Research Article

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Micromotion Phenomena at the Implant Bone Interface: A Biomechanical and Histomorphometric Study

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Abstract

Purpose: Excessive micromotion at the implant-bone interface may result in fibrous encapsulation instead of osseointegration of dental implants. This study quantified micromotion of implants placed in polyurethane foam and sheep tibia and tried to establish correlations with histologic parameters.

Method: Dental implants (n=5) were placed in the tibiae of two sheep and allowed to heal for five and twenty weeks respectively (total of 10 implants). Identical implants were placed in polyurethane foam with densities of 10 pcf and 20 pcf and a 3 mm thick cortical layer with a density of 40 pcf (n=5 per bone type; total of 10 implants). For determining micromotion at the implant bone interface, specimens were loaded in a universal testing machine and extensometers were used for recording implant displacement during loading. Implant stability, bone mineral density (BMD) and bone to implant contact (BIC) were determined additionally. Statistical analysis was based on Wilcoxon rank sum tests and Spearman rank correlation tests with the level of significance set at $p \leq 0.05$.

Results: An increase in trabecular bone density and healing time caused a basic trend towards greater implant stability ($p < 0.05$ for polyurethane foam; $p > 0.05$ for sheep) and less implant displacement as a consequence of loading. The histologic parameters BIC and BMD also increased with healing time, however, this effect was only significant for BMD in the cervical ($p = 0.02$) and apical ($p = 0.05$) part. No difference in micromotion was found between implants placed in sheep and those placed in polyurethane foam with trabecular density of 10 pcf. Only few and inconsistent correlations were found between the parameters evaluated.

Conclusions: Bone quality seems to affect implant micromotion although the exact determinants remain unclear. Implants placed in cellular polyurethane foam with density 10 pcf combined with a 3 mm layer of solid foam with density 40 pcf showed biomechanical behavior comparable to implants placed in sheep tibia.

Keywords: Implant-bone interface; Micromotion; Bone quality; Bone mineral density; Bone implant contact

Introduction

Besides proper three-dimensional positioning, achieving

primary implant stability is the major goal in implant surgery [1]. A multitude of parameters seem to be of great importance in this context including bone quantity and

bone quality [2], the surgical technique applied as well as the micro and macro morphology of the implant system used [3-5].

Apart from clinical considerations, the level of primary stability achieved determines the loading protocol applied [6]. While immediate loading seems to be feasible in implants showing high stability, implants with limited primary stability are often allowed to osseointegrate prior to loading thereby significantly increasing treatment times [7]. The concept behind this clinical decision making process is to avoid potentially detrimental levels of micromotion at the implant bone interface caused by masticatory loads [8,9]. The most widely accepted threshold value for micromotion, above which fibrous encapsulation instead of osseointegration occurs, seems to lie in the range between 50 and 150 μm relative displacement between implant and alveolar bone [10-14].

For quantifying primary stability in a clinical setting, implant insertion torque measurements [2], the determination of damping characteristics [1] using the Periotest device (Medizintechnik Gulden, Modautal, Germany) and resonance frequency analysis [2] using the Osstell device (Osstell AB, Gothenburg, Sweden) are frequently applied. However, considering the variables governing primary implant stability mentioned above, such measurements can at best serve as a rough reference for a given implant system [1].

While from a practical point of view it hardly seems feasible to experimentally measure micromotion directly at the implant-bone interface, different authors have used various surrogate measures such as lateral and vertical implant displacement [10,15] and finite element modelling [16,17] for estimating micromotion phenomena. Recently, a novel experimental approach using extensometers [18,19] in conjunction with a specifically designed mechanical apparatus has been shown to allow for reasonable quantification of implant-bone micro movements [20]. The measurement values obtained correlated with implant insertion torque values and with the density of the bone surrogate materials used. As a next step, the goal of this study was to quantify micromotion of implants osseointegrated in sheep tibia and implants placed in biomechanical test blocks made from polyurethane foam. Implant stability measured by resonance frequency analysis (RFA) as well as bone-implant contact (BIC) and bone mineral density (BMD) were determined as controlling factors. Apart from relating micromotion measurements with the above mentioned parameters, it also was the

goal to check whether polyurethane foam constitutes a replacement for living bone.

