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Intraoperative compressive tests to evaluate bone quality – an experimental study

Intraoperative Drucktests zur Bestimmung der Knochenqualität – eine experimentelle Studie

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Widmung

Ich widme diese Arbeit meiner Familie.

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Summary

Introduction

Achieving adequate primary stability during implant placement is the decisive parameter for successful osseointegration. This is significantly influenced by three main factors.

Firstly, the macrodesign of the implant is important. In modern implant systems it differs in thread type, thread depth and thread pitch as well as in the design as conical or parallel-walled implant. These factors influence its mechanical anchorage in cortical and trabecular alveolar bone and thus the primary stability.

Furthermore, the surgical protocol is assumed to play an important role. By taking into account the complex composition of the human aloveolar bone and adapting the necessary measures, it can be optimized. Finally, the bone quality of the insertion site is of crucial importance for successful healing of the implant. The classification introduced by Lekholm and Zarb was based solely on the surgeon's sense of touch during the drilling process and was primarily a subjective assessment. An objective assessment of bone quality is facilitated by computed tomography scans and thus by the evaluation of the Hounsfield Units (HU), which is considered a reliable indicator of bone density. The frequently used cone beam computed tomography scans, on the other hand, provide grey scale values that cannot be converted into HU values.

In the search for a method to determine bone quality before implant placement, a testing device called BoneProbe was developed, which allows intraoperative compressive testing after pilot drilling. It consists of a segmented cylinder that can be inserted into a 2.8 mm osteotomy and expanded step by step, while measuring the force required for a certain level of expansion. The BoneProbe allows for objective evaluation of the mechanical quality of both cortical and trabecular bone.

The aim of the present study was to test the BoneProbe in an intraoral animal model and to examine the data obtained for possible correlations with other clinical and histologically determined parameters of bone quality and primary implant stability.

Material and Methods

After approval by the Ethics Committee, two operations each were carried out on four mini-pigs in strict compliance with international guidelines for animal experiments. During the first intervention all premolars of the lower jaw were extracted and the alveolar bone was reduced and smoothed. After a healing phase of twelve weeks, a total of 17 BoneLevel implants were placed in a second procedure. After implant site preparation, compressive tests were performed with the BoneProbe to determine the quality of cortical and trabecular bone. During the subsequent implant placement, a surgical motor was used to record the applied implant insertion torque (IT). Resonance frequency analysis using the Ostell

device was employed to determine the primary stability of the implants in the bucco-lingual and mesio-distal direction. The average of the two ISQ values was taken for analysis.

After the animals had been euthanized, 17 mandibular segments, each with one implant, were obtained and reduced to rectangular blocks of 20x20x15 mm using a diamond band saw. For fixation, the samples were stored in neutrally buffered formalin for eight weeks.

For microradiographic and histomorphometric analysis, the bone specimens were prepared according to the method described by Donath. At least two histological sections with a thickness of 200 to 250 µm were obtained per implant and reduced to 120 µm with a grinding system, so that a total of 57 sections of 17 implants were available for analysis. Micro X-ray images were taken to measure bone mineral density (BMD). The Region of Interest (ROI) was determined unilaterally along the longitudinal axis of the implant with a width of 70µm. The gray scale was calibrated to allow differentiation of the bone from other structures such as bone marrow and fatty tissue. The BMD was calculated as a percentage of the mineralized tissue found to the total volume of the ROI.

The samples were then reduced to a thickness of 80µm and stained with toluidine-O-blue solution. The bone-to-implant contact (BIC) was determined using a light microscope in combination with a color image analysis system. The Region of Interest (ROI) was determined between the first and the last thread of the implant. To calculate the BIC, the total length of the contact surface of the implant to the surrounding tissue within the ROI was measured, as well as the length of the contact surface of implant and bone. In this way the percentage BIC could be calculated. As between two and four slices were obtained per implant, the average of the samples obtained from the implant was used to analyze BMD and BIC.

Statistical analysis

Three of the 17 implants examined were accidentially inserted into tooth germs, reducing the sample size to 14 implants. The maximum insertion torque (IT), compressive bone quality (BP cortical, BP trabecular), primary stability (ISQ), bone mineral density (BMD), and bone-to-implant contact (BIC) were to be presented and their relationships demonstrated using Spearman's rank correlation test.

Results

The parameters BoneProbe and insertion torque revealed a high variation, while consistent measurements were found for primary stability of the implants (ISQ), bone mineral density (BMD) and bone-to-implant contact (BIC).

The BoneProbe showed mean values of 0.68[1] (± 0.41) for cortical and 1.25 (± 0.61) for trabecular measurement. The mean value of both readings from the BoneProbe was 0.96 (± 0.48). Each BoneProbe measurement, cortical and trabecular, and the mean value of both correlated positively with the implant

insertion torque. The BoneProbe mean showed a slightly stronger correlation with the implant insertion torque (Spearman's rho 0.66; p = 0.01) than the trabecular or cortical measurement alone (Spearman's rho 0.60; p = 0.02). No correlation could be identified between the BoneProbe and ISQ, BMD or BIC.
The mean insertion torque was 39.72 Ncm (± 10.73). Apart from the positive correlation with the BoneProbe measurements, no other correlations could be observed.
The ISQ measurements showed similar results regarding the orientation of the measurement (mesio-distal and bucco-lingual). The average ISQ of 69.04 (± 6.24) used for Spearman's rank correlation tests correlated negatively with the BMD (Spearman's rho -0.61; p = 0.03). None of the other parameters showed a significant correlation.
Microradiographic and histomorphometric analysis revealed an average BMD of 75.36% (± 5.59) and a BIC of 91.03% (± 2.13). A positive correlation was found between both parameters (Spearman's rho=0.53; p-value = 0.05).

Discussion

In the study presented, clinical as well as microradiographic and histomorphometric parameters of bone quality and primary implant stability were assessed in an animal model. During implantation, the BoneProbe was used to perform intraoperative compressive tests for evaluation of the bone quality of cortical and cancellous bone in the drill canal. Subsequently, the primary stability of the freshly placed implants was determined by recording the insertion torque and using resonance frequency analysis. After euthanasia of the animals, histomorphometric evaluation and microradiographic analysis of the bone tissue around the implants were performed.
The aim of the study was to present and evaluate potential correlations between clinical and histological parameters of bone quality and implant stability on a clinically relevant scale.
Among the clinical measurements, a significant correlation was found between BoneProbe compressive test values and implant insertion torque, and between bone implant contact (BIC) and bone mineral density (BMD). A negative correlation was observed between BMD and implant stability, while the other parameters showed weak correlations due to the high variability of the measured values.

Compressive bone testing

The results presented seem to be consistent with previous studies in this field, which investigated the influence of trabecular bone modulus of elasticity and cortical bone thickness on the primary stability of an implant and which did not correlate fully linearly with insertion torque and stability measurements. The benefit of an intraoperative bone compression analysis is the possibility to adapt the implant-surgical procedure with the aim to avoid overloading the cortical bone and thus to avoid bone damage and the associated bone resorption. Another advantage of the BoneProbe analysis is the separate

assessment of cortical and trabecular bone, since both cortical and trabecular bone have an influence on primary implant stability.

Surgical and prosthetic measures

With implantology coming into widespread use, there is a need for reliable diagnostics of alveolar bone quality. Particularly young practitioners, who are still gaining experience, would benefit from such a diagnostic procedure. The values obtained from the BoneProbe analysis and a related intraoperative classification could serve as a basis for surgical decision-making with regard to implant length, as well as for a potential adaptation of the drilling protocol with regard to the diameter of the implant site.

From a prosthetic point of view, a reliable assessment of alveolar bone quality would be useful as early as the planning phase in order to reduce the implantation extent for the patient to a necessary minimum and thus keep the surgical and financial burden on the patient low.

Histological sections

The histological preparation of the sections is demanding from a technical perspective, since the materials lying next to each other within a section have physical properties that differ greatly from each other. Despite careful approach, four samples were damaged during the cutting and grinding process and could not be analyzed.

Each cut is associated with a loss of substance of 0.37 mm, which corresponds to the thickness of the saw blade. Four cuts correspond to a total loss of 1.5 mm, which is almost half the implant diameter. Additional limiting factors are the slightly tapered design of the implant and the outer portion of the implant consisting only of threads, which cannot be used for analysis. The maximum number of implants is therefore limited to four cuts. The described difficulties led to a different number of samples per implant, therefore the average values of the implants were used for further analysis.

Microradiographs

A classification of the alveolar bone on the basis of X-rays would be desirable. However, current technology allows for evaluation of bone density only by means of CT scans in Hounsfield units. However, the CBCT scans mainly used in implantological planning merely provide gray values which are not suitable for determining bone density. In addition, there is a clear difference between pure bone density and bone quality, since the latter also includes architectural properties of the bone such as connectivity or the cortical and trabecular shape, which remind of the structur of an archway.

Limitations of the study

The compressive tests used during implant surgery are not comparable with the compressive tests of a universal testing machine, where parameters such as sample size and speed of the apparatus can be better controlled. The BoneProbe therefore does not provide exact data on the mechanical properties of the bone such as elastic modulus and strength, but allows for an objective classification of bone quality on a clinical relevant scale.

The simulation of clinically relevant conditions of a living organism required the use of an intraoral animal model. With regard to the clinical transferability of the animal experiments, certain restrictions must be respected. The minipig model allowed for the use of dental implants of normal length and diameter. However, partly due to the bone smoothing performed, the required height for implant placement was not available in the entire jaw region, which limited the number of implants placed. Only the status directly after implant placement was evaluated, so that no predictions can be made about bone healing and possible resorption processes.

Conclusion

The BoneProbe is a useful diagnostic medium for the implantologist, by the help of which bone quality at the implantation site can be analyzed. Furthermore, objective information regarding the primary stability of the implant can be derived. An advantage of the procedure is the time of the measurement and thus the possibility to change and adapt the surgical and prosthetic treatment plan intraoperatively. Additional studies on a larger scale are required to determine corresponding measurement values that characterize different bone classes.

Zusammenfassung

Einleitung

Das Erreichen adäquater Primärstabilität bei der Implantatinsertion ist nach Brånemark 1977 der entscheidende Parameter für eine erfolgreiche Osseointegration. Dies wird maßgeblich von drei Hauptfaktoren beeinflusst. Zunächst ist das Makrodesign des Implantates entscheidend. Bei modernen Implantatsystemen unterscheidet es sich hinsichtlich Gewindetyp, Gewindetiefe und Gewindesteigung sowie in der Formgebung als konisches oder parallelwandiges Implantat. Diese Faktoren bewirken die mechanische Verankerung im kortikalen und trabekulären Alveolarknochen und beeinflussen somit die Primärstabilität. Weiterhin wird dem chirurgischen Protokoll eine bedeutende Rolle zugeschrieben. Durch Berücksichtigung der komplexen Zusammensetzung des menschlichen Aloveolarknochen und Anpassung der erforderlichen chirurgischen Maßnahmen kann es optimiert werden. Schließlich ist die Knochenqualität der Insertionsstelle von entscheidender Bedeutung für eine erfolgreiche Einheilung des Implantates. Die von Lekholm und Zarb 1985 eingeführte Klassifizierung beruht allein auf dem Tastgefühl des Chirurgen während des Bohrvorgangs und stellt eine vornehmlich subjektive Einschätzung dar. Eine objektive Beurteilung der Knochenqualität wird durch CT-Scans und damit durch die Auswertung der Hounsfield Units (HU) ermöglicht, die als zuverlässiger Indikator der Knochendichte angesehen werden. Die häufig verwendeten CBCT-Scans liefern dahingegen Graustufenwerte, die nicht in HU-Werte umgerechnet werden können.

