal and lingual values are not significantly different from each other, nor are the mesial and distal values[178]. The manufacturer of Osstell recommends taking measurements in both directions, to ensure that any discrepancies are identified.

6.1.2 Repeatability of measurements

Good reproducibility of ISQ measurements has been demonstrated by several authors, with many indicating a difference in the range of 1-2%[9, 33, 34, 63]. Very good reproducibility was also reflected in the results from the present study.

6.2 Patient-Related Factors

6.2.1 Age and gender

A trend for lower mean ISQ was found for implants placed in younger patients, however the difference among genders and age groups was not statistically significant. Results reported in the literature have been conflicting. A study by Turkyilmaz et al (2006) [50] found significantly higher ISQ values in men and in older patients; however, it was hypothesized that this was due to a greater proportion of implants placed in dense bone in the anterior mandible in older patients, as well as hormonal differences between the genders. Other authors have found higher values in males[99, 117] but the difference has been observed to dissipate with time[31]. Zix et al (2005) [115] found a significantly lower ISQ value in post-menopausal women, compared with men in the same age group. Another study found a significantly lower ISQ value in men[60]; however, in this study females received more implants in denser bone in the mandible and the sample size was quite small. Another study failed to find any difference between genders[43].

6.2.2 Diabetic status

This report did not show a statistically significant association between Type 2 diabetes and ISQ value; however, it is important to note that all diabetic patients were required to demonstrate acceptable diabetic control prior to receiving implant surgery. At the time of implant placement, all diabetic patients were considered to be well-controlled. The level of diabetic control (glycosylated hemoglobin, HbA1c), however, was often self-reported by the patients. Even with poor control (defined as HbA1c between 7.5 and 11.4%), Khandelwal et al (2011) [179] demonstrated implant success of 98% based on 48 Straumann implants placed in the mandible at least 4 months after extraction. Further, the implants had high baseline ISQ values (means ranging from 70.1 to 75.4), which increased significantly until 16 weeks (means ranging from 78.8 to 79.3).

6.2.3 Smoking status

The current study failed to find a statistically significant difference in mean ISQ for smokers, ex-smokers, and non-smokers. Only 6% and 22% of the population, however, were smokers and former-smokers, respectively, and smoking status was self-reported. There was a wide range of cumulative exposure to tobacco smoking, with pack-years ranging from 1 to 60, but this did not significantly impact the ISQ values. Balatsouka et al (2005) [118] also failed to show a significant effect of smoking on RF values in a study on rabbits. While the differences were not statistically significant in the current study, it was interesting to observe the frequency with which smokers experienced complications and had ISQ values below the expected ranges.

6.3 Implant Design-Related Factors

6.3.1 Implant type

Despite some trends, the current study failed to find any statistically significant difference between implant types. An important consideration, however, is that 63.0% of the implants were Nobel Biocare and only 22.7% and 14.3% were Straumann and Astra Tech, respectively. Another study comparing Straumann and Astra Tech implants found similar values for both types (mean ISQ 79.0 and 77.3, respectively) [53]. In contrast, a comparison of 6 implant types including both Brånemark and Straumann[125] found that the mean ISQ was above 60 for Brånemark implants and below 60 for Straumann implants. The reliability of comparing ISQ values of these two implant systems has been questioned and the difference attributed to variations in design and stiffness of components[115], as well as the typical placement of the Straumann implants in these studies in a supracrestal position, compared with placement of the Brånemark implants at the bone level[9, 130].

6.3.2 Implant dimensions

A statistically significantly higher ISQ value was obtained for short implants (≤9mm), compared with regular length (10-12mm) and long (≥13mm) implants; however, when the maxilla was evaluated in isolation there was no statistical significance. The greatest difference between implants of various lengths was seen for implants placed in the mandible, with short implants having significantly higher ISQ values than both regular and long implants. A significant difference was also found between regular and long implants, with longer implants having a mean ISQ 4.6 units lower than regular length implants.

The mean ISQ for short implants (<10mm) placed in the maxilla was 79.6, whereas that in the mandible was 82.7 and this difference reached statistical significance. The ISQ for short implants placed in the incisor or canine region was similar to that of implants placed in the premolar or molar region, with the mean difference less than 1 ISQ unit. There was an uneven distribution of short implants, however, with 76.7% placed in the mandible and only 16.3% placed in the incisor or canine sites. The increased use of short implants in the posterior mandible was related to limited vertical height superior to the inferior alveolar nerve canal and, in this area, the use of wider implants may have compensated for any effect on ISQ that the reduced height may have had. This is reflected in the fact that, of all 43 short implants, only one was narrow and this was placed in a maxillary incisor site.