Method

Implants placed in bone surrogate materials

Two types of composite bone surrogate materials (Figure 1) referred to as Sawbones 10 & 40 and Sawbones 20 & 40 were used for this study.

Figure 1: Bone surrogate materials used in this study consisting of a layer of trabecular bone with a density of 10 and 20 pcf and a 3 mm layer of cortical bone with a density of 40 pcf.

These bone blocks consisted of a layer of trabecular bone either with a density of 10 pcf or 20 pcf (Cellular rigid polyurethane foam; Sawbones Europe AB, Malmö, Sweden) and a 3 mm layer of solid cortical bone with a density of 40 pcf (Solid rigid polyurethane foam; Sawbones Europe AB).

Tissue level implants ($n=5$ per bone type) with a diameter of 4.1 mm and a length of 10 mm (Straumann Standard; Straumann, Basel, Switzerland) were placed following the clinical guidelines set by the implant manufacturer with the polished implant collar extending beyond the surface of the artificial bone. Following implant placement, primary implant stability was measured using resonance frequency analysis (Osstell ISQ) and the implant-bone assemblies were positioned in a universal testing machine (inspect mini 3 kN, Hegewald und Peschke, Nossen, Germany) at an angle of 30° relative to the long axis of the implants. During loading of the implant with a force of 100 N at a crosshead speed of 1 mm/s implant displacement was quantified using a custom made device which transferred the movement of the implant on to bars equipped with extensometers

(Sandner Messtechnik GmbH, Biebesheim, Germany). A measurement amplifier (Quantum X; Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany) and analysing software (catman, Hottinger Baldwin Messtechnik GmbH) allowed visualising the force exerted on the implants and the displacement resulting [19,20].

Implants Placed in Animal Bone

Following ethics commission approval (Comitetului de Etica a Cercetarii, State Medical and Pharmaceutical University "Nicolae Testemitanu", Chisinau, Moldova), two sheep with a mean age of 2.5 years and a mean body weight of 42kg were allocated for this study. The animals were sedated with Diazepam (Diazepam AbZ 10 mg Ampullen, AbZ Pharma GmbH, Blaubeuren, Germany) while a combination of Ketamin (Ketamin-ratiopharm 50 mg, Ratiopharm GmbH, Ulm, Germany) and Xylazine (Phoenix Xylazine, Phoenix Pharm Distributors Ltd, Auckland, New Zealand) was administered i.v. for inducing and maintaining general anesthesia. Heart rate, respiratory rate, O₂ saturation and expiratory CO₂ were monitored throughout the surgical procedure (Low Flow Capnograph V900040LF, Surgi VetInc, Waukesha, WI, USA). The surgeries were performed on the rear left tibia of each animal. All sites were prepared by shaving and disinfection (Betadine solution, Purdue Pharma L.P., Stamford, CT, USA) before local anesthesia was administered (Septocaine with epinephrine 1:100.000; Septodont GmbH, Niederkassel, Germany). Incisions were made on the outer skin parallel to the anterior aspect of the tibia and the dissection continued through the subcutaneous tissue and muscle. The periosteum was carefully reflected and the medial and lateral aspects of the tibia were exposed. A total of five tissue level implants (Straumann Standard, 4.1 × 10 mm) were placed in each tibia following standard surgical protocols and primary implant stability (ISQ implant stability quotient; Osstell ISQ) was measured using resonance frequency analysis [1].

The soft tissue was subsequently closed with the deeper layers being sutured with a 3.0 resorbable suture (Vicryl, Ethicon, Inc. Johnson & Johnson Company, Somerville, NJ, USA) and the skin with a 4.0 non-resorbable suture material. Upon completion of the surgery, all animals received opiod based analgesics (Omnopon 2% 1 ml, San Farm-Prim SA, Zdorovie Narodu, Ukraine).