Auf der Suche nach einer Methode zur Bestimmung der Knochenqualität vor der Implantatinsertion wurde ein Prüfgerät mit der Bezeichnung BoneProbe entwickelt, das nach der Pilotbohrung intraoperative Drucktests ermöglicht. Es besteht aus einem segmentierten Zylinder, der in eine 2,8-mm-Bohrung eingeführt und schrittweise erweitert werden kann, wodurch eine objektive Bestimmung der mechanischen Qualität sowohl kortikalen als auch trabekulären Knochens ermöglicht wird. Ziel der vorliegenden Studie war es, das BoneProbe-Prüfgerät in einem intraoralen Tiermodell zu testen und die gewonnenen Daten auf mögliche Korrelationen mit weiteren klinischen und histologisch ermittelten Parametern der Knochenqualität und Primärstabilität zu untersuchen.

Material und Methoden

Nach Genehmigung der Ethikkommission wurden unter strenger Einhaltung der internationalen Richtlinien für Tierversuche an vier Minischweinen jeweils zwei Eingriffe durchgeführt. Während des ersten Eingriffes extrahierte man alle Prämolaren des Unterkiefers und reduzierte und glättete den Alveolarknochen. Nach einer Abheilphase von zwölf Wochen wurden in einem zweiten Eingriff insgesamt 17 BoneLevel-Implantate gesetzt. Nach der Pilotbohrung erfolgten mittels des BoneProbe-Gerätes Drucktests zur Bestimmung der Knochenqualität des kortikalen und trabekulären Knochens. Bei der anschließenden Implantatinsertion zeichnete man mit dem Chirurgiemotor das aufgebrachte

Implantat-Drehmoment (IT) auf. Zur Bestimmung der Primärstabilität der Implantate diente die Resonanzfrequenzanalyse mittels Ostell-Gerät, in bukko-lingualer und medio-distaler Richtung. Zur Analyse nutzte man den Durchschnitt der beiden ISQ-Werte.

Nachdem die Tiere eingeschläfert waren, konnten 17 Unterkiefersegmente mit jeweils einem Implantat gewonnen und mittels Diamantbandsäge auf rechteckige Blöcke von 20x20x15 mm reduziert werden. Zur Fixierung wurden die Proben acht Wochen lang in neutral gepuffertem Formalin gelagert.

Zur mikroradiographischen und histomorphometrischen Analyse wurden die Knochenpräparate nach der von Donath beschriebenen Methode aufbereitet. Pro Implantat konnten mindestens zwei histologische Schnitte mit einer Dicke von 200 bis 250µm gewonnen und mit dem Schleifsystem auf 120 µm reduziert werden, sodass von 17 Implantaten insgesamt 57 Schnitte zur Analyse vorlagen.

Zur Messung der Knochenmineraldichte (BMD) wurden Mikroröntgenaufnahmen angefertigt. Die Region of Interest (ROI) wurde einseitig entlang der Längsachse des Implantats mit einer Breite von 70µm festgelegt. Die Graustufenskala wurde so kalibriert, dass eine Differenzierung des Knochens von den übrigen Strukturen wie beispielsweise Knochenmark und Fettgewebe möglich war. Man berechnete die BMD als Prozentsatz des gefundenen mineralisierten Gewebes zum Gesamtvolumen der ROI.

Anschließend wurden die Proben auf eine Dicke von 80µm reduziert und mit Toluidin-O-Blau-Lösung gefärbt. Der Knochen-Implantat-Kontakt (BIC) wurde mit Hilfe eines Lichtmikroskopes in Kombination mit einem Farbbildanalysesystem ermittelt. Die Region of Interest (ROI) wurde zwischen dem ersten und dem letzten Gewindegang des Implantates festgelegt. Zur Berechnung des BIC wurde die Gesamtlänge der Kontaktfläche des Implantats zum umgebenden Gewebe innerhalb der ROI gemessen, ebenso wie die Länge der Kontaktfläche von Implantat und Knochen. Auf diese Art ließ sich der prozentuale BIC berechnen. Da pro Implantat eine Anzahl zwischen zwei und vier Schnitten gewonnen werden konnte, diente zur Analyse von BMD und BIC der Durchschnitt der von dem Implantat vorliegenden Proben.

Statistische Auswertung

Drei der untersuchten 17 Implantate waren unglücklicherweise in Zahnkeime inseriert, weshalb die statistischen Analysen an 14 Implantaten erfolgten. Dabei sollten das maximale Eindrehmoment (IT), die kompressive Knochenqualität (BP kortikal, BP trabekulär), Primärstabilität (ISQ), Knochenmineraldichte (BMD) und Knochenimplantatkontakt (BIC) dargestellt und deren Beziehungen anhand des Spearmans'schen Rangkorrelationstests aufgezeigt werden.

Ergebnisse

Die Parameter BoneProbe und Eindrehmoment wiesen eine hohe Variation auf, während für die Primärstabilität der Implantate (ISQ), die Knochenmineraldichte (BMD) und den Knochen-Implantat-Kontakt (BIC) konsistente Messwerte gefunden wurden.

Die BoneProbe-Analyse zeigte Mittelwerte von 0,68 (± 0,41) für die kortikale und 1,25 (± 0,61) für die trabekuläre Messung. Der Mittelwert beider BoneProbe-Werte betrug 0,96 (± 0,48). Jede BoneProbe-Messung, kortikal und trabekulär sowie der Mittelwert aus beiden korrelierten positiv mit dem Implantat-Insertionsdrehmoment. Dabei zeigte der BoneProbe-Mittelwert eine etwas stärkere Korrelation mit dem Implantatinsertionsdrehmoment (Spearman's rho 0,66; p = 0,01) als die trabekuläre oder kortikale Messung allein (Spearman's rho 0,60; p = 0,02). Zwischen BoneProbe-Werten und ISQ, BMD oder BIC konnte keine Korrelation festgestellt werden.

Das mittlere Insertionsdrehmoment betrug 39,72 Ncm (± 10,73). Abgesehen von der positiven Korrelation mit den BoneProbe-Messungen konnten keine weiteren Korrelationen beobachtet werden.

Die ISQ-Messungen zeigten ähnliche Ergebnisse hinsichtlich der Orientierung der Messung (mesiodistal und bukkolingual). Der durchschnittliche ISQ von 69,04 (± 6,24), der für die Spearman'schen Rangkorrelationstests verwendet wurde, korrelierte negativ mit der BMD (Spearman's rho -0,61; p = 0,03). Keiner der anderen Parameter zeigte eine signifikante Korrelation.

Die mikroradiographische und histomorphometrische Analyse ergaben eine durchschnittliche BMD von 75,36% (± 5,59) und einen BIC von 91,03% (± 2,13). Zwischen beiden Parametern konnte eine positive Korrelation gefunden werden (Spearman'scher rho=0,53; p-Wert = 0,05).

Diskussion

In der vorliegenden Studie wurden anhand eines Tiermodells klinische sowie mikroradiographische und histomorphometrische Parameter der Knochenqualität und der Primärstabilität erhoben. Während der Implantation erfolgten mit dem BoneProbe-Gerät intraoperative Kompressionstests zur Bestimmung der Knochenqualität von Kortikalis und Spongiosa im Bohrkanal. Anschließend wurde über die Aufzeichnung des Eindrehmoments und mittels Resonanzfrequenzanalyse die Primärstbilität der frisch inserierten Implantate ermittelt. Nach Euthanasie der Tiere erfolgten zusätzlich histomorphometrische Auswertung und mikroradiographische Analyse des Knochengewebes um das Implantat.

Ziel der Studie war es, potenzielle Korrelationen zwischen klinischen und histologischen Parametern der Knochenqualität und Implantatstabilität auf einer klinisch relevanten Skala darzustellen und zu bewerten. Unter den klinischen Messungen wurde eine signifikante Korrelation zwischen den Werten der BoneProbe-Kompressionstests und dem Implantateindrehmoment sowie zwischen dem Knochenimplantatkontakt (BIC) und der Knochenmineraldichte (BMD) festgestellt. Eine negative

Korrelation wurde zwischen BMD und Implantatstabilität beobachtet, wobei die anderen Parameter aufgrund der großen Variabilität der Messwerte nur schwache Korrelationen aufwiesen.

Kompressive Knochenprüfung

Die vorgestellten Ergebnisse scheinen in Einklang mit früheren Studien auf diesem Gebiet zu sein, in denen der Einfluss des Elastizitätsmoduls des trabekulären Knochens sowie der Dicke des kortikalen Knochens auf die Primärstabilität des Implantates eruiert wurden und welche nicht vollständig linear mit den Messungen des Insertionsdrehmoments und der Primärstabilität korrelierten.

Der Nutzen einer intraoperativen Druckanalyse des Knochens besteht in der Möglichkeit der Adaptation der implantat-chirurgischen Vorgehensweise mit dem Ziel, eine Überlastung der Kortikalis zu verhindern und damit Knochenschädigungen und die damit verbundene Knochenresorption zu vermeiden. Als weiteren Vorteil der BoneProbe-Analyse ist die getrennte Beurteilung von kortikalem und trabekulärem Knochen anzusehen, da sowohl kortikaler als auch trabekulärer Knochen Einfluss auf die Primärstabilität haben.

Chirurgische und prothetische Maßnahmen

Mit der Verbreitung der Implantologie in der Allgemeinpraxis resultiert der Bedarf einer sicheren Diagnostik der alveolären Knochenqualität. Insbesondere junge Behandler, die noch Erfahrung sammeln, würden hiervon profitieren. Die gewonnenen Werte der BoneProbe-Analyse und eine damit zusammenhängende intraoperative Klassifizierung könnten als Grundlage der chirurgischen Entscheidungsfindung in Bezug auf Implantatlänge dienen, ebenso wie auf eine potentielle Adaptation des Bohrprotokolls in Bezug auf den Durchmesser des Implantatbettes.

Aus prothetischer Sicht wäre eine zuverlässige Bewertung der alveolären Knochenqualität bereits in der Planungphase sinnvoll, um den Implantationsumfang für den Patienten auf ein notwendiges Minimum zu reduzieren und somit die chirurgische als auch die finanzielle Belastung des Patienten gering zu halten.

Histologische Schnitte

Die histologische Aufbereitung der Schnitte ist technisch anfällig, da die innerhalb eines Schnittes nebeneinander vorliegenden Materialien stark voneinender abweichende physikalischen Eigenschaften besitzen. Trotz sorgfältiger Vorgehensweise wurden vier Schnitte beim Schneide- und Schleifvorgang beschädigt und konnten nicht analysiert werden.

Jeder Schnitt ist mit einem Substanzverlust von 0,37 mm verbunden, was der Dicke des Sägeblattes entspricht. Vier Schnitte entsprechen einem Gesamtverlust von 1,5 mm, was fast der Hälfte des Implantatdurchmessers entspricht. Zusätzlich limitierend sind das leicht konisch zulaufenden Designs des Implantats und der äußere nur aus Gewinden bestehende Anteil des Implantates, welcher nicht zur

Analyse verwendet werden kann. Die maximale Anzahl eines Implantats ist somit auf vier Schnitte begrenzt. Die beschrieben Schweirigkeiten führten zu einer unterschiedlichen Anzahl an Schnitten pro Implantat, weshalb die durchschnittlichen Werte der Implantate zur weiteren Analyse herangezogen wurden.

Mikroröntgenaufnahmen

Eine Klassifikation des Alveolarknochens auf Grundlage von Röntgenaufnahmen wäre wünschenswert. Nach derzeitigem Stand lässt sich jedoch nur die Knochendichte mittels CT-Scans in Hounsfield-Einheiten darstellen. Die in der implantologischen Planung vorwiegend angewendeten CBCT-Scans liefern jedoch lediglich Grauwerte, welche nicht zur Bestimmung der Knochendichte geeignet sind. Dazu tritt der Umstand, dass ein deutlicher Unterschied zwischen der reinen Knochendichte und der Knochenqualität besteht, da letztere auch architektonische Eigenschaften des Knochens wie Konnektivität oder die Anordnung von kortikalem und trabekulären Knochens berücksichtigen, die torbogenartig zueinander angeordnet sind.

Einschränkungen der Studie

Die im Rahmen der Implantatchirurgie durchgeführten Drucktests sind nicht mit Drucktests einer Universalprüfmaschine vergleichbar, bei der Parameter wie Probengröße und Geschwindigkeit der Apparatur besser kontrolliert werden können. Das BoneProbe-Gerät liefert somit keine exakten Daten über die mechanischen Eigenschaften des Knochens wie Elastizitätsmodul und Festigkeit, sondern ermöglicht eine objektive Klassifizierung der Knochenqualität in Anlehnung an das Lekholm- und Zarb-Schema.

Die Simulation klinisch relevanter Bedingungen eines lebenden Organismus erforderte die Verwendung eines intraoralen Tiermodells. Hinsichtlich der klinischen Übertragbarkeit der Tierversuche sind gewisse Einschränkungen zu beachten. Das Minischwein-Modell erlaubte die Verwendung von Zahnimplantaten normaler Länge und Breite. Zum Teil bedingt durch die durchgeführte Knochenglättung lag jedoch nicht im gesamten Kieferbereich die erforderliche Höhe für Implantation vor, was die Anzahl der gesetzten Implantate einschränkte. Es wurde nur der Status direkt nach Implantatinsertion bewertet, so dass keine Vorhersagen über die knöcherne Einheilung und mögliche Resorptionsprozesse gemacht werden können.

Schlussfolgerung

Die BoneProbe-Analyse stellt für den Implantologen ein nützliches diagnostisches Medium dar, mit dem er die Knochenqualität am Implantationsort erkennt und objektive Hinweise auf die Primärstabilität des Implantates erhält. Ein Vorteil des Verfahrens ist der Zeitpunkt der Messung und damit die Möglichkeit, den chirurgischen und prothetischen Behandlungsplan intraoperativ zu adaptieren. Zur

Festlegung entsprechender Messwerte, die verschiedene Knochenklassen charakterisieren, bedarf es zusätzlicher Studien größeren Maßstabes.

Introduction

Current dental implant systems show high success rates and dental implantology can therefore be considered a predictable and reliable treatment concept (Karl et al. 2017 A). Among several other success parameters, achieving primary stability at implant placement has been defined as a prerequisite for successful osseointegration (Brånemark et al. 1977). Apart from different surgical skills of clinicians, three main factors seem to determine the degree of implant stability at implant placement surgery (Karl et al. 2018 A). These are the macrodesign of an implant, particularly in terms of thread geometry and pitch (Karl et al. 2017 B), then the surgical protocol that leads to some undersizing of an osteotomy, and finally the bone quality that is present in a specific anatomical site (Lekholm & Zarb 1985).

The macro-designs of current dental implant systems differ vastly in terms of thread type, thread depth and pitch. In addition to these variables, there are different external shapes of the implant, which can be parallel-walled or conical. All these factors influence the velocity of the insertion process, the mechanical stability of the cortical and trabecular parts of the alveolar bone and the extent of bone damage caused during insertion (Ikar et al. 2020).

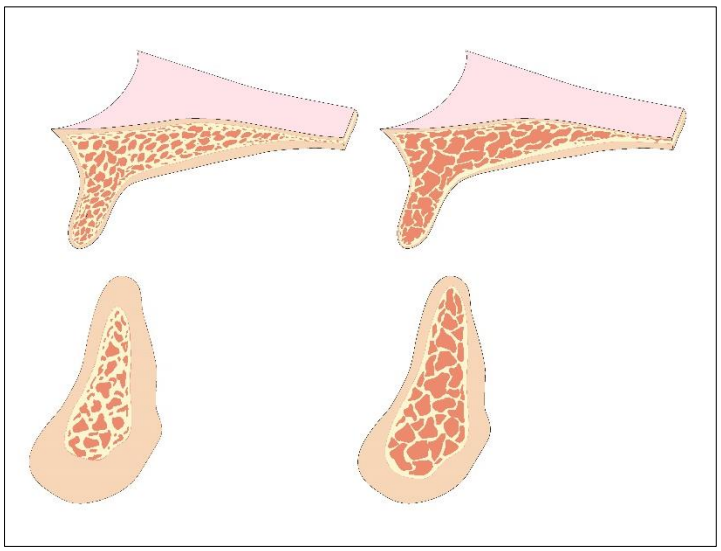


Figure 1: Schematic representation of human alveolar bone as defined by Lekholm and Zarb (1985) ranging from type I bone with thick cortical and dense trabecular bone to type IV with only a thin cortical layer and sparse trabeculae in cancellous bone.

Implant manufacturers have become aware of the complex composition of human alveolar bone and advocated site-specific modifications to the surgical protocol with the aim to create larger diameter osteotomies in stiffer, more cortical bone. It is crucial to identify the correct drilling protocol that avoids high torques at implant placement in order not to cause plastic deformation or damage to the bone and not to potentially harm the implant-abutment interface (Karl et al. 2017 C). In contrast, implants that

require only low torque levels exhibit a higher degree of micromotion, i.e. a relative displacement between implant body and bone, which could possibly result in fibrous encapsulation instead of osseointegration (Karl et al. 2018 B; Winter et al. 2013; Brunski 1999). This occurrence is of particular concern in immediate loading situations (Szmukler-Moncler et al. 2000).

The bone quality classification by Lekholm and Zarb (1985; Fig. 1) was originally based on the tactile sensation of the surgeon during the drilling process. Meanwhile several authors have pointed out that this approach is highly dependent on the individual surgeon and is therefore not reliable (Trisi et al. 2007; Ribeiro-Rotta et al. 1999). It has also been noted that the evaluation of conventional two-dimensional radiographs to assess bone quality leads to unreliable results (Truhlar et al. 1997). The advent of 3D radiographic techniques such as CT and CBCT scans has improved the situation, with Hounsfield Unit (HU) being a reliable indicator of bone density (Norton et al. 2001; Turkyilmaz et al. 2007). However, the more frequently used CBCT scans only yield grey scale values that cannot be converted into HU values (Stoppie et al. 2006).

The evaluation of primary stability of the implant following the insertion process include measurements of insertion torque (Lee et al. 2007) as well as resonance frequency analysis (RFA; Meredith et al. 1998 A; Meredith et al. 1998 B) and damping capacity (Lukas et al. 1992; Schulte et al. 1992; Nkenke et al. 2003). Insertion torque measurements can be performed with current surgical motors while RFA requires a separate device (Osstell AB, Gothenburg, Sweden). Damping capacity measurements were originally introduced to assess tooth mobility and have since proven not to be sensitive enough to precisely assess implant stability (Winter et al. 2010). Based on a clinical study using forward torque testing of implants after healing, it was shown that RFA cannot be used to predict an onset of osseointegration (Krafft et al. 2015). In addition to the strong dependence of the implant stability measurements on the specific implant system used, these measurements are conducted after insertion when an adjustment of the surgical protocol is no longer possible.

In search of a method to determine the bone condition before implant placement, a testing device for bone quality (Hernandez et al. 2006) was developed that enables intraoperative pressure tests after pilot drilling (Krafft et al. 2012; Karl et al. 2013). In biomechanics, compression tests on bone samples are widely spread and it has been shown that such tests can be used to assess minor changes in bone quality caused by adaptation processes after tooth loss (Giesen et al. 2003; Giesen et al. 2004).

Based on a novel material law and finite element analysis (Winter et al. 2011), a device has been constructed that consists of a segmented cylinder that can be inserted into a 2.8 mm drill hole and expanded gradually (Figure 2). By measuring the torque required for a certain expansion level, an objective measurement of the mechanical bone quality can be obtained. Due to the constructive properties of the device separate measurements can be obtained for cortical bone and for trabecular bone.

In preliminary investigations, prototypes of this device have been tested in bone surrogate materials (Karl et al. 2019) and in an extraoral animal model with adequate reliability (Karl et al. 2013). An advanced prototype with the designation BoneProbe was developed which can be used with a conventional surgical drilling unit (Figure 3). The aim of this study was to test the BoneProbe in an intraoral animal model and try to correlate clinical and laboratory determinants of implant anchorage.

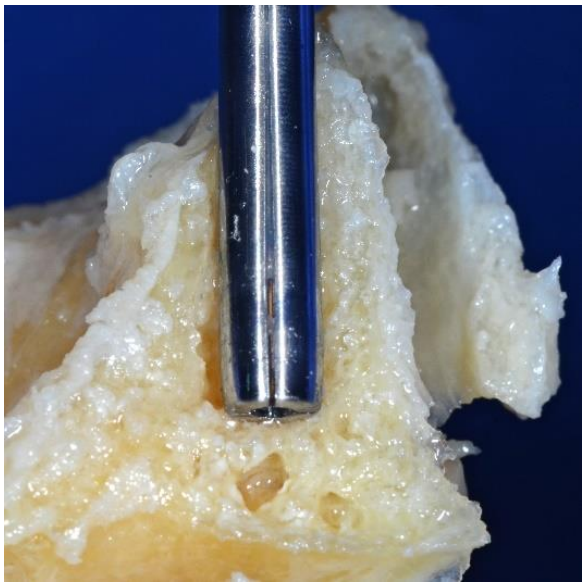


Figure 2: Bone Probe sensor inserted into a pilot drill hole created in human cadaver bone. Via an internal mechanism (not shown here) the segments of the cylindrical sensor can be expanded for elastically compressing alveolar bone.

Figure 3:BoneProbe in the development status as used in this study. A surgical contra angle has been modified to house the BoneProbe mechanism while the drill unit can be used for monitoring the torque required for a certain level of expansion.

Material and Methods

The study protocol was approved by the local ethics commission (Comitetului de Etica a Cercetarii; State Medical and Pharmaceutical University "Nicolae Testemitanu", Chisinau, Moldova). A total of four minipigs with a mean age of 21.8 months and a mean body weight of 46.5 kg were allocated for this study. They were housed in a controlled facility and fed with soft food and water ad libitum.