Most studies have shown that implant length either has little effect on ISQ or that shorter implants have higher values than longer implants. Pattjin et al (2007) [79] found slightly lower ISQ values for longer implants placed in dense bone. Similarly, Ostman et al (2006) [99] obtained higher values for shorter implants and attributed this to design features of the implant with a reduced diameter in the coronal area for longer implants, as well as increased drilling needed to place longer implants. Other studies have found that implant length has very little effect on ISQ values[9, 29, 73, 90, 117]. Valderrama et al (2007) [29] noted that additional length has less effect once sufficient stability is obtained in the marginal area and related this to the fact that added implant length tends to be located in trabecular bone, rather than the dense cortical bone found in the crestal region.

In the current study, implant diameter was divided into three groups and a significantly lower ISQ was obtained for narrow implants (<4mm), compared with both of the wider groups. Narrow implants were found to have a mean ISQ 5.7 units lower than regular diameter implants and 5.5 units lower than wide implants in the maxilla, and 8.4 and 10.0 units lower in the mandible, respectively. In both arches, the difference between regular and wide diameter implants did not reach statistical significance.

While some studies have found that implant diameter has little bearing on ISQ values[90, 114], others have reported a significant correlation between implant diameter and ISQ[57, 73, 117]. Further, some studies have reported only a trend for lower values with narrow implants[84, 104] and Akkocaoglu et al (2005) [67] concluded that ISQ value is determined not by the overall implant diameter, but rather by the diameter at the neck of the implant. With this in mind, a comparison was done between all narrow-diameter Nobel Replace implants (n=6) and Nobel Active implants (n=70), both of which have the same platform diameter. The mean ISQ values of the two groups did not differ significantly but the number of narrow Nobel Replace implants was very low.

Implant dimensions were further analyzed according to surface area for Nobel Biocare implants. A positive correlation was found between total surface area and ISQ but the value was very low. This finding is not particularly surprising, given the higher ISQ for shorter implants, which could dilute the differences found between narrow and wider implants. Further, as discussed previously, several studies have discussed the importance of the crestal bone-implant contact in determining ISQ value.

6.4 Implant Placement-Related Factors

6.4.1 Insertion torque value

No statistically significant association was found between insertion torque and ISQ taken at second stage. In support of this finding, several authors have reported a significant association between insertion or cutting torque and initial ISQ[43, 45] but often this difference is no longer significant after a period of initial healing[16]. Becker et al (2006) [46] found that, for every 1-unit increase in torque, the ISQ increased by 0.3 units at the time of implant placement, but decreased by 0.2 units after 3 months. This was attributed to pressure necrosis caused by placement of the implant at a higher torque and similar results were obtained by Nkenke et al[47]. In contrast, others have reported no significant correlation between insertion or cutting torque and ISQ value[10, 54, 55] and Karl et al (2008) [57] argued that insertion torque provided little clinical benefit, given that it can be used only at the time of implant placement and has little association with stability after a period of healing.

6.4.2 Bone density

Although initial ISQ has been shown to be lower in soft bone, the ISQ taken after healing appears to be similar regardless of bone density[9, 31, 87, 89-91]. Barewal et al (2003) [9] observed the lowest ISQ in all bone types at 3 weeks, with a large drop in ISQ from baseline to 3 weeks in softer type 4 bone, followed by a large increase until 10 weeks. At 5 weeks, there was no significant difference in ISQ based on different bone densities. Bischof et al (2004) [90] found that the values equalized among different densities by 12 weeks. In contrast to these reports, the current study found a significantly lower mean ISQ for implants placed in soft bone, compared with medium or dense bone, even after several months of healing. It is important to consider, however, that the measurement of bone density was based on tactile sensation and was at the surgeon's discretion. It may be argued that it is inappropriate to compare these subjective measurements, taken by several different surgeons in different clinical environments. As such, subsequent analysis was done of only the implants placed in private practice by an experienced periodontist, for which stability values were available (n=96). Results of this analysis showed borderline significance (p=0.06), with the highest values in bone of medium density and the lowest values in soft bone. However, the distribution between groups was uneven, with 15 implants placed in dense bone, 64 in medium bone, and 17 in soft bone. Further, the standard deviation of implants placed in soft bone was very high and nearly reached 8 ISQ units.

6.4.3 Number of implants

A lower mean ISQ was obtained in patients who received more implants and this bordered on statistical significance (p=0.054). It may be important to consider why these patients lost multiple teeth and whether the predisposition to multiple tooth loss could also predispose to a lower implant stability.

6.5 Anatomic Site-Related Factors

6.5.1 Arch and location in arch

A statistically significantly higher mean ISQ was obtained for mandibular implants compared with maxillary implants but the difference was clinically small. Implants placed in the incisor position were found to have a significantly lower ISQ than those at the premolar or molar sites but no significant difference was found between implants at any other positions. When the arches were analyzed independently, the difference between anterior and posterior sites was found to pertain only to mandibular implants. In the mandible, implants in the canine position had significantly lower ISQ values than those at molar sites and those at incisor sites had significantly lower ISQ values than those at premolar and molar sites. The only significant difference between the arches was found at molars, which had statistically significantly higher ISQ values in the mandible.

Barewal et al (2003) [9] followed implants up to 10 weeks and found higher values in the mandible at all time points. In this patient population, no maxillary implants were placed in dense type 1 bone and a greater proportion of maxillary implants were placed in soft type 4 bone, which likely accounts for the difference between the arches. Balshi et al (2005) [31] had similar findings up to 90 days. Other authors have also observed higher values in the mandible[53, 94, 99] but not all studies support these findings and some reports show no significant difference between the arches[59, 70, 72].

Although some studies have shown that the difference between the arches diminishes over time[100, 101], a common finding was a continued higher ISQ for mandibular implants. Bischof et al (2004) [90] demonstrated that the difference was still significant at 12 weeks, and that the increase in maxillary ISQ was slower, becoming significant only after 12 weeks, compared to 6 weeks for mandibular implants. At 12 months, Horwitz et al (2007) [102] still found a significantly higher ISQ for mandibular implants.

Ostman et al (2006) [99] found higher values in the posterior and reasoned that this was due to the use of wide-platform implants in the posterior, compared with regular- or narrow-platform implants in the anterior. Other authors have also supported this finding[57, 59] and Karl et al (2008) noted that the highest values were in the posterior mandible and the lowest values in the anterior maxilla. Becker et al (2005) [100], however, did not find a significant difference between implants placed in the anterior or posterior, nor did Kahraman et al (2009) [45] and 2 cadaver studies even found a higher mean ISQ at anterior sites[19, 49].

6.6 Bone Grafting-Related Factors

6.6.1 Guided bone regeneration

Most studies on GBR have been done using autogenous bone. Kramer et al (2005) [78] reported good success of implants after a fibula graft, with progressively increasing ISQ values over 12 months. Brechter et al[170] found a similar pattern of stability over 12 months, for implants after sinus elevation without graft material or with a ramus graft, and for autogenous (iliac crest) onlay or interpositional bone grafting. Sjöström et al (2005) [6] compared the ISQ of implants placed in native bone or after autogenous onlay or interpositional grafts and found similar values in all groups. Similar values at grafted and native sites were also shown by Özkan et al (2007) [5], with autogenous symphyseal grafts, and by Tong et al (2008) [4] with autogenous grafts in the anterior maxilla.

The present study sought to determine if the ISQ value would also be similar between implants placed in native bone and those placed in bone augmented with bone allograft. Overall, no significant difference was found, whether or not a lateral ridge augmentation was performed, and this finding was confirmed for both an overall mean ISQ value, as well as for ISQ taken only from the buccal. Since there was only one case treated with alloplast, this case was excluded, leaving 12 implant sites treated with autogenous bone, 64 treated with allograft, and 22 treated with xenograft. No significant difference in ISQ was found for autograft or allograft, however sites treated with xenograft had significantly lower ISQ values. Similarly, no significant difference in ISQ was found for sites treated with socket preservation, compared with native bone, regardless of the material used and the duration of healing prior to implant placement.