The two animals were sacrificed after 5 weeks and 20 weeks of healing and block sections of the tibiae containing all implants and adjacent bone were harvested and subsequently divided into single specimens containing

one implant each by means of a diamond band saw (EXAKT 300, EXAKT Advanced Technologies GmbH, Norderstedt, Germany). Using a dental surveyor and auto polymerising polyurethane resin (Biresin, Sika Deutschland GmbH, Bad Urach, Germany), the single bone blocks were mounted in specimen holders with the implant long axis oriented perpendicularly. Then the specimens were positioned in the universal testing machine as described above. Following implant stability measurements (Osstell ISQ), implant displacement during loading with 100 N was measured.

Upon completion of the biomechanical test, the bone blocks were removed from the specimen holders and fixed in 10% neutral-buffered formalin for 48h followed by dehydration in alcohol solutions of increasing concentrations. All bone samples were then clarified in xylene and embedded in polymethyl methacrylate (Technovit 9100, Heraeus Kulzer, Hanau, Germany). One anterior-posterior section parallel to the long axis of the implant was obtained per specimen by a cutting and grinding technique [21]. With the sections reduced to a thickness of 120 µm, microradiographs were obtained (Faxitron X-ray, Lincolnshire, IL, USA; 14 kV, 0.3 mA, 2.5 min; Insight Dental Film, Care stream Health Inc., Rochester, NY, USA) for measuring bone mineral density (BMD) in an area defined by the first and third thread of the implant (Figure 2a). Subsequently, the specimens were further reduced to a thickness of 70 µm and stained with toluidine blue O solution after preprocessing in 10% H₂O₂ solution for measuring bone implant contact (BIC) histomorphometrically using a microscope (Zeiss Axio A1, Carl Zeiss Jena, Jena, Germany). BIC was determined at four areas per implant i.e. the first and third thread on both sides of the implant (Figure 2b). A color image analyzing system (Bio Quant Osteo 7.10.10, BIOQUANT Image Analysis Corporation, Nashville, TN) was utilized for quantifying both, BIC and BMD [22].

Statistical Analysis

Assuming a fully elastic behavior and consequently a linear relationship between loading magnitude and displacement, correction factors for the parameters displacement and residual displacement were calculated for normalizing data to a loading magnitude of 100 N (Table1).

The parameters determined in this study were implant stability before (ISQ 1) and after (ISQ 2) load application, maximum implant displacement and residual implant displacement for both polyurethane foam materials (Sawbones) and animal bone (Sheep).

Table 1: Mean load magnitude (SD) exerted on implants in different bone types as well as correction factors employed for normalizing displacement and residual displacement values.

	Mean load magnitude [N]	Correction factor
Sawbones 10 & 40	95.01 (0.69)	1.053
Sawbones 20 & 40	95.95 (0.30)	1.042
Sheep 5 weeks	109.53 (0.80)	0.915
Sheep 20 weeks	109.99 (1.68)	0.909

Figure 2a: Characteristic microradiograph of an osseointegrated implant used for the determination of bone mineral density.

Figure 2b: Characteristic histologic section of an osseointegrated implant used for the determination of bone implant contact.

Postsurgical fracture of the tibia occurred in both animals. As a consequence, one implant per animal could neither be used for biomechanical testing nor for histologic analysis. The mean values and standard deviations for all parameters investigated are given in figure 3.

Additionally, implant stability at surgery, bone mineral density in the cervical and apical part of an implant (BMD cervical, BMD apical) as well as bone to implant contact in these regions (BIC cervical, BIC apical) were determined for implants placed in animal bone. Comparative statistical analysis for these variables was based on Wilcoxon rank sum tests, while Spearman rank correlation tests were used for describing correlations between different parameters. The level of significance was set at $\alpha=0.05$ for all operations conducted.

Results

All surgeries could successfully be completed although sufficient primary implant stability often could only be achieved through bicortical fixation of the implants. Primary stability of the implants at surgery did not differ between both animals (Wilcoxon rank sum test; $W = 5$; $p=0.49$).

Figure 3: Mean values and standard deviations for all parameters investigated in this study. Normalized values are given for displacement and residual displacement. Please note the different units: [ISQ] for implant stability, μm for displacement and % for BIC and BMD.

An increase in trabecular bone density and healing time respectively caused a basic trend towards greater implant stability and less implant displacement as a consequence of loading. The histologic parameters, BIC and BMD also increased with healing time, however, this effect was only significant for BMD in the cervical and apical part ($p=0.02$ for BMD cervical and $p=0.05$ for BMD apical; Table 2).