General course and clinical procedures

All surgical interventions were carried out under general anesthesia which was induced and maintained through intravenous application of Diazepam (Diazepam 10mg – Rotexmedica Injektionslösung, Rotexmedica GmbH Arzneimittelwerk, Trittau, Germany), Ketamin (Ketamin-hameln 50mg/ml, hameln pharma plus GmbH, Hameln, Germany) and Acepromazine maleate (Castran, Interchemie werken "De Adelaar" B. V., La Waalre, The Netherlands). For antibiotic and analgesic treatment Ceftriaxon (Ceftriaxon-ratiopharm, ratiopharm GmbH, Ulm, Germany) and Dexketoprofen (Keral, Menarini International Operations Luxembourg SA, Luxemburg) were administered as single shot dose. During anesthesia vital signs were monitored, including heart rate, respiratory rate, O_2 saturation and expiratory CO_2. After additional local anesthesia (UDS forte, Sanofi, Frankfurt am Main, Germany) chlorhexidine (Chlorhexamed FORTE alkoholfrei 0.2%, GlaxoSmithKline Consumer Healthcare, Bühl, Germany) was used for intraoral disinfection.

The surgical procedure was carried out during two interventions according to the following protocol:

After performing periosteal incisions all mandibular premolars were extracted, followed by vertical reduction of alveolar bone and smoothing all bone edges (Figure 4). Primary wound closure was achieved using absorbable suture material (4-0 Vicryl, Ethicon, Norderstedt, Germany) and the sites were allowed to heal for a period of twelve weeks.

For implant placement, the edentulous ridges were exposed by midcrestal incisions in both quadrants of the mandible and mucoperiostal flaps were deflected. A total of 17 Straumann bone level implants (BoneLevel Implant 3.3 x 8mm NC SLActive, Straumann GmbH, Freiburg, Germany) could be inserted. The implant manufacturer's 1.4mm round burr, the 2.2mm pilot drill 1 and the 2.8mm pilot drill 2 (Straumann GmbH, Freiburg) were used for implant site preparation. Subsequently, the BoneProbe (Karl 2013) was used for compressive testing of cortical and trabecular bone. A typical graph of a Bone Probe measuring sequence is shown in Graph 1. While inserting one titanium implant per study site (Figure 5, Figure 6) the maximum implant insertion torque (Sierra-Rebolledo 2016) was measured using a surgical motor (iChiropro, Bien-Air Dental, Biel, Switzerland). To determine the primary implant stability, an Osstell mentor device and implant-specific SmartPeg abutments (Osstell AB, Gothenburg, Sweden) were used for resonance frequency analysis. The measurements were taken in bucco-lingual and medio-distal directions. For statistical analysis the average of both ISQ values was calculated.

Immediately following implant placement, the minipigs were euthanized through intracardiac injections of T61 (0,12ml/kg bodyweight; Merck Animal Health, Madison, NJ, USA).

Mandibular block sections containing the study sites were harvested removing any soft tissue attached to bone. The specimens were further reduced to rectangular blocks with an average dimension of 20x20x15mm containing only one implant each. For that process and for all further cuttings, a diamond band saw EXACT 300 (EXACT Advanced Technologies GmbH, Norstedt, Germany) was used. For fixation, the specimens were kept in neutrally buffered formalin for eight weeks.

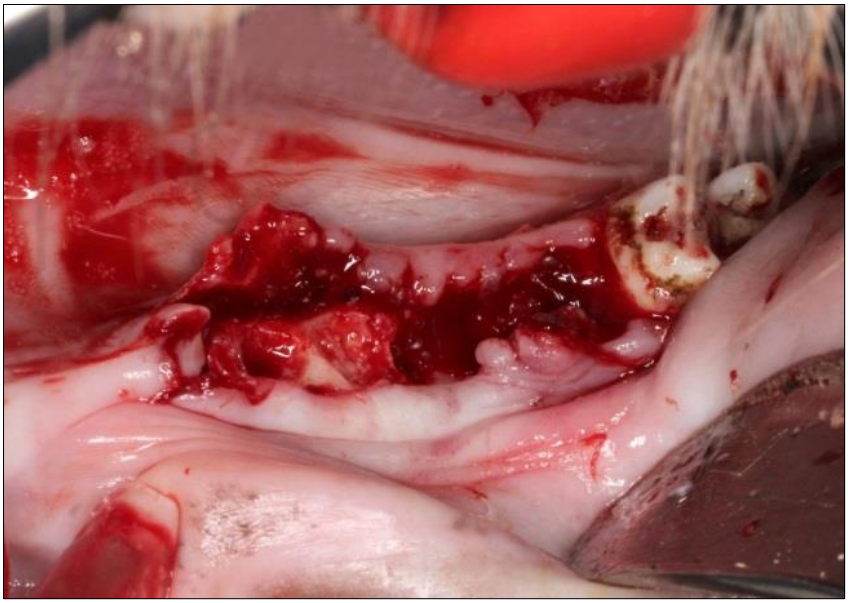
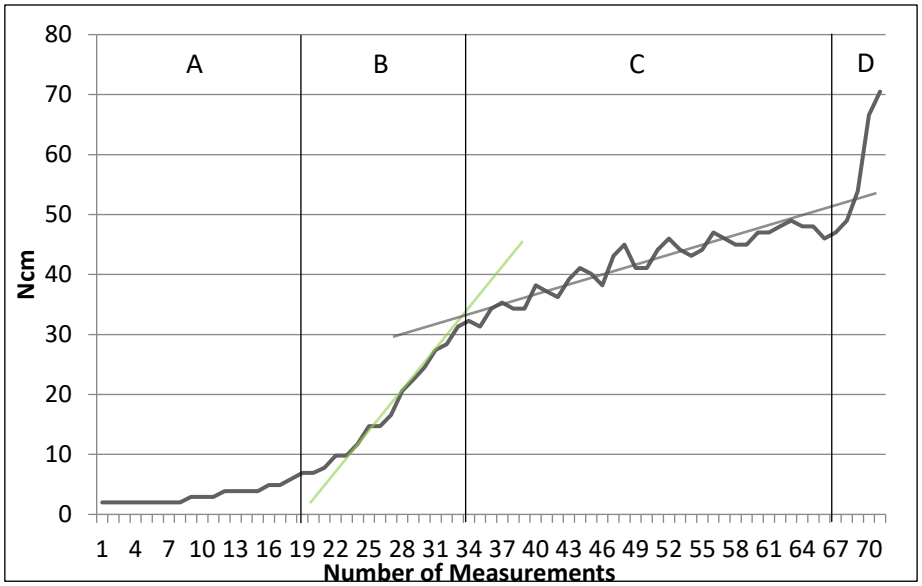


Figure 4: Clinical situation during initial surgery after extraction of all mandibular premolars and prior to wound closure.



Graph 1: Exemplary graph of a BoneProbe measurement sequence with a sampling rate of 1/200ms. The graph shows torque over time during the expansion of the sensor.

‘A’: The graph shows a typical plateau which represents the expansion of the sensor up to the first contact with the surrounding tissues.

‘B’ and ‘C’: The main section of the graph is divided in two rising sections of different mean gradients.
The first part ‘B’ represents the contact with the surrounding tissues, predominantly bone debris remaining after implant bed preparation. The second part ‘C’ represents the contact with the surrounding bone, which is actively compressed in this phase and the mean gradient is therefore considered as the decisive value for the BoneProbe measurement.

‘D’: The graph´s steep increase can be explained by the mechanical stop of the sensing element.

Figure 5: BoneLevel Implant (3.3 x 8mm NC SLActive, Straumann GmbH) placed on a transfer piece for insertion.

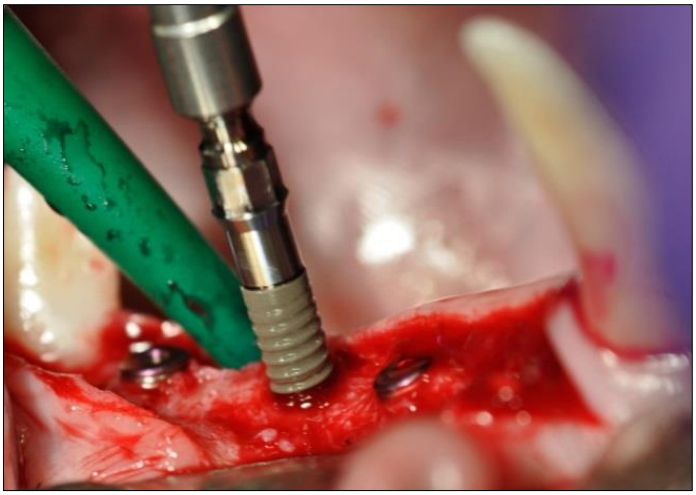


Figure 6: According to the drilling protocol one titanium implant (BoneLevel Implant 3.3 x 8mm NC SLActive, Straumann GmbH) was inserted per study site.

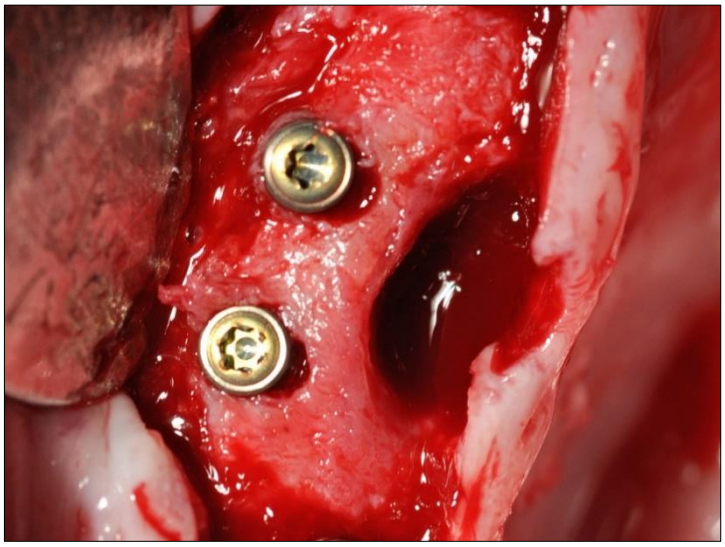


Figure 7: Clinical situation after completion of the second surgical intervention. The implants have been inserted successfully and thus could be used for preparation of bone specimens.

Histomorphometric and microradiographic analysis

All bone specimens were prepared according to the cutting and grinding technique described by Donath (1995).

For successive dehydration, ethanol solutions of increasing concentrations (70%, 80%, 90%, 96% and 100%) were used for seven days each. Afterwards the bone blocks were put into the cleaning agent xylenole for two days. Prior to resin infiltration with Technovit 9100 (Heraeus Kulzer, Hanau, Germany), the samples underwent three pre-infiltration procedures in I: xylene and basis solution at a ratio of 1:1 for two days, II: basis solution (200ml); hardener I (1g) at room temperature for six days

and III: basis solution destabilized with Al_2O_3 (200ml); hardener I (1g) at 39°F for six days. For the subsequent infiltration the specimens were first embedded in basis solution destabilized (250 ml); hardener I (1g); PMMA powder (20g) at 39°F for six days, followed by the final infiltration mix, containing two stock solutions A and B at a ratio of nine to one (A: basis solution destabilized (500ml); hardener I (3g); PMMA powder (80g) and B: basis solution destabilized (50ml); hardener II (4ml); regulator (2ml)) at 39°F for one week.

Specimen preparation	Materials used	Duration
Dehydration	Ethanol solutions (70%, 80%, 90%, 96% and 100%)	7 days each
Cleaning	Xylenole	2 days
Pre-infiltration	Xylene + Basis solution (ratio 1:1)	2 days
Pre-infiltration	Basis solution (200ml) + Hardener I (1g)	6 days
Pre-infiltration	Basis solution destabilized (200ml) + Hardener I (1g)	6 days
Infiltration	Basis solution destabilized (250ml) + Hardener I (1g) + PMMA powder (20g)	6 days
Infiltration	Stock solution A + B (ratio 9:1) A. Basis solution destabilized (500ml) + Hardener I (3g) + PMMA powder (80g) B. Basis solution destabilized (50ml) + Hardener II (4g) + Regulator (2ml)	7 days

Table 1: Protocol used for fixation of the specimens with Technovit 9100 (Heraeus Kulzer, Hanau, Germany).

The infiltrated specimens were cut into two parts along the longitudinal axis of the implant and then fixed with the opposite site on roughened acrylic glass microscope slides with Technovit 4000 (Heraeus Kulzer, Hanau, Germany), using an EXACT Advanced Precision Press (EXACT Advanced Technologies GmbH, Norstedt, Germany) to guarantee proper alignment of the implant parallel to the slides. The orientation was controlled with a micrometer with a reading accuracy of 25mm ± 0.001mm (Figure 8). Inaccuracies greater than 30µm were adjusted by hand with the grinding system TegraPol-31 (Struers A/S, Ballerup, Dänemark) using silicon carbid abrasive paper with different grain sizes (WS FLEX 18 C P 320, 800, 1200, 2500, Hermes Schleifmittel GmbH, Hamburg).

Figure 8: Micrometer with a reading of 25mm ± 0.001mm used for measurements according to Fig. 9 and for control of parallelism.

A graphic description of the exact methodology for obtaining parallel sections of the specimens is given in Figure 9. The abbreviations (capital letters A to E) used for specific distances are defined in this figure.

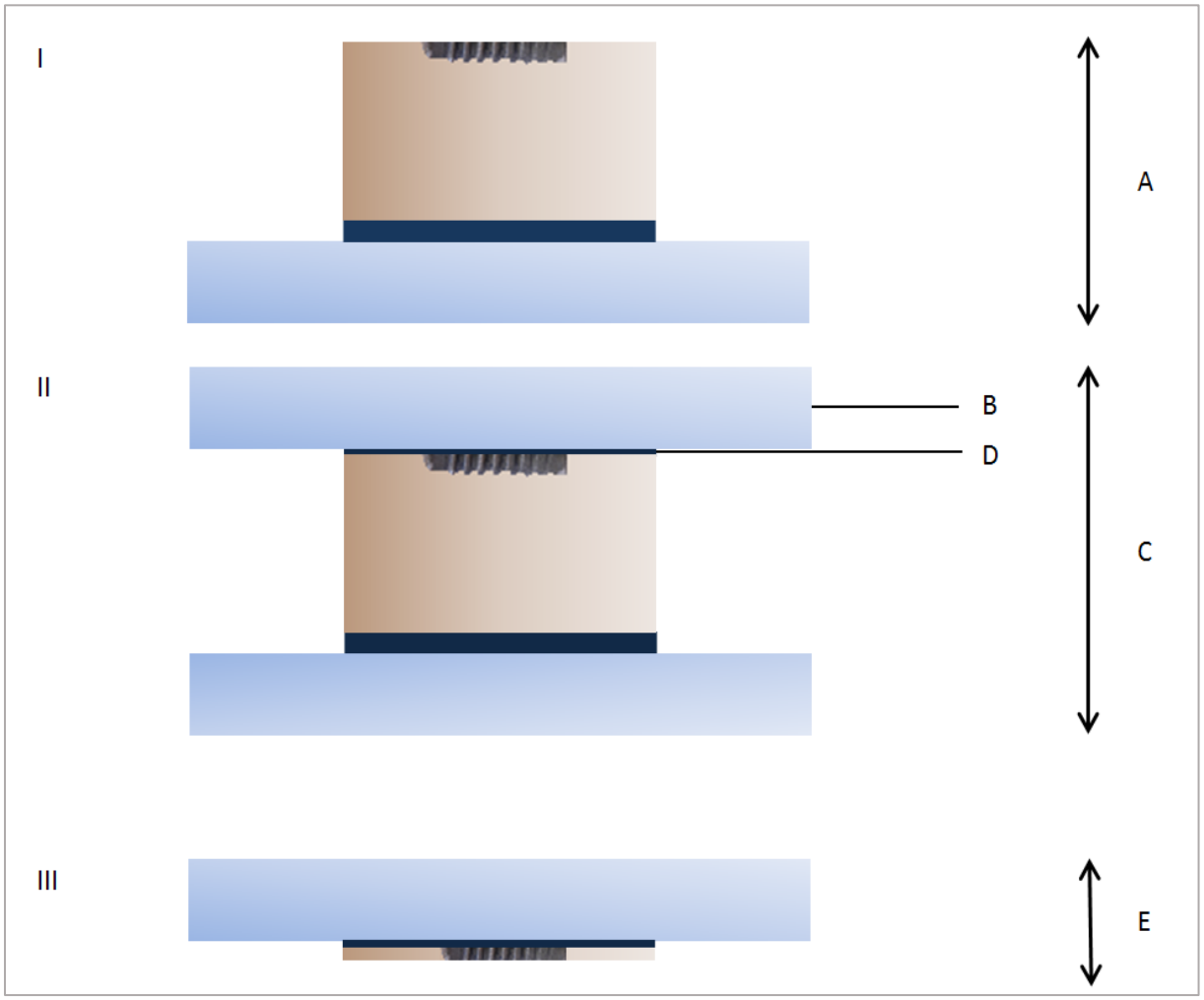


Figure 9:

I. A = Specimen containing one half of an implant parallelized to a slide after fixation using Technovit 4000 (Heraeus Kulzer, Hanau, Germany)
II. C = 'A' fixed on another slide with known thickness (B) using precision adhesive Technovit 7210 (Heraeus Kulzer, Hanau, Germany)
III. Cut specimen of unknown thickness fixed on the slide

The parameters A, B and C were evaluated for calculation of the parameters

D = C-A-B

E = B+D+120µm.

For later calculations of the adhesive layer thickness (D), the thickness of the sections (A) and of the slides (B) was determined with a micrometer. After cleaning of the specimens with kerosene, the precision adhesive Technovit 7210 (Heraeus Kulzer, Hanau) was used with the aid of an EXACT Advanced Precision Press (EXACT Advanced Technologies GmbH, Norstedt) for precision adhesion of the specimens on acrylic glass slides. Another thickness measurement of the prepared 'sandwiches' (C) was taken. Sections with a thickness of 200 to 250µm were cut out of these sandwiches and reduced to 120 µm with the grinding system (Figure 10). For precise adjustment, the adhesive layer was calculated according to the formula "D=C-B-A" and also the total thickness of the section (E) according to the formula "E=B+D+120µm".
A total of 57 sections were prepared for further measurements.

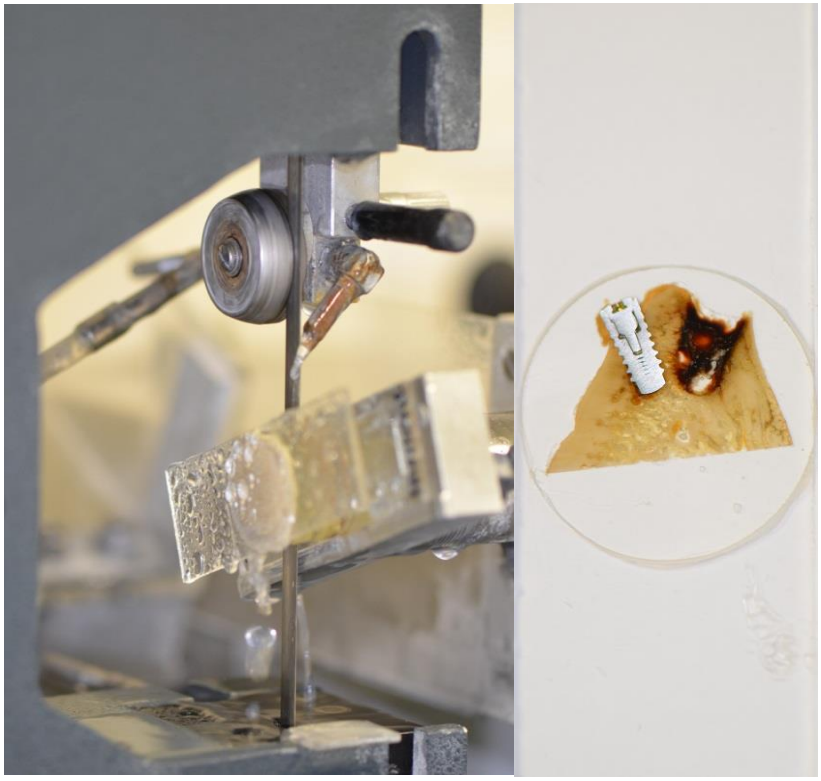


Figure 10: Sawing process of the section (left) and the completed section ready for further analysis (right).

For measuring bone mineral density (BMD), microradiographs were obtained (Faxitron X-ray (Lincolnshire, IL, USA; 14 kV, 0.3 mA, 2.5 min; Insight Dental Film, Carestream Health Inc., Rochester, NY, USA). The region of interest (ROI) was set along one longitudinal axis of the implant with a width of 70µm (Figure 11; LEICA Application Suite, LEICA Phase Expert, LEICA Mikrosysteme Vertrieb GmbH, Wetzlar). The grey level scale was calibrated such way that the differentiation of bone from remaining structures such as marrow and fatty tissue was possible (Figure

12). Bone mineral density was calculated as the percentage of mineralized tissue found in the total volume of the region of interest.

Following BMD determination, the specimens were prepared by reducing and polishing them to a final thickness of 80µm. Prior to staining, the sections were pretreated in 10% H_2O_2 for five minutes, rinsed in water and dried under ambient conditions. Staining was done with toluidine O blue solution for 15 minutes, with the staining medium consisting of two solutions A (distilled water (800ml); Borax, 6306 (8g); toluidine blue (8g)) and B (distilled water (200ml); Pyronin G (2g)) at a ratio of 1:1 (Donath, 1982) (Figure 13). Bone to implant contact (BIC) was then analyzed using a light microscope (LEICA DM4B, LEICA Mikrosysteme Vertrieb GmbH, Wetzlar, Germany) in combination with the color image analyzing system described earlier. The region of interest (ROI) was set on one site of the implant between the first and the last thread. The total length of the contact area of the implant to the surrounding tissues was measured in the ROI, as well as the lengths of the segmental contact areas of the implant to the bone (Figure 14). With those values the percentage BIC could be calculated.

Since there was a different number of sections for each implant, for later analysis the BMD and BIC was calculated as the average of the results of all sections of one implant.

Statistical analysis

Of the 17 implants investigated in this study, only 14 could be used for statistical analysis as three implants (STM 21, 22, 36) had accidentally been inserted into tooth germs without notice during surgery. The clinical measurements taken during surgical interventions i.e. maximum insertion torque (IT), compressive bone quality testing in both cortical and trabecular bone (BP cortical, BP trabecular) and primary implant stability (ISQ) alongside the measurements determined by microradiographic and histomorphometric analysis i.e. bone mineral density (BMD) and bone implant contact (BIC) were subject to analysis. Following descriptive statistics including mean values and standard deviations, comparative statistics were based on Spearmans rank correlation test. The level of significance was set at $\alpha = 0.05$.

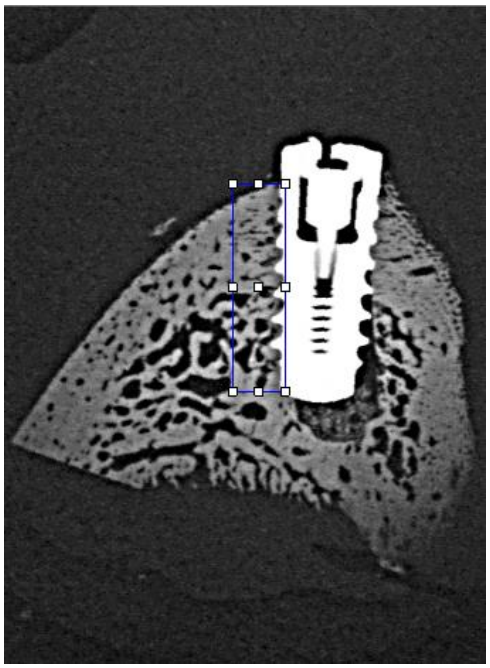


Figure 11: Region of interest (ROI) for bone mineral density (BMD) measurement, set at the longitudinal axis of the implant (width=70µm)

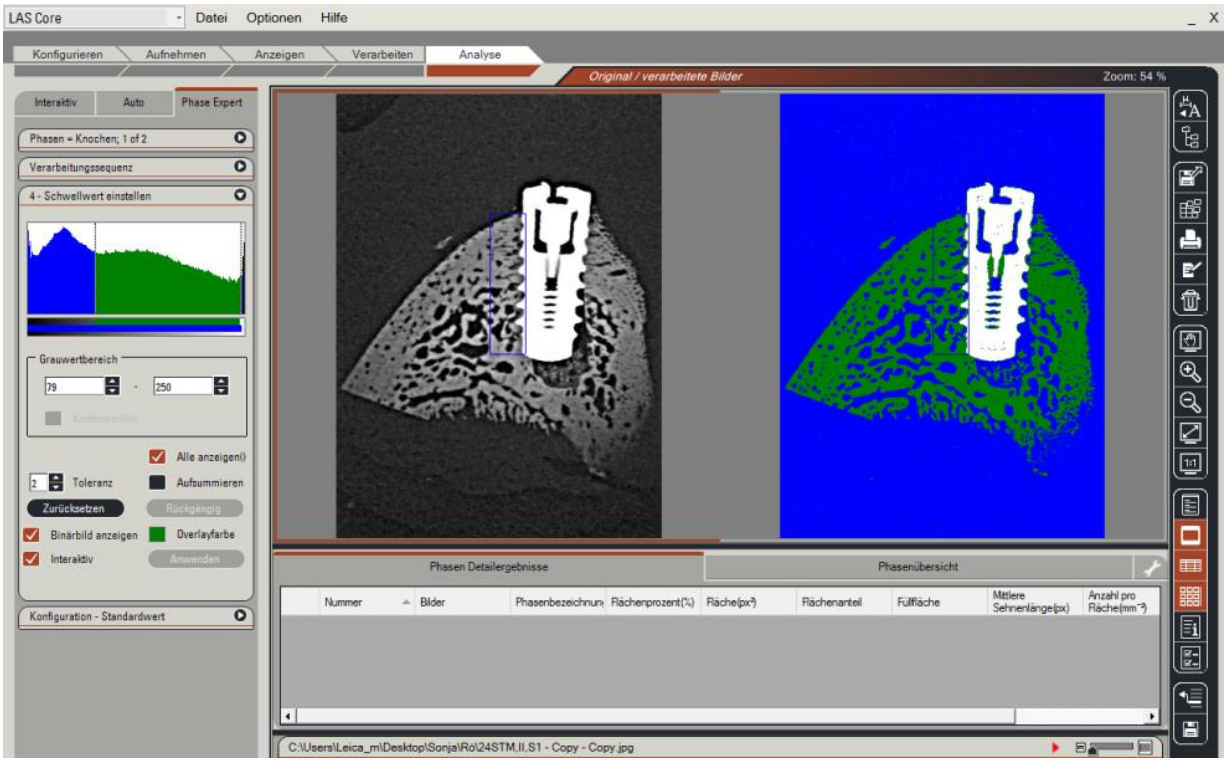


Figure 12: Calibration of the grey levels to define the percentage of bone mineral in the region of interest

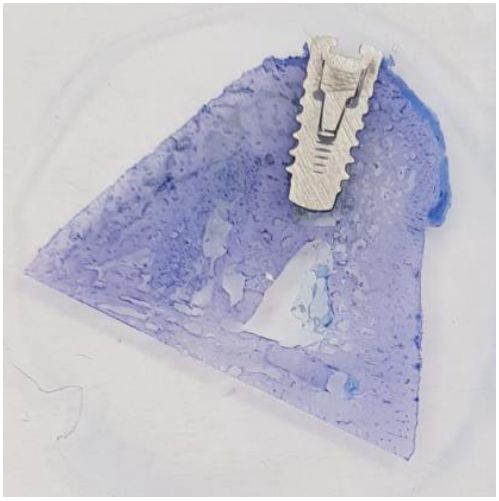
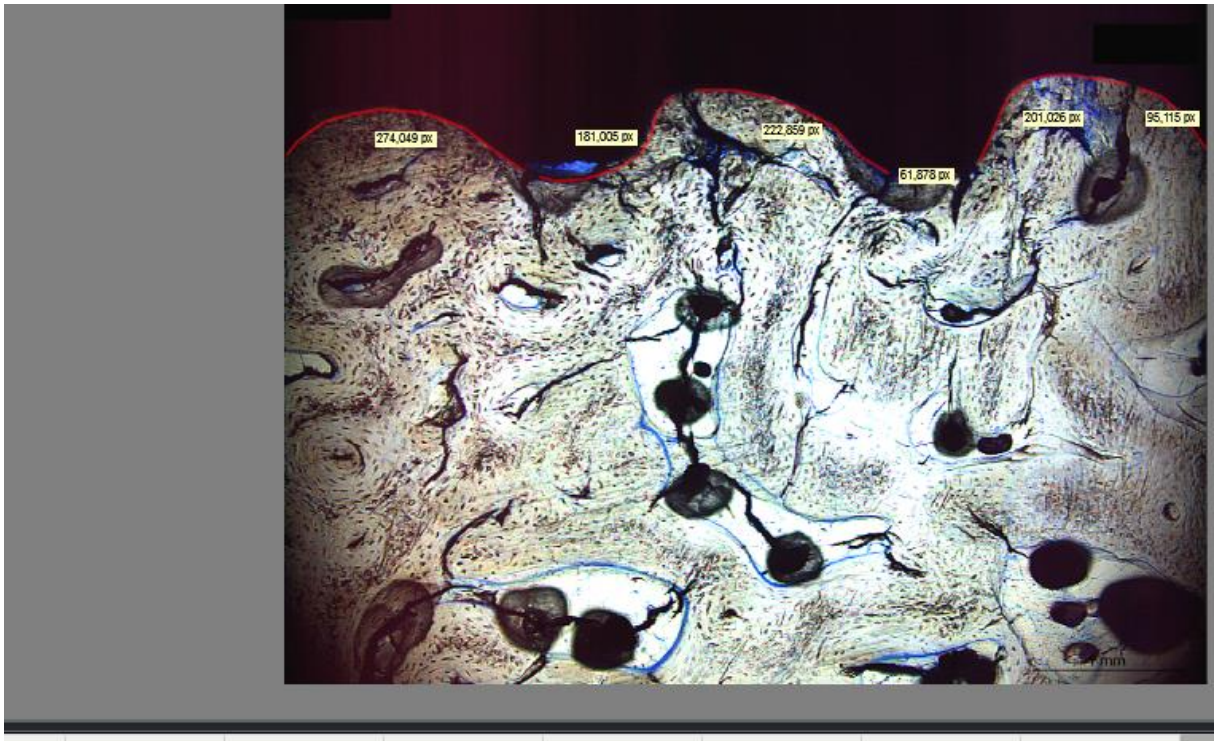


Figure 13: Section after staining with Toluidine-O-blue ready for histomorphometric analysis.



	Messung Nr.	Bildname	Tool	Linienlänge (px)	Breite (px)	Höhe (px)	Endpunktdistanz (px)
▶	1	Unbenannt.PNG	Segment	1.118,208	932,046	108,106	932,065
	2	Unbenannt.PNG	Segment	274,049	242,507	62,818	243,039
	3	Unbenannt.PNG	Segment	181,005	137,323	87,653	160,598
	4	Unbenannt.PNG	Segment	222,859	197,220	84,732	214,651
	5	Unbenannt.PNG	Segment	61,878	61,357	5,844	61,514
	6	Unbenannt.PNG	Segment	201,026	150,471	89,114	169,897
	7	Unbenannt.PNG	Segment	95,115	68,662	61,357	92,082

Figure 14: Histormorphometric analysis using a colour imaging system.

Results

Surgical procedures

The surgical procedures were completed without complications and all 17 implants were inserted successfully. The healing period was uneventful as well. The ISQ of one implant (STM 27) could not be recorded due to an electric malfunction.

Manufacturing process according to the Donath Protocol (1995)

While processing the sections, four of them were damaged due to technical difficulties with the cutting and grinding technique applied. Nevertheless, a minimum of two sections of each implant could be prepared and used for histomorphometric and microradiographic analysis, which led to a total of 57 sections of 17 implants. Throughout the determining of BMD and BIC, sections of three implants (STM 21, 22 & 36) showed an insertion of the implant into tooth germs leading to the exclusion of pertaining measurement data.

In both microradiographs and histological sections, some similarities could be detected.

Microradiographs

A monocortical anchorage could be seen in all implants. A small amount of bone debris could be detected as radiodense structures (Figure 15). Most implants showed drill holes deeper than the implant (Fig. 15-20) and some showed an implant axis differing from the axis of the drill hole (Figure 17, Figure 18). In the latter case the implants drifted away from a higher percentage of cortical bone and into a higher percentage of trabecular bone. Those deviations from the axis of the drilling hole reached angles of up to 10°.

Plastic deformation of bone caused by the BoneProbe device could not be detected in any section.

Regarding the bone structure, the following observations were made. A clear differentiation between cortical and cancellous bone was not evident in every specimen. A rather fluent transition could be seen in several sections (Figure 17). The thickness of the cortical layer showed high variation between the specimens as well as in the specimens themselves. As a result, some implants were surrounded by mostly cortical bone (Figure 18) while others showed a comparably low amount of cortical fixation (Figure 19). Some implants showed an insertion into cortical bone on one side and into trabecular bone on the other side (Figure 20).

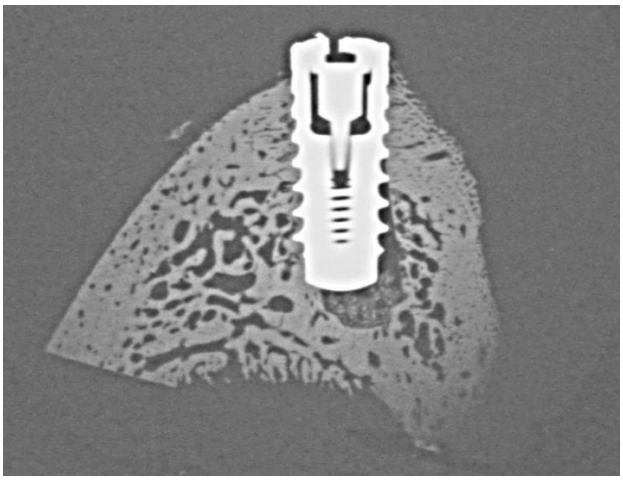


Figure 15: Microradiograph showing bone debris in the drill hole and a slightly corrected axis of the implant in relation to the drill axis; Specimen # 24.

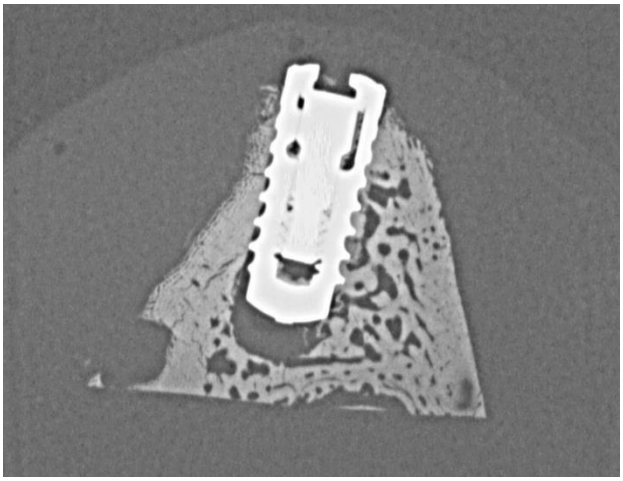


Figure 16: Typical implant position: The drill hole is deeper than the insertion depth; Specimen # 37.

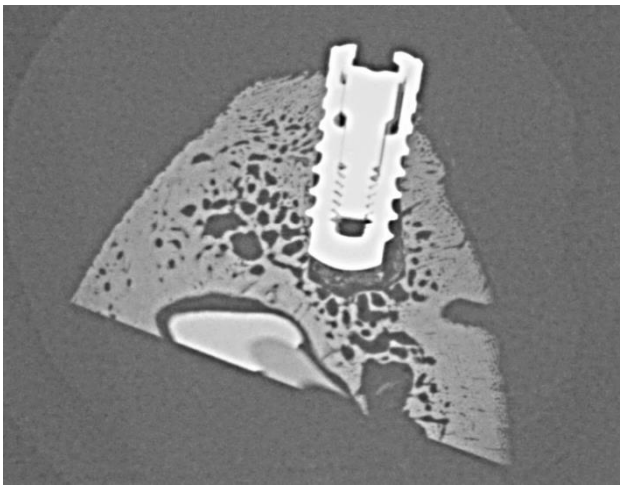


Figure 17: Fluent transition from cortical to cancellous bone; Specimen # 26.

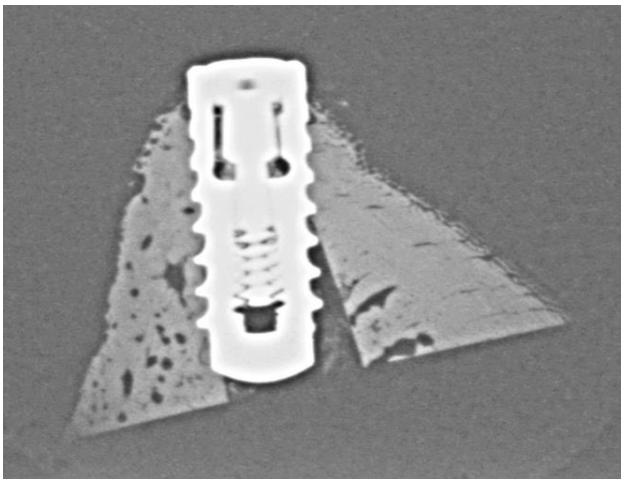


Figure 18: Thick cortical layer; Specimen # 31.

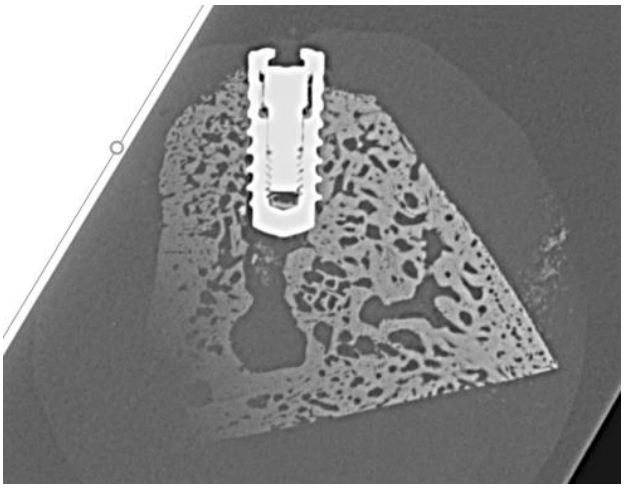


Figure 19: Thin cortical layer; Specimen # 34.

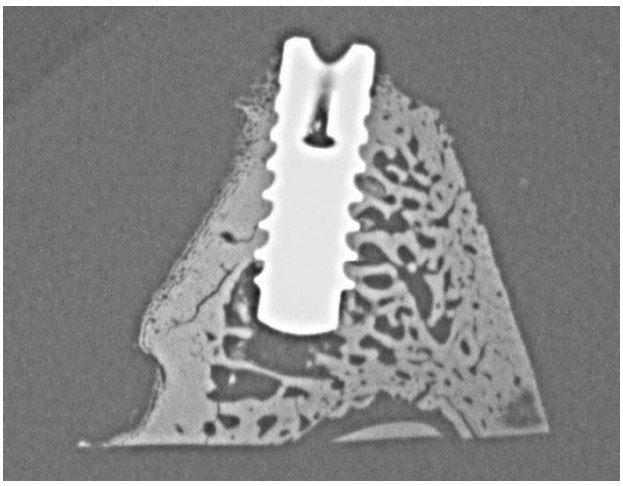


Figure 20: Surrounding bone showing cortical bone on one side of the implant and trabecular bone on the other; Specimen # 37.

Histological sections

Corresponding to the microradiographs, bone debris in addition to the soft tissue remnants were seen in the osteotomies (Figure 21). The alveolar bone showed a lamellar bone structure. Since the bone specimens were harvested directly after implantant placement, no signs of ossification could be seen around the implant.

Due to the cutting and grinding technique applied, the large part of the samples showed a gap between the implant and the surrounding tissue because of the shear forces all samples were exposed to during processing (Figure 22). The partial detaching of bone from the implant surface was not taken into account in the analysis of the BIC but was considered as an artefact.

Figure 21: Histological section showing bone debris as well as soft tissue remaining in the drill hole; Specimen # 24.

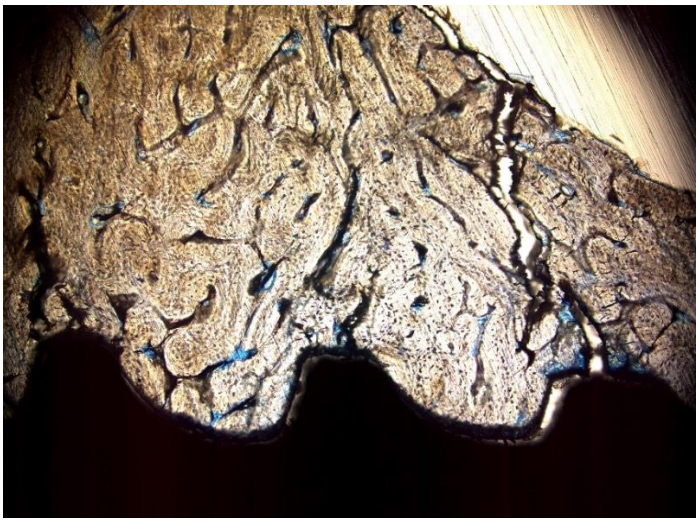


Figure 22: Partially detached bone from the implant surface because of the shear forces the specimens were exposed to during the preparation; Specimen # 35.

Overview of all measurements

All values determined by clinical measurements as well as later analyses are shown in Table 2 (data excluded from analysis is shown in grey). The mean values and standard deviations are given in Table 3. For statistical analysis, Spearmans rank correlation tests were applied with the level of significance set at $\alpha = 0.05$. The results are given in Table 4.

Specimen #	BIC [%]	BMD [%]	Bone Probe - cortical	Bone Probe - trabecular	Insertion Torque [Ncm]	ISQ 1	ISQ 2	ISQ mean
21	86,83	64,02	0,70	1,10	39,20	53	61	57
22	85,21	67,93	0,32	0,55	26,40	62	63	62,5
23	91,17	77,57	0,64	1,63	34,30	48	55	51,5
24	93,61	71,92	0,86	1,35	40,10	72	75	73,5
25	88,15	65,71	0,29	0,68	30,40	66	71	68,5
26	93,09	76,36	0,72	0,70	37,20	72	76	74
27	93,78	81,53	1,11	2,12	70,50			
28	90,01	70,92	1,24	2,34	48,00	74	76	75
29	89,86	68,17	1,17	1,18	37,20	70	74	72

30	89,15	76,92	0,33	1,09	36,20	66	67	66,5
31	92,73	85,34	1,15	1,47	51,90	66	69	67,5
32	87,96	73,78	0,24	0,80	37,20	66	70	68
33	90,35	83,21	0,37	0,63	31,30	61	68	64,5
34	89,86	75,27	0,35	0,55	31,30	72	74	73
35	94,45	77,11	0,05	0,77	36,20	68	71	69,5
36	85,57	79,83	0,58	0,68	43,10	70	70	70
37	90,22	71,29	1,02	2,13	34,30	71	77	74

Table 2: All values determined.

		Mean Value	Standard Deviation
Clinical measurements	BoneProbe cortical	0.68	0.41
	BoneProbe trabecular	1.25	0.61
	BoneProbe overall	0.96	0.48
	Insertion Torque [Ncm]	39.72	10.73
	ISQ	69.04	6.24
Microradiography	BMD [%]	75.36	5.59
Histomorphometry	BIC [%]	91.03	2.13

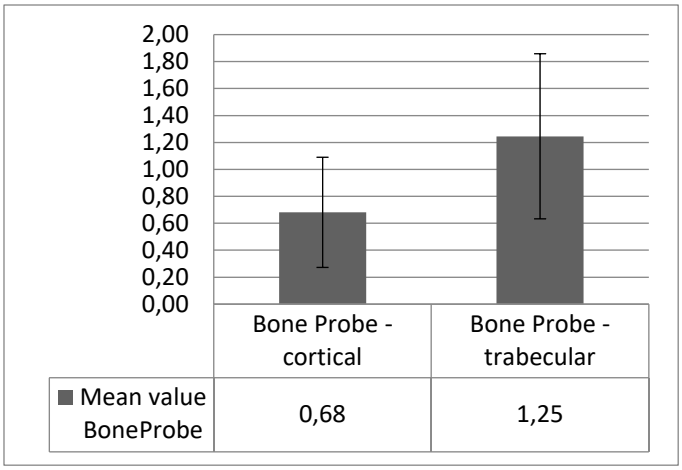
Table 3: Results of clinical, microradiographic and histomorphometric measurements.

	BIC	BMD	BoneProbe cortical	BoneProbe trabecular	BoneProbe overall	Insertion Torque	ISQ mean
	Spearman's rho						
BIC		0.53	0.23	0.24	0.17	0.41	0.15
BMD	**0.05**		-0.09	-0.05	-0.04	0.17	-0.671
BoneProbe - cortical	0.44	0.77		0.68	0.88	0.60	0.44
BoneProbe - trabecular	0.41	0.88	**0.01**		0.91	0.60	0.21
BoneProbe - overall	0.56	0.89	**0.00**	**0.00**		0.66	0.29
Insertion Torque [Ncm]	0.14	0.55	**0.02**	**0.02**	**0.01**		0.31
ISQ	0.63	**0.03**	0.13	0.49	0.33	0.30	
	p-value						

Table 4: Results of Spearman rank correlation tests for all parameters recorded in this study. Significant correlations are written in bold.

In general, the parameters BoneProbe and Insertion Torque showed high levels of variation resulting in greater standard deviations, while for primary implant stability (ISQ), bone mineral density (BMD) and bone to implant contact (BIC) consistent measurement values were found.

The BoneProbe showed mean values of 0.68 (± 0.41) for the cortical and 1.25 (± 0.61) for the trabecular measurement (Graph 2). The overall BoneProbe calculated as the mean of both values, was 0.96 (± 0.48). Each BoneProbe measurement, cortical and trabecular as well as the average of both, positively correlated with the implant insertion torque. Interestingly, the overall BoneProbe showed a slightly stronger correlation with the implant insertion torque (Spearman's rho 0.66; $p = 0.01$) than the trabecular or cortical measurement alone (Spearman's rho 0.60; $p = 0.02$). No correlation could be detected between BoneProbe and ISQ, BMD or BIC.

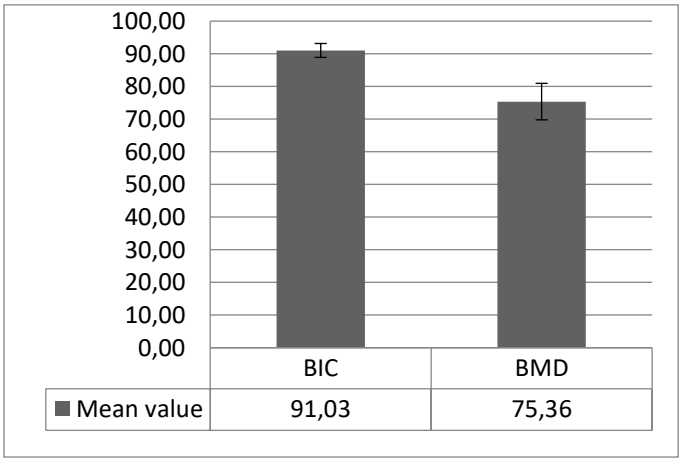


Graph 2: Mean value and standard deviation of BoneProbe measurements.

The mean implant insertion torque was 39.72Ncm (± 10.73). Aside from the positive correlation with the BoneProbe measurements as described above, no other correlations could be observed.

The ISQ measurements showed similar results regarding the orientation of the measurement (mesio-distal and bucco-lingual). The average ISQ of 69.04 (± 6.24), which was used for Spearman's rank correlation tests, negatively correlated with BMD (Spearman's rho -0.61; p = 0.03). None of the other parameters showed a significant correlation.

The microradiographic and histomorphometric analysis resulted in an average BMD of 75.36% (± 5.59) and BIC of 91.03% (± 2.13) (Graph 3). A significant positive correlation could be found between both parameters (Spearman's rho=0.53; p-value = 0.05).



Graph 3: Mean value and standard deviation of percentage BIC and BMD.

Discussion

In this study, the diagnostic device BoneProbe, which is a novel method based on intraoperative compression of bone, was used next to histomorphometric evaluation, microradiographic analysis, insertion torque recording and resonance frequency analysis. The aim of the study was to present and evaluate potential correlations between clinical and histological parameters of bone quality and implant stability on a clinically relevant scale.

Among the clinical measurements, a significant correlation was found between the compressive testing values and implant insertion torque and also between bone implant contact (BIC) and bone mineral density (BMD). A negative correlation was observed between BMD and implant stability, whereby the other parameters revealed only weak correlations due to the great variability of the measurement values.

Compressive testing

The findings presented seem to be in line with previous studies in this field (Degidi et al. 2013; Huang et al. 2011; Wang et al. 2015). Degidi et al. found partially contradicting correlations of insertion energy with histologic parameters of implant stability (Degidi et al. 2013) whereas Huang et al. found elastic modulus of trabecular bone and cortical thickness having an impact on primary stability but were not totally linearly correlated with insertion torque and stability measurements (Huang et al. 2011). Similarly, an increase in bone density or the presence of a cortical layer led to higher primary stability in an in vitro study, but the interrelationships among the measurements made remained unclear (Wang et al. 2015).

The benefit of intraoperative pressure testing of the bone could be the possibility to adapt the surgical protocol (Sierra-Rebolledo et al. 2016) in order to avoid overloading the cortical bone (Duyck et al. 2015) and to try to avoid bone damage that causes bone resorption (Eom et al. 2016; Menicucci et al. 2012). Another advantage of the BoneProbe, in addition to its independence from a specific implant system, could be that it allows separate assessment of cortical and trabecular bone, which takes into account that trabecular bone can also contribute to primary implant stability (Dorogoy et al. 2017). However, thresholds for compression tests that define different classes of bone are still missing.

Surgical Procedures

With implant dentistry coming into widespread use, the number of expert implantologists having gathered an enormous level of experience from placing thousands of implants are getting less. While these surgeons are certainly able to judge bone quality on their personal scale and make the right decisions in adapting their surgical workflow, this may be next to impossible for beginners and general practitioners. Consequently, the evaluation of alveolar bone quality as a basis for surgical decision-making with respect to implant length and diameter as well with respect to the drill protocol applied

remains being challenging. Modern surgical motors already have the drill sequences of major implant brands implemented in their software but these have to selected based on the clinicians evaluation of bone quality. From a prosthetic point of view, reliable evaluation of alveolar bone quality already during the planning phase would be beneficial as standard treatment concepts for larger reconstructions could be personalized with the aim of reducing the number of implants and consequently the financial burden of the patients treated.

Processing and analysis of histological sections

The cutting and grinding technique used in this dissertation was introduced by Donath in 1995. It is used for specimens which can not be processed with conventional tequniques such as the heterogen specimen presented, consisting of jawbone and a titan implant (Donath 1995).

Although the method allows the histological analysis of these specific specimens, there are certain characteristics, which should be taken into account when working according to the Donath protocol.

Each cut is related to a loss of substance corresponding to the thickness of the blade, which amounts 0,37mm. To achieve four slides for one implant the total loss of 1,5mm represents almost half of the implant diameter. Because of the slightly tapered design of the implant and the fact that the outer region only consist of threads and can therefore not used for analyzation, the sample size of one implant is limited to four slices. Other irregularities leading to a reduced number of slices is technical failure, since there were specimens that were destroyed during the cutting process. As a result there is an uneven number of slices per specimens. The irregularity was adapted by taking the average results for further analyzation.

Because of the high difference in hardness between the titan implant and the jawbone a convexness of the specimen could been detected. The difference between the implant and the surrounding bone could be held low (maximum difference of 20 µm) and did not influence the histological analysis, especially since the region of interest was not heavily affected.

Artefacts occuring during histological analysis are the gap between the implant and the surrounding bone, which is a result of the shear forces affecting the specimens during preparation and the small bubbles occurring with gluing the slices.

By considering those characteristics while working, the technique provides the possibility to analyze the difficult combination of titan implants and jawbone.

Microradiographs

Several attempts have been made for defining classes of alveolar bone based on radiographic assessments (Rozé et al. 2009, Stoppie et al. 2006). With the current status of 3D imaging technology (Shapurian et al. 2006), it only appears being feasible to identify bone density as Hounsfield units using

CT scans (Lee et al. 2007). The more frequently applied CBCT scans do not allow for generating HU data but only lead to grey scale values (Pauwels et al. 2015). While not properly used in the dental community, a distinct difference exists between pure bone density and bone quality with the latter one also subsuming architectural properties of bone such as trabecular shape and connectivity (Hernandez et al. 2006, Felsenberg et al. 2005). It has been pointed out that µCT imaging (Ulrich et al. 1997) is required for assessing bone quality which of course is not feasible in clinical practice.

Limitations of the study

It is well acknowledged that the compressive tests conducted as part of implant surgery cannot be compared to compressive tests in a universal testing machine where parameters such as specimen size and velocity of the apparatus can be much better controlled (Giesen et al. 2003, Gieson et al. 2004, Keaveny et al. 1994). The BoneProbe is not intended to provide exact data on bone's mechanical properties such as elastic modulus and strength (Keaveny et al. 2001) but to allow for a predictable and reliable classification according to the Lekholm and Zarb scheme. Consequently, simulating clinically relevant conditions of a life organism required the use of an intraoral animal model, which allowed to place full size dental implants.

Certain limitations have to be considered with respect to clinical transferability of this animal research. The intraoral minipig model allowed the use of regular-sized dental implants and represents a frequently applied test scenario (Catros et al. 2013), but limited vertical bone volume hindered from using all potential sites. In part, this was due to the bone reduction carried out after tooth extraction in order to achieve primary wound closure. In addition, the bone found in the different surgical sites in this animal model showed a much more pronounced cortical compartment as compared to the situation in human patients. Furthermore, only the status at implant insertion was evaluated, and consequently, no predictions can be made about osseous healing and potential resorption processes.

As all clinical measurements were carried out by one single surgeon, repeatability of the measurements could not be checked as part of this experiment. Based on a previous study (Karl et al. 2019) using the BoneProbe in human cadaver bone, a reasonable level of repeatability and reliability could be assumed.

Conclusion

Within the limitations of this study and the weak correlations of BoneProbe measurements found with insertion torque values of a specific implant system, this diagnostic device may be useful for predicting implant stability at a stage where the clinician is still able to modify the surgical and the prosthetic treatment plan. Assuming that the weak correlations observed were due to the limited sample size, studies at a much greater scale involving various implant systems would however be required. Prior to clinical application, where the BoneProbe might assist in finding the optimal drill protocol, the optimal number of implants and the optimal loading scenario, a database would have to be created in order to define different bone classes.

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Publications

Grobecker-Karl T, Palarie V, Schneider S, Karl M (2019) Does intraoperative bone density testing correlate with parameters of primary implant stability? A pilot study in minipigs. Clinical and Experimental Dental Research 5:594-600
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S. Schneider, V. Palarie, M. Karl, T. Grobecker-Karl (2019) Korrelieren intraoperative Drucktests zur Bestimmung der Knochenqualität mit der primären Implantatstabilität? Posterdemonstration 33. Kongress der DGI (Hamburg)

Curriculum vitae

Aus datenschutzrechtlichen Gründen wird der Lebenslauf in der elektronischen Fassung der Dissertation nicht veröffentlicht.

Appendix

Grobecker-Karl T, Palarie V, Schneider S, Karl M (2019)

Does intraoperative bone density testing correlate with parameters of primary implant stability? A pilot study in minipigs.

Clinical and Experimental Dental Research 5:594-600