6.6.2 Sinus lift

A total of 59 implants in this population were placed at sites that received sinus lifting and no significant difference in ISQ was found, whether or not sites had been treated. The majority of the sinus lifts were performed using allograft or xenograft and no significant difference was found with the different materials. Only one case had been treated with autogenous bone and this treatment was not performed at either of the centres included in this study. The case was transferred to the clinic, having been previously treated with an autogenous sinus lift. Since full records were not available, this case was not considered for further analysis. Degidi et al (2007) [168] also compared implants placed in previously sinus-grafted sites (50% autograft, 50% xenograft) with those placed in healed bone and found no significant differences. The similarity of ISQ values, whether or not sinus augmentation has been performed, likely relates to the relative importance of the crestal portion of the bone-implant contact, compared with any added length that may be obtained from performing a sinus augmentation.

6.6.3 Presence of buccal dehiscence at implant placement

With the Osstell ISQ device, magnetic pulses cause vibrations in two perpendicular directions, therefore a low ISQ in one direction should indicate if bone is missing on only one side of the implant[8]. In this study, the presence and length of a buccal dehiscence was noted at the time of implant placement. No statistically significant difference in ISQ was found after initial healing, regardless of the length of the dehiscence (0-5-2mm or >2mm). There were also no significant findings when only the buccal ISQ was considered. The lack of significance could be due to the relatively small size of the dehiscence defects. Merheb et al[74] found that significant differences were detected only above 6-mm in length. These authors noted that the Osstell was most sensitive at detecting marginal bone loss (threshold 2mm) but not very sensitive with other patterns of peri-implant bone loss, including dehiscence-type defects. Further, larger dehiscence defects were typically treated with bone grafting at the time of implant placement and it's possible that this affected the ISQ at second surgery.

6.7 Factors Related to Implant Timing

6.7.1 Immediate placement

Immediately placed implants were found to have a significantly lower ISQ value compared with implants placed in healed bone. This is likely due to the coronal gap, which is typically present between immediate implants and the surrounding socket. Since ISQ values are highly dependent upon coronal stability and bone-implant contact in the coronal region, this may have led to lower ISQ values for immediate implants. In the present study, however, lower values were observed to persist after several months of healing. Bogaerde et al[101], found a lower ISQ value for implants placed immediately (65.8 at placement and 67.5 at 6 months), compared with those placed in healed bone (68.1 at placement and 73.6 at 6 months).

In contrast, Lindeboom et al (2006) [138] obtained the same ISQ at 6 months after implant insertion (64.5), whether implants were placed immediately after extraction or delayed by 3 months. Nordin et al (2007) [139] also obtained the same ISQ for immediate implants and those placed in healed sites. Palattella et al (2008) [140] observed lower surgical ISQ values for Straumann implants, but the final ISQ values were similar.

6.8 Experience of Surgeon

A trend was noted for higher ISQ values for implants placed by an experienced periodontist, compared with periodontics residents; however the difference did not reach statistical significance. While a similar protocol for ISQ measurement was used at both centres, a different Osstell ISQ device was used at each location.

6.9 Prediction of Failure

The mean ISQ for the three implants that failed and were removed were 70, 74, and 51 at the time of second surgery. The value of 51 was the lowest recorded ISQ of the entire data set and clearly indicated a failing implant. The values of 70 and 74, however, were closer to the overall mean of all implants (78) and were not as clearly associated with failure.

One patient had four implants placed (sites 12, 32, 42, 45) and experienced peri-implant bone loss at two of his implants within 18 months of placement (sites 42 and 45). For the implant placed at site 42, the initial mean ISQ measurements were 70.3, 72.7, 73.0, 72.0 from the buccal, lingual, mesial, and distal, respectively. The corresponding values taken 9 months later were 59.0, 56.7, 57.0, and 57.0. The implant was exposed surgically (Illustration 1), revealing circumferential bone loss, most advanced on the buccal. The patient also had an implant placed at site 32 at the same appointment and both were Straumann BL SLA 3.3mm x 12mm, placed at bone level with an insertion torque of about 25Ncm in dense bone. Surgery was unremarkable with no complications. No bone augmentation needed prior to or in conjunction with implant placement and a two-stage protocol was used. The implant placed at site 32 had initial mean ISQ values of 66.0, 67.0, 68.3, and 68.3 (buccal, lingual, mesial, distal). At 9 months, the corresponding values were 64.3, 66.3, 68.7, and 64.7. This implant did not present with the same degree of bone loss but did show about 1mm of crestal bone loss. This particular patient reported a history of 50 pack years of smoking. He was able to refrain from smoking for several weeks prior to implant placement but resumed smoking at a reduced volume two weeks after implant placement. Following this, he continued to smoke at a much higher volume, reaching up to 1 pack per day at the time of osseointegration check. The other implant with advanced bone loss in this patient was placed at site 45 (Straumann BL SLA 4.1mm x 12mm), flush with the bone crest in medium density bone with an insertion torque of 20Ncm. Again, this surgery was unremarkable and a two-stage protocol was used (Illustration 2). The mean initial ISQ values were 68.3, 67.0, 66.3, and 66.7. Seven months later, the corresponding ISQ values were 68.0, 69.7, 68.7, and 68.7. This implant showed significant circumferential bone loss, despite the relatively stable (or increasing) ISQ values. In this particular situation, the ISQ value did not provide an early indication of failure.

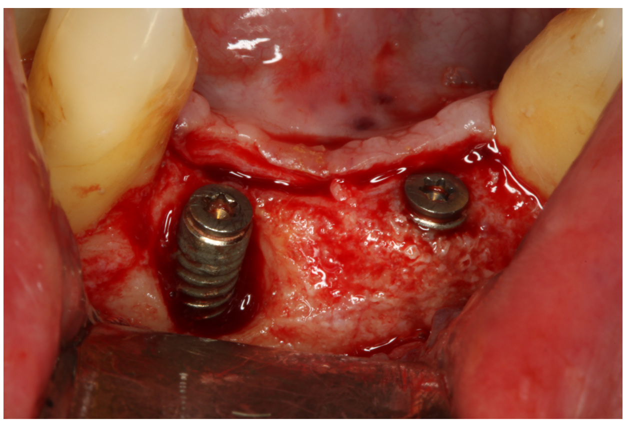


Illustration 2: Implants at sites 32 and 42, with advanced bone loss at 42

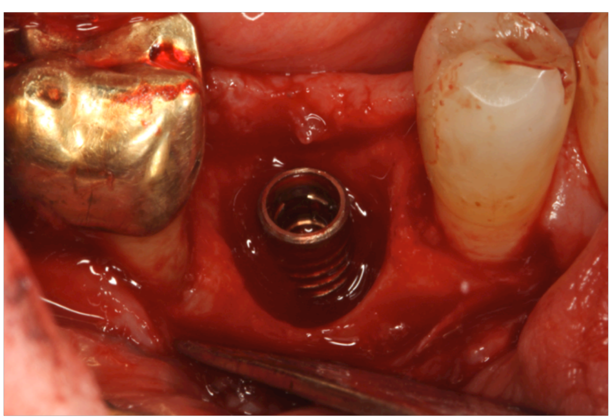


Illustration 3: Circumferential bone loss at site 45

Another patient experienced mobility of an implant placed at site 17 (Nobel Replace Straight Groovy 5.0mm x 12mm) and the implant was removed. No bone loss was detected on the facial or palatal, however the site was filled with granulation tissue. The implant was placed using a one-stage protocol in bone of medium density with an insertion torque of 20Ncm. This site had been treated with a sinus augmentation 9 months prior to implant placement using xenograft. Surgical ISQ values were not available but seven months after implant placement, the ISQ ranged form 68-70 from all directions. This patient also reported a heavy smoking history of 40 pack years but was not a current smoker at the time of surgery. Another mobile implant was noted at site 27 in a non-smoker. This was a Nobel Replace Tapered Groovy 5.0 x 15.0mm implant placed using a one-stage protocol in soft bone with an insertion torque of 15Ncm. The ISQ values taken at 5 months ranged from 48-52. No initial ISQ values were available for comparison.

Implant loss was also experienced by another former-smoker (10 pack year history), at site 12. The same patient had an implant placed at site 15, which showed radiographic bone loss to the third thread. Both implants were Nobel Replace Tapered Groovy 4.3mm x 10mm and were placed with insertion torques of 25 and 45Ncm, respectively. Neither received any bone augmentation and both were allowed to heal for 11 months prior to obtaining ISQ values. The ISQ values at the failed 12 implant were 62 and 63 from the buccal and lingual, and 71 from the mesial and distal. The ISQ values at the 15 were 62 from the buccal and lingual and 78 from the mesial and distal.

A low or reduced ISQ has been reported for failing or failed implants in several studies[6, 47, 92, 102, 132, 146, 159, 172-175] and some reported reduced ISQ values prior to clinical detection of mobility[132, 146], indicating prediction of implant failure. In the present study, with measurements taken only once or twice for each implant, monitoring decreasing ISQ values was not possible.

6.10 Limitations of Study

This retrospective study had a large sample size in general, however some comparisons were not possible due to the low number of subjects for certain conditions. The study was conducted at two different centres and by a number of different practitioners, with different levels of experience. Different Osstell units were used at each centre, however they were the same model and were used with the same protocol and each was calibrated prior to each use. No standardization or calibration was possible between practitioners and patients were treated on an individual basis, at the discretion of the surgeon. The healing time prior to osseointegration check varied widely and was also at the surgeon's discretion. Measurement of bone density was subjective and no standardization was possible between practitioners. However, a simplified classification was used, with distinction made only between soft, medium and dense bone. Initial placement data was not available for all patients and, logistically, ISQ could not be measured if the implants did not meet a minimum insertion torque. This was to avoid potentially rotating the implant in the osteotomy while attaching the SmartPeg. Information was not collected regarding the extent of bone grafting that was necessary. It is possible that patients receiving a very large volume of graft material would have lower stability values; however they were pooled with sites having only minimal grafting and this could have diluted the results. Finally, ISQ values were not followed beyond the time of osseointegration check and after loading of the implants.

Completion of statistical analysis was done at the implant-level for most implant-related variables, however an attempt was made to evaluate systemic factors at the patient-level, to reduce the effect of patients with multiple implants. By performing the analysis at the implant-level, the sample size was increased but the data could have been more heavily weighted towards patients receiving multiple implants. Similarly, averaging the ISQ values for many patients may have diluted extreme results; however, box plots were used to highlight the range of results and to indicate the number of outliers.

7. CONCLUSION

Based on the results from this study, the following conclusions can be drawn:

- The Osstell ISQ device provides good repeatability but measurements may need to be taken in both buccal-lingual and mesial-distal directions, since the difference was found to be statistically significant.
- ISQ values are significantly affected by implant dimensions, with higher values for short implants, compared with long implants, and higher values for regular- or wide-diameter implants, compared with narrow implants.
- ISQ values are significantly affected by implant site, with higher values in the mandible than the maxilla and lower values for incisor sites. This likely relates to the selection of certain sized implants for different regions of the jaws.
- ISQ values were not significantly affected by a history of lateral ridge augmentation, socket preservation or sinus lifting using bone allograft, regardless of the time that had passed between grafting and implant placement.
- Patient-related factors did not seem to affect the ISQ value. This included age, gender, diabetes, and smoking.

Although the Osstell ISQ device is useful to determine implant stability, there remain some challenges with widespread use. The ISQ value appears to be most valuable in following one particular implant over time to detect failures, as well as to determine when to functionally load the implant. A wide range of ISQ values has been reported for successful implants of various designs so it is difficult to draw conclusions regarding a particular implant based on a single measurement.

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APPENDIX 1

NobelActive Internal

Implant Specifications

Platform		Tip Diameter	Major Diameter	Collar Height	Thread Height	Double Lead Thread: Thread Spacing	Double Lead Thread: Thread Pitch	Surface Area	Material
NP	3.5x10mm	2.6	3.5	0.9	8.54	1.2	2.4	125	Ti CP-4
	3.5x11.5mm	2.6	3.5	0.9	10.04	1.2	2.4	146	Ti CP-4
	3.5x13mm	2.6	3.5	0.9	11.54	1.2	2.4	168	Ti CP-4
	3.5x15mm	2.6	3.5	0.9	13.54	1.2	2.4	195	Ti CP-4
RP	4.3x10mm	3.2	4.3	1.3	8.13	1.2	2.4	158	Ti CP-4
	4.3x11.5mm	3.2	4.3	1.3	9.63	1.2	2.4	186	Ti CP-4
	4.3x13mm	3.2	4.3	1.3	11.13	1.2	2.4	214	Ti CP-4
	4.3x15mm	3.2	4.3	1.3	13.13	1.2	2.4	249	Ti CP-4
RP	5.0x10mm	3.6	4.9	1.3	8.2	1.2	2.4	189	Ti CP-4
	5.0x11.5mm	3.6	4.9	1.3	9.6	1.2	2.4	223	Ti CP-4
	5.0x13mm	3.6	4.9	1.3	11.1	1.2	2.4	253	Ti CP-4
	5.0x15mm	3.6	4.9	1.3	13.1	1.2	2.4	295	Ti CP-4

*All Units in millimetres, surface area approximation given in square millimetres

Table 2. Surface area specifications of Nobel Active implants

NobelReplace Straight Groovy

Implant Specifications

Platform		Collar Diameter	Tip Diameter	Minor Diameter	Major Diameter	Collar Height	Thread Height	Thread Pitch	Surface Area	Material
NP	3.5x10mm	3.54	2.6	2.95	3.45	1.5	7.75	0.5	123	Ti CP-4
	3.5x11.5mm	3.54	2.6	2.95	3.45	1.5	9.25	0.5	153	Ti CP-4
	3.5x13mm	3.54	2.6	2.95	3.45	1.5	10.75	0.5	184	Ti CP-4
	3.5x15mm	3.54	2.6	2.95	3.45	1.5	12.75	0.5	207	Ti CP-4
RP	4x10mm	4.3	3.1	3.36	4	1.5	7.75	0.6	168	Ti CP-4
	4x11.5mm	4.3	3.1	3.36	4	1.5	9.25	0.6	190	Ti CP-4
	4x13mm	4.3	3.1	3.36	4	1.5	10.75	0.6	226	Ti CP-4
	4x15mm	4.3	3.1	3.36	4	1.5	12.75	0.6	245	Ti CP-4
	4x18mm	4.3	3.1	3.36	4	1.5	15.75	0.6	302	Ti CP-4
WP	5x10mm	5.01	3.8	4.08	4.93	1.5	7.75	0.8	209	Ti CP-4
	5x11.5mm	5.01	3.8	4.08	4.93	1.5	9.25	0.8	219	Ti CP-4
	5x13mm	5.01	3.8	4.08	4.93	1.5	10.75	0.8	253	Ti CP-4
	5x15mm	5.01	3.8	4.08	4.93	1.5	12.75	0.8	298	Ti CP-4
	5x18mm	5.01	3.8	4.08	4.93	1.5	15.75	0.8	394	Ti CP-4

*All Units in millimetres, surface area approximation given in square millimetres

Table 3. Surface area specifications of Nobel Replace Straight Groovy implants

NobelReplace Tapered Groovy

Implant Specifications

Platform		Collar Diameter	Tip Diameter	Minor Diameter	Major Diameter	Collar Height	Thread Height	Thread Pitch	Surface Area	Material
NP	3.5x8mm	3.5	2.11	2.96	3.5	1.5	7	0.64	115	Ti CP-4
	3.5x10mm	3.5	2.11	2.96	3.5	1.5	9.02	0.64	144	Ti CP-4
	3.5x13mm	3.5	2.11	2.96	3.5	1.5	12.07	0.64	184	Ti CP-4
	3.5x16mm	3.5	2.11	2.96	3.5	1.5	15.12	0.64	197	Ti CP-4
RP	4.3x8mm	4.3	2.56	3.67	4.3	1.5	7	0.71	133	Ti CP-4
	4.3x10mm	4.3	2.56	3.67	4.3	1.5	9.02	0.71	170	Ti CP-4
	4.3x13mm	4.3	2.56	3.67	4.3	1.5	12.07	0.71	213	Ti CP-4
	4.3x16mm	4.3	2.56	3.67	4.3	1.5	15.12	0.71	245	Ti CP-4
WP	5x8mm	5	2.98	4.18	5	1.5	7	0.75	170	Ti CP-4
	5x10mm	5	2.98	4.18	5	1.5	9.02	0.75	212	Ti CP-4
	5x13mm	5	2.98	4.18	5	1.5	12.07	0.75	278	Ti CP-4
	5x16mm	5	2.98	4.18	5	1.5	15.12	0.75	331	Ti CP-4
6.0	6x8mm	6	3.54	4.97	5.9	1.5	7	0.79	205	Ti CP-4
	6x10mm	6	3.54	4.97	5.9	1.5	9.02	0.79	258	Ti CP-4
	6x13mm	6	3.54	4.97	5.9	1.5	12.07	0.79	334	Ti CP-4
	6x16mm	6	3.54	4.97	5.9	1.5	15.12	0.79	390	Ti CP-4

*All Units in millimetres, surface area approximation given in square millimetres

Table 4. Surface area specifications of Nobel Replace Tapered Groovy implants