Table 2: Pairwise comparisons between Sheep bone harvested after 5 and 20 weeks of osseointegration based on histologic parameters. Significant differences are written in bold.

BIC apical	0.24
BIC cervical	0.27
BMD apical	0.05
BMD cervical	0.02

Using trabecular bone with density of 20 pcf as compared to 10 pcf led to a significant increase in implant stability both, before and after load application ($p=0.01$ for ISQ 1 and $p=0.02$ for ISQ 2; Table 3a). On the contrary, no difference in ISQ values was found between implants placed in sheep following 5 and 20 weeks of healing ($p=0.38$ for ISQ 1 and $p=0.47$ for ISQ 2; Table 3a). Moreover, implants placed in Sawbones 20 & 40 showed significantly higher levels of implant stability as compared to implants placed in sheep, both in the condition before and after load application ($p<0.05$ for all comparisons; Table 3a). In terms of stability, implants placed in Sawbones 10 & 40 only differed from implants osseointegrated in sheep bone for 20 weeks in the condition after loading ($p=0.02$; Table 3a).

Table 3a: Pairwise comparisons between different bone samples based on ISQ values measured before and after load application; Wilcoxon tests; Significant differences are written in bold.

	ISQ 1			
	Sawbones 10 & 40	Sawbones 20 & 40	Sheep 5 weeks	Sheep 20 weeks
Saw-bones 10 & 40		0.01	0.21	0.31
Saw-bones 20 & 40	0.02		0.02	0.02
Sheep 5 weeks	0.12	0.03		0.38
Sheep 20 weeks	0.02	0.02	0.47	
	ISQ 2			

Maximum displacement and residual displacement did not differ between implants placed in both groups of Sawbones ($p=0.04$ and $p=0.03$; Table 3b). Also, no difference in maximum displacement was found between implants placed in sheep bone ($p=0.66$) whereas residual displacement was significantly different ($p=0.03$; Table 3b). After a healing period of 20 weeks, a minor rebound effect of the implants was seen following unloading comparable to the situation of implants placed in Sawbones 10 & 40 ($p=0.66$; Table 3b). However, after 5 weeks of healing the implants remained in a displaced position to some extent causing significant differences ($p=0.03$ for all comparisons; Table 3b). No difference in maximum displacement was found between implants placed in sheep and those placed in Sawbones 10 & 40. Implants placed in Sawbones 20 & 40 showed significantly lower maximum displacement as compared to implants in sheep following 20 weeks of healing ($p=0.02$; Table 3b).

Table 3b: Pairwise comparisons between different bone samples based on displacement values; Wilcoxon tests; Significant differences are written in bold.

	Maximum displacement			
	Sawbones 10 & 40	Sawbones 20 & 40	Sheep 5 weeks	Sheep 20 weeks
Saw-bones 10 & 40		0.04	0.71	0.71
Saw-bones 20 & 40	0.03		0.54	0.02
Sheep 5 weeks	0.03	0.03		0.66
Sheep 20 weeks	0.66	0.03	0.03	
	Residual displacement			

No significant correlations could be established between any of the parameters evaluated based on the experiments conducted in Sawbones ($p>0.05$ for all combinations; Table 4a). For implants osseointegrated in sheep bone for 5 weeks, a significant correlation existed between maximum and residual displacement ($p=0.00$; Table 4b). After a healing period of 20 weeks, BIC in the apical and cervical parts of the implants correlated significantly ($p=0.00$; Table 4b) while BMD in the apical part correlated with maximum implant displacement ($p=0.00$).

Table 4a: Pairwise correlations between different parameters measured in Sawbones; Spearman rank correlation tests tests; Significant differences are written in bold

	Sawbones 10 & 40			
	ISQ 1	ISQ 2	Displacement	Residual displacement
ISQ 1		0.85	0.27	0.68
ISQ 2	0.31		0.72	0.22
Displacement	0.58	0.74		0.2
Residual displacement	0.26	1	0.8	
	Sawbones 20 & 40			

Table 4b: Pairwise correlations between different parameters measured in animal bone; Spearman rank correlation tests tests; Significant differences are written in bold

		Sheep 5 weeks						
	ISQ 1	ISQ 2	Displacement	Residual displacement	BIC apical	BIC cervical	BMD apical	BMD cervical
ISQ 1		0.05	0.89	0.89	0.79	0.94	0.79	0.37
ISQ 2	0.68		0.8	0.8	1	0.79	0.6	0.6
Displacement	0.68	0.2		0	0.6	0.79	0.2	0.2
Residual displacement	0.37	0.2	0.6		0.6	0.79	0.2	0.2
BIC apical	0.05	0.8	0.6	0.6		0.05	0.8	0.8
BIC cervical	0.05	0.8	0.6	0.6	0		0.68	0.89
BMD apical	0.68	0.2	0	0.6	0.6	0.6		0.4
BMD cervical	0.68	0.8	0.6	0.6	0.4	0.4	0.6	
Sheep 20 weeks								

Discussion

Using a combined in vitro and ex vivo approach, this investigation tried to correlate clinical (implant stability), biomechanical (maximum and residual implant displacement) and bone-specific parameters (BIC, BMD) with each other. With the exception of maximum implant displacement in sheep bone following 20 weeks of healing, it could be verified that greater bone quality and healing time result in greater levels of implant stability. The fact that permanent implant displacement was seen in immature bone (sheep 5 weeks) as in contrast to all other bone specimen may further support this assumption. Despite comparable values for bone to implant contact after 5 and 20 weeks, latter implants showed higher levels of bone mineral density which may have prevented permanent implant displacement. These findings are supported by an in vitro study using contact endoscopy as measurement technique for quantifying micro movement of dental implants in which Engelke and coworkers showed that both loading magnitude and bone quality influenced the amount of implant displacement [15]. In addition, a previous parametric finite element analysis on the factors

governing micromotion at the implant-bone interface [17] came to similar results. In this context, the presence of a cortical bone plate with sufficient thickness seems to play a major role for achieving primary implant stability [16].

Previous studies conducted with the same [20] or with a comparable [6] experimental setup, to some extent showed positive correlations between micromotion at the implant bone interface and implant insertion torque, a frequently applied clinical measurement for implant stability which was not determined in this study. Neither in well-controlled bone surrogate materials nor in animal bone, any correlation between implant stability as measured by resonance frequency analysis and any of the additional parameters determined could be established which seems to be in line with a previous study in human cadavers [23]. The use of implant stability measurements as a basis for clinical decision making on the loading protocol applied therefore is questionable.

Besides limited sample size, several aspects have to be taken into account as potential limitations of this experiment. The setup applied with angulated loading

relative to the implant axis [19] resembles a frequently used scenario which is also applied for fatigue testing of dental implants [24,25]. The measurement apparatus applied does not allow for axial displacement measurements at the implant bone interface. However, accepted concepts describe micromotion as a phenomenon occurring parallel to the long axis of the implant bone interface when an implant is subject to axial load [11,12]. As the direction of loading potentially affects the loading pattern at the implant bone interface [17], the micromotion values presented should only be interpreted on a relative scale.

The animal model used allowed for simplified surgical protocols for instance not requiring tooth extractions and healing prior to implant placement as is the case in intraoral animal models. However, sheep tibia cannot fully resemble human alveolar bone [22]. Furthermore, fracture of the tibia in both animals reduced the sample size as the implants placed in this area potentially were affected by an inflammatory reaction. The healing times chosen were intended to reflect early and late phases of osseointegration but the differences obviously were very minor. Using polyurethane foam for mounting both bone surrogate materials and bone specimens may be considered as being problematic as the implant bone interface might have been altered. However, in no specimen any remnant of resin could be detected.

Conclusions

While frequently used for biomechanical research [26,27], polyurethane foam as used here in the form of dual layer structures seems not to perfectly mimic bone. However, it can be claimed based on implant stability measurements and displacement measurements that cellular polyurethane foam with density 10 pcf combined with a 3mm layer of solid foam with density 40 pcf allows for realistic biomechanical experiments in implant dentistry.

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