Simon Zabler[a], Tatjana Rack[b], Alexander Rack[c], Katja Nelson[d]

[a] University of Würzburg, Department of Physics and Astronomy - LRM, Germany

[b] Charité University Medicine, Department of Oral- and Maxillofacial Surgery, Germany

[c] European Synchrotron Radiation Facility, Grenoble, France

[d] University Medicine Freiburg, Department of Oral- and Maxillofacial Surgery, Germany

Fatigue induced deformation of taper connections in dental Titanium implants

The present study deals with in-situ microgap measurements in the internal taper connections of dental implants. Using x-ray phase contrast microtomography, the connecting interface between implant and abutment is probed non-destructively in three dimensions. Interference fringes across the conical interface occur due to the presence of microgaps, their intensity being a measure of the gap's width. Thus, for each point on the interface, interferences are extracted from the volumetric image in terms of normal projection maps which are, at selected points, compared to forward simulations to quantify the local gap width. Four designs of dental implants are tested in the 'as-received' state as well as after application of cyclic extra-axial load. Results show different degrees of microgap opening by cyclic deformation according to the implants' design as well as a great amount of detail on the actual interface, i.e. fretting scars, grooves and wear debris.

Keywords: Microtomography; X-ray imaging; Phase-contrast; Dental implants; Fatigue

1. Introduction

Dental screw implants made of Titanium and Titanium alloys have been used for many decades for the partial and full restoration of the upper and lower jaw [1]. Under the daily exercise of chewing these implants have to be biocompatible and withstand corrosion as well as fatigue forces [2-5]. Dental implants can either be designed as one-piece or two-piece devices [6]. The latter comprises the hollow screw implant and the abutment. Two-piece implants have both medical and mechanical advantages over a one-piece design [7]: I. After inserting the implant it is covered easily with tissue to allow for safe healing before the abutment is added a few weeks later, and II. The plug-socket connection between implant and abutment is fastened with an additional abutment screw which acts as a preloaded spring holding the two pieces together. The tightening force of the abutment screw is set to remain below its yield when random chewing forces apply [8,9]. Thanks to this design, the bending fatigue strength of two-piece implants has been shown to be superior to any bulk one-piece design [6,10,11]. Concerning the geometry of the implant-abutment connection (IAC) a variety of designs has been tested [2,3,12]. While the traditional concept is based on a horizontal butt joint connection, a significant part of modern dental implants feature taper connections of varying taper ratio and angle [10,13]. This step towards tapered IACs was mostly motivated by mechanical considerations. In mechanical engineering butt joints are mainly used for axially loaded connections. Consequently, technical failures such as screw loosening and/or fracture occur when extra-axial bending moments are applied, as is the case in vitro during chewing [8,9]. Compared to butt joints, taper connections have been found to perform much better in bending fatigue, because the moments mainly turn into elastic deformation at the IAC and do not become a lever for straining the abutment screw [6,7]. Consequently, implant and screw fractures can be avoided [14-16]. However, due to geometric imperfections both butt joints and taper joints contain hollow spaces inside the IAC which have direct contact with the oral cavity. Risk of bacterial infiltration (through the IAC and into the inner implant cavities) and of crevice corrosion are the consequences [4,17-19]. For the strains of bacteria present in the oral cavity, a few micrometer wide gap is considered sufficiently “open” for infiltration [20-22]. Despite the commonly acknowledged existence of such microgaps, relatively little is known about fretting and cyclic plastic deformation, in other words the possible enlargement of initially small microgaps to larger cavities [5,23-25]. For tapered IACs the geometry, i.e. the taper angle, the joint diameter and length, have been shown to play an important role for the implant's fatigue properties suggesting that the latter can be judged from the time-evolution of microgaps during fatigue [3,12,26,27].

By means of high-resolution radiography it has been demonstrated that microgaps exist in conical IACs under load [28]. These microgaps result from incongruent fit of implant and abutment. Independent of this misfit, taper connections give a certain mobility to the assembly which can be considered advantageous as long as the resulting strains along the IAC are purely elastic and do not accumulate to fatigue damage in terms of cyclic deformation. By means of quantitative phase-contrast radiography the width of microgaps has been determined in different taper connections from 30 µm down to ca. 0.1 µm spaces depending on the desgin and the applied force vector [29]. Cyclic fatigue has been shown to enlarge, in other words, to 'open up' these microgaps permanently [30]. This work is an extension to these radiographic observations: by applying phase contrast x-ray microtomography (XMT), the entire conical interface across the IAC is mapped non-destructively along with the distribution of microgaps and their local width. Four different commercially available implant systems are thus analysed. For each system a virgin implant was mapped along with another one which has been exposed to cyclic fatigue prior to the XMT measurement.

2. Materials and method

Four commercially available implant systems were chosen for this study, all featuring a taper connection between implant and abutment: Two systems are manufactured by Friadent Dentsply, Germany: Ankylos (abbreviated 'Anp') and Ankylos c/x ('An'). The third system is produced by Astra Tech (labelled 'Ch'), Germany and the fourth being the Bone Level system from Straumann, Switzerland ('St'). Dimensions of implants and abutments as well as torque of the abutment screws are listed in Table 1. Since the systems 'Anp' and 'An' feature an almost identical design, the three main implant layouts are depicted in Fig. 1. Note that unlike the Ankylos the 'c/x' version of the implant has an internal positioning index (hex) below the IAC and therefore has a shorter joint length (1.8 mm instead of 2.2 mm). Figure 1 further shows a magnified inset of the Ankylos taper indicating the basic mechanism of force transmission over a lever, with the main pivot located on the implant shoulder. Thus, along with taper ratio (major diameter over length) and taper (half) angle, the lever angles with respect to the IAC are listed in Table 1. All systems have a lever angle around 60° with the exception of the system 'St' which features an angle >90°. The IAC in both Ankylos systems has a standard 10:1 taper (i.e., a taper angle of 5.71° similar to grounded glass joints) with a diameter-length ratio (DLR) of 2.5/1.8 and 2.5/2.2 (in mm). Unlike the traditional Straumann ITI system with its well known 8° morse-taper, Bone Level ('St') features an IAC with a DLR of 3.3/0.7 and a larger taper angle (16°). Finally, the 'Ch' implant features a 11.2°-taper with a DLR of 3.8/2.4. For each system a pair of 2 samples were purchased and prepared whereby one sample was scanned after cyclic load which was applied prior to the measurement while the other one was imaged in the 'as-received' state [30]. Sample preparation involved embedding the implant bodies in a brass cylinder (15 mm diameter and height) by using methyl meta-acrylate (X60 cement from HBM Inc. US), then tightening the abutments with the system specific abutment screws and torques. Finally a 10 mm steel ball was cemented to each abutment, using the X60 meta-acrylate. Assembly of the implants and cyclic testing are according to ISO 14801:2007 standard and schematically shown in Fig. 2. One sample from each pair was then subjected to cyclic compression whereby 12-to-120 N (peak-to-valley) forces were applied under 30 degrees inclination to the samples' main axes. The stress ratio was $R = \sigma_{lo}/\sigma_{up} = 0.1$ according to ISO 14801:2007. During each test, 5×10^6 sinusoidal load cycles were applied to the samples at 15 Hz frequency in ambient atmosphere (test were performed at the Fraunhofer Institut für Werkstoffmechanik, Freiburg, Germany).

As determined by energy dispersive x-ray analysis (EDX) in electron microscopy (ZELMI TU Berlin, Germany using a Hitachi 4400) the Ankylos systems ('An' and 'Anp') are produced in the standard materials configuration: the implant being made of cp-Ti grade 4 (ASTM F-67), abutment and abutment screw of Ti-6Al-4V ELI alloy (grade 5, ASTM F-136). Unlike the Ankylos abutment those from Astra and Straumann ('Ch' and 'St') are made of the same material as the implant, i.e. cp-Ti grade 4. The abutment screw is made of Ti-6Al-4V ELI in all systems except for 'St' which has a screw made of Ti-6Al-7Nb alloy (ISO 3.0731), a new Vanadium-free version of the high strength grade 5 alloy.

Samples were scanned by phase contrast x-ray microtomography (XMT) using the imaging station at the BAM*line* (BESSY-II synchrotron light source of the Helmholtz-Centre Berlin, Germany). The XMT setup has been described in detail by Rack et al. [31]. For this work an x-ray energy of 50 keV was chosen, the sample-to-detector (propagation-) distance was 0.74 m and the effective pixel size 1.86 µm, about half the width of the detector point spread function (~4 µm), thus accounting for Shannon’s sampling condition. 1800 projection radiographs were recorded for each scan corresponding to a sample rotation of 180°. Because the field of view (3.7 mm x 2.6 mm) was insufficient to capture the Astra and Bone Level implants (4.5 mm and 4.1 mm respectively), scan area extension (known as stitching) was applied by recording two scans for each implant whereby the samples were displaced horizontally and perpendicular to the x-ray beam by 2 mm between the two scans along with their rotation axes. Then, before starting the reconstruction, the two scans were recombined into a single one. Tomographic volume reconstruction was performed on a supermicro™ Linux server using PyHST software of the European Synchrotron Radiation Facility [32].

Figure 3 displays how the XMT data was processed: For each reconstructed 3D volume the major axis inertia of the implant was determined by searching the (x,y)-centre of every horizontal cut (z-slice) trough the IAC. Microgaps in this interface become visible thanks to x-ray phase contrast. Note, that mounting the samples upright for XMT put them in quasi-vertical position, hence justifying the approximation of the elliptical cut through the IAC by a circle. From the resulting (x,y,z) centre-values the main implant axis was estimated by linear regression, then conical surfaces with a radius corresponding to the IAC were extracted from the volume in terms of cylindrical projection maps (the cones are projected onto a cylinder which then is unrolled to a flat map, cf. Fig. 3). In order to capture the entire IAC, maps were extracted like onion layers, starting from the inside (abutment) ca. 56 µm 'above' the IAC and going to the outside (implant) ca. 56 µm 'below' the IAC, by increasing the cone radius 0.93 µm (half a pixel) after each mapping, yielding a total of 120 maps (= 2*56µm/0.93µm) .The horizontal axis in the projection maps shows the azimuth (0°-360°) for which the number of angular increments was chosen to match $2\pi r_{IAC}/0.00186$ with r_{IAC} the major radius of the IAC (in mm) at the top of the taper. Thus, 4200 angular steps were used for 'An' and 'Anp', 5530 for 'St' and 6440 for 'Ch'. Assuming that the peak-to-valley intensity of the dark and bright radial phase-contrast interference lobes at the IAC are a measure for the local microgaps' width, the difference between maximum and minimum projections were calculated for each series of 120 projection maps. In order to draw quantitative conclusions by inferring this max-min value to the real gap width [29], numerical forward simulations of the IAC phase contrast were carried out using GNU OCTAVE™ [33].

3. Results

The max-min projection maps of the Ankylos samples Anp01 (virgin) and Anp02 (tested) are shown in Fig. 4a and b along with three magnified regions of interest (ROI, each region measuring approx. 0.98 mm in the horizontal and 0.56 mm in the vertical direction) in Fig. 4c. Both projection maps are shown on the same grey-scale in order to compare the 'tested' with the unbiased state of the system, whereby brightness is used as a measure of the microgap width. Unlike Anp01 the 'loaded' Anp02 shows two adjacent bright halos (gaps) on the upper IAC, horizontally set 180° apart (cf. Fig. 4b). Two more symmetrical gaps of minor vertical extension and width appear at the bottom of the IAC. The brightest halo (top left in Fig. 4b) can be clearly identified as the pivotal point where the cyclic load applied leaving a dent in the IAC. Furthermore both projection maps 'Anp01' and 'Anp02' show vertical and horizontal brightness modulations. Scanning through the 120 cylindrical projection maps of the IAC from the 'inside' to the 'outside' identifies the vertical stripes as grooves on the inner implant surface whereas the horizontal stripes originate from the abutment surface. As can be seen from Fig. 4c not only the local microgaps are imaged, but also microscopic surface damage (fretting scars and scratches on the implant and on the abutment surfaces) are marked with high detail by the phase contrast XMT. Circles and squares in the projection maps of Fig. 4 mark the points where representative radial profiles were extracted from the stack of projection maps (referred to below).

Max-min projection maps of the Ankylos c/x samples 'An01' (virgin) and 'An02' (tested) are shown in Fig. 5a and b along with three magnified ROIs in Fig. 5c. Surprisingly, both implants – tested and virgin – show microgaps in the upper IAC with the overall intensity being slightly brighter for 'An02'. The latter shows a bright halo – very similar to the one observed in Fig. 4b - on the upper right IAC (cf. Fig. 5b). 180° to the left, on the opposite side (upper left of Fig. 5b) a less pronounced microgap can be seen which is – unlike the area around the pivotal point - marked by numerous vertical scars some of which are shown in the magnified inset (number 3 in Fig. 5c). No gap is seen on the lower IAC probably because the indexed part (hex) of the IAC is not included in Fig. 5.

Unexpectedly, the projection map of the virgin sample An01 (Fig. 5a) shows a bright halo very similar to and only mildly less pronounced than the one observed in Fig. 5b. Yet, the sample has not been tested in cyclic fatigue. Like sample An02, the microgap in the upper left IAC is accompanied by an adjacent halo of lesser brightness seen 180° to its right. Random scratches appear to be part of the interfaces in 'An01' an 'An02' whereas pronounced fretting scars are only present for the tested sample (cf. Fig. 5c). Similar to the Ankylos system horizontal and vertical stripes patterns can be seen in the “c/x” version with only discrete contact points at the intersecting dark stripes.

Max-min maps of the virgin (Ch01) and tested (Ch02) Astra samples are depicted in Fig. 6. Deformation and opening of a microgap appear less severe when compared to the Ankylos systems, i.e. overall brightness of the projection maps in Fig. 6a and b is similar. A fatigue induced enhancement of the microgap is only found at the rim of the upper right IAC of the tested sample 'Ch02' while a broad bright halo is observed on the diametric opposite lower left IAC (cf. Fig. 6b). An interesting particulate microstructure is observed on the magnified insets of the virgin samples IAC (insets 1 and 2 in Fig. 6c) while different interface damage appears for sample 'Ch02' (inset 3 in Fig. 6c). Microscopic damage and fretting scars are found superimposed onto the turning grooves of the Astra abutment and appear all over the IAC of both samples.

Unlike the Ankylos and Astra systems, the IACs of sample 'St01' (virgin) and 'St02' (tested) show severe wear, mostly in the upper part (i.e. close to the implant neck) of the IAC (cf. Fig. 7a and b). Cyclic loading is found to increase the total width of the IAC (i.e. Fig. 7b appears globally brighter, hence more 'open' than Fig. 7a). A 'local' microgap is observed in the lower left IAC of the tested sample ('St02'), and is accompanied by another opening on the diametric opposite upper right IAC (Fig. 7b). Superimposed onto the local gaps are fretting and wear scars (mostly vertical). This damage appears to increase significantly under cyclic load as shown by the three magnified insets in Fig. 7c (insets '2' and '3' show the damage at 'St02' as compared to 'St01' shown in '1').

Prior to analysing the select radial profiles for measuring the microgaps' width forward simulations were carried out using the same approach as detailed by Zabler et al. [29] and adding tomographic reconstruction to the simulation. The results of these simulations are shown on a surface plot in Fig. 8: Here, intensity is a function of the radius (x) and of the gap width ranging from 0.05 to 30 µm. Sub-micrometer gaps mainly cause a bright intensity maximum, confined by less pronounced minima. This maximum increases steadily for gaps larger than 1 µm, whereby a pronounced valley is forming left to the intensity peak. Both peak and valley reach similar amplitudes at a gap of approx. 4 µm width. For gaps as large as ~14 µm gap the valley reaches an intensity minimum. Hence, for larger gaps the interferences are basically broadening while the peak-to-valley difference increases faintly. Three radial profiles were extracted for 'Anp01' and 'Anp02' as marked by the symbols in Fig. 4. In order to get sufficient statistics, 2x2 binning and a Gauss filter of 3 pixels radius were applied to the whole stack of projection 120 maps before extracting the desired radial profiles which are depicted in Fig. 9. The circular symbol in each max-min map (cf. Figs. 4, 5, 6 and 7) corresponds to the brightest 'spot' whereas the bulk rectangle marks a spot of medium brightness at the side of the IAC opposite to the pivot, and the hollow rectangle the darkest point on each map. The most pronounced radial profile in Fig. 9a mainly consists of a bright fringe surrounded by two darker lobes and matches with the forward simulation of a 1.0 µm wide microgap. On the opposite side of the conical IAC (bulk square symbol) the opening of the gap reaches only 0.4 µm. The actual “contact” between the mating implant and abutment surfaces takes only place at those points where the horizontal and vertical dark stripes intersect in the projection map and a continuous transition from one material to the next is observed without interference fringes (dashed profile). Profiles from the tested sample Anp02 are shown in Fig. 9b. The fringe contrast of the 'brightest spot' appears inversed: two bright lobes surrounding a minimum. Forward simulations reveal a microgap of 14 µm width whereas a 9 µm gap is found on the adjacent side (bulk square symbol).

The radial profiles for the samples 'An01' and 'An02' (tested) are shown in Fig.10a and b, respectively. The analysis of the profiles confirms the observations from Fig. 5. An opening of 10 µm is found for the brightest area of the 'as-received' sample 'An01' while 1.5 µm are measured on the adjacent side of the IAC. The brightest point in the max-min map of the tested sample 'An02' corresponds to a 16 µm gap. Two profiles were calculated at points of intermediate brightness (bulk square and bulk circle in Fig. 5b) revealing gaps of 6 µm and 1 µm width. Note that the interference fringes of the different profiles in Fig. 10 appear to be shifted by 3-10 µm indicating cyclic deformation of implant and abutment. A similar shift is observed in Fig. 9b. Hence, the circular cross-section of the IAC became slightly elliptical.

Three representative radial profiles for each Astra sample (cf. Fig. 6) are shown in Fig. 11a and b. A maximal opening of 0.7 µm was found for the microgap in the virgin sample 'Ch01' whereas this value rose slightly during cyclic testing to 1.2 µm for sample 'Ch02' (Fig. 11b). None of the profiles of intermediate intensity (bulk square symbol) could be quantified in these two samples. From the weakly pronounced interferences it can be concluded that the opening is <0.1 µm.

Radial profiles for both Straumann samples are shown in Fig. 12a and b whereby a maximal microgap of 0.15 µm width is found in the upper IAC of 'St01' increasing to 0.6 µm in 'St02'. Again profiles corresponding to intermediate brightness in Fig. 7 are found of <0.1 µm width.

4. Discussion

Using non-destructive phase contrast XMT together with extraction of three-dimensional interference patterns at the implant-abutment connection of four commercially available dental implant systems, the tightness of the latter was characterized in virgin and after cyclic fatigue. With the exception of An01 (Ankylos c/x) all systems showed a reasonably tight IAC in the unbiased 'as-received' state, with local microgaps of 0.15 - 1.0 µm width interrupted by local contact points. After cyclic fatigue, all systems showed an increase in gap width with a maximum of 16 µm for sample 'An02'. As an additional result of the cyclic fatigue all systems showed plastic deformation at the IAC, accompanied by occurrence of wide and broad gaps around the pivotal point of the force vector and, to a milder extent, at the diametric opposite side of the IAC (counter-pivot). Obviously, the extra-axial force turned the abutment into a crowbar, which through its lever deformed the IAC into a slightly elliptical shape after $5x10^6$ cycles. Unlike all the other virgin samples, 'An01' (Ankylos c/x) showed similar characteristics, i.e. a broad localized gap, although it had not been tested in cyclic fatigue. The two only possible explanations for this observation are (a) either the implant had been manufactured with tolerances as large as the microgaps that were measured in this study, or that (b) the implant had been loaded in some unknown post-production process or test.

By using numerical forward simulations brightness in the max-min projections was translated into local gap width. But these maps are not just a measure of the incongruent fit of implant and abutment surfaces. They also mark with high detail numerous kinds of microscopic surface damage at the IAC. Thus surface scratches, grooves and particulate debris were observed in the unbiased as well as in the tested state of all implant systems. Some of these defects are likely to result from the production process of implant and abutment but other probably occur during tightening of the abutment screw, e.g. the severe longitudinal scars on the abutment surface in 'St01'. During cyclic fatigue these initial defects appear to grow worse and new defects are likely to occur with a particular emphasis on friction marks and scratches which are oriented along the main (vertical) implant axis.

Hence, the Straumann implant does appear to reply in the same way as the Astra and Ankylos systems. Deformation of the latter can be easily explained by the cyclic forces acting through a 'lever' across the IAC, yet the lever angle of the Straumann system is superior to 90° which means that the plug-and-socket connection is not self-locking by mere friction at the IAC. The dislocation of the abutment is prevented by the screw (which has a tapered head and a higher torque compared to the other systems). Bending causes straining the screw, the 'lever' is most likely established underneath the IAC where the rotational index touches the implant. Hence, the distribution and interactions of bending moments, screw and implant depend on the stiffness of these components, force, clearance between the parts and overall geometry. Recent bending tests on tapered systems have confirmed the large deformability at the IAC, but also attested a bending strength similar to 'Ch' and 'Anp' [34]. Among the three other systems, sample Ch02 (Astra) appears to show by far the highest resistance to cyclic loading, the microgap width being most homogeneous and its enlargement - due to fatigue – minimal (1.2 µm for 'Ch02'). An apparent explanation for the difference between the Astra Tech system and its competitors from Ankylos is that system 'Ch' has a larger contact interface thus distributing the tensile and compressive forces over a greater area, whereas the local surface pressure for the Ankylos system is much higher. The choice of Ti grade-4 for the abutment material does not seem to have a negative effect on the microgap evolution. Depending on the geometry, a smaller stiffness and a higher ductility of the abutment could even be beneficial. The results of this study, match with the microgap opening that was already observed under static load, as investigated by phase-contrast radiography [30].

5. Conclusions

The most important conclusion of this study is that plastic deformation at the implant-abutment interface is evident after cyclic loading with a force amplitude as low as 120 N. Experimental S-N plots (components strength vs. number of cycles) of implants with tapered

IACs indicate that the fatigue strength of this implant type always lies in the range between 400 N and 600 N [2,3,12,26]. Consequently, deformation under cyclic load with an amplitude as low as 120 N should be totally elastic, yet this study proofs the contrary. It is known that microcracks can occur even in the elastic range. This study indicates that deformation and microgap enlargement - observed from the IAC - reach a 'steady-state', and do not – in extremis - lead to the failure of the implant, at least not during the 5×10^6 cycles which are routinely applied. Yet, there are significant differences according to the implants' design: the most severe deformation was observed in the Ankylos systems while Astra Tech and Straumann remained relatively 'close'. In-vivo, microgap opening will increase the risk of bacterial infiltration and consequently of implant loosening through a retarded infection [35,36]. In conclusion, implant systems should be optimized to have as little 'opening' at the IAC as possible.

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References

[1] P. P. Binon: Int. J. Oral Maxillofac. Impl. 1 (2000) 76.

[2] S. A. Hoyer, C. M. Stanford, S. Buranadham, T. Fridrich, J. Wagner, D. Gratton: J. Prosth. Dent. 85 (2001) 599.

[3] A. Khraisat, R. Stegaroiu, S. Nomura, O. Miyakawa: J. Prosth. Dent. 88 (2002) 604.

[4] M. A. Khan, R. L. Williams, D. F. Williams: Biomater. 17 (1996) 2117.

[5] S. Fayeulle, P. Blanchard, L. Vincent: Tribol. Transact. 2 (1993) 267.

[6] M. R. Norton: Clin. Oral Implants Res. 11 (2000) 458.

[7] M. C. Cehreli, K. Akça, H. Iplikçioğlu: Clin. Oral Implants Res. 15 (2004) 481.

[8] Y. Hattori, C. Satoh, T. Kunieda, R. Endoh, H. Hisamatsu, M. Watanabe: J. Biomechanics 42 (2009) 1533.

[9] T. Morneburg, P. A. Proeschel: Int. J. Prosthodont. 15 (2002) 20.

[10] B. R. Merz, U. C. Belser: Int. J. Oral Maxillofac. Impl. 15 (2000) 519.

[11] M. R. Norton: J. Prost. Dent. 83 (2000) 567.

[12] I. S. Park, S. Y. Won, T. S. Bae, K. Y. Song, X. W. Park, T. G. Eom, C. M. Jeong: Metals Mater. Int. 14 (2008) 133.

[13] K. Akça, M. C. Cehreli, H. Iplikçioğlu: Clin. Oral Implants Res. 14 (2003) 444.

[14] N. T. Green, E. E. Machtei, J. Horwitz, M. Peled: Implant Dentistry 11 (2002) 137.

[15] M. G. Manda, P. P. Psyllaki, D. N. Tsipas, P. T. Koidis: J. Biomed. Mater. Res. B: Appl. Biomater 89 (2009) 264.

[16] A. Piattelli, M. Piattelli, A. Scarano, L. Montesani: Int. J. Oral Maxillofac. Impl. 13 (1998) 561.

[17] J. P. Aloise, R. Curcio, M. Z. Laporta, L. Rossi, A. M. da Silva, A. Rapoport: Clin. Oral Implants Res. 21 (2010) 328.

[18] P. G. Coelho, P. Sudack, M. Suzuki, K. S. Kurtz, G. E. Romanos, N. R. Silva NR: J. Oral Rehabil. 35 (2008) 917.

[19] S. Harder, B. Dimaczek, Y. Açil, H. Terheyden, S. Freitag-Wolf, M. KernM: Clin. Oral Investig. 14 (2010) 427.

[20] S. Dibart, M. Warbington, M. F. Su, Z. Skobe: Int. J. Oral Maxillofac. Impl. 20 (2005) 732.

[21] V. K. Jansen, G. Conrads, E. J. Richter: Int. J. Oral Maxillofac. Impl. 12 (1997) 527.

[22] M. Gross, I. Abramovich, E. I. Weiss: Int. J. Oral Maxillofac Impl. 14 (1999) 94.

[23] P. D. Miller, J. W. Holladay: Wear 2 (1958) 133.

[24] K. G. Budinski: Wear 151 (1991) 203.

[25] R. M. Cibirka, S. K. Nelson, B. R. Lang, F. A. Rueggeberg: J. Prosthet. Dent. 85 (2001) 268.

[] Zipprich, H., Weigl, P., Lauer, H.-C., Lange, B., Implantologie 15 (2007), 31-45

[26] L. Steinebrunner, S. Wolfart, K. Ludwig, M. Kern: Clin. Oral Impl. Res. 19 (2008) 1276.

[27] W. Semper, S. Kraft, J. Mehrhof, K. Nelson: Int. J. Oral Maxillofac. Impl. 25 (2010) 752.

[28] A. Rack, T. Rack, M. Stiller, H. Riesemeier, S. Zabler, K. Nelson: J. Synchrotron Radiat. 17 (2010) 289.

[29] S. Zabler, T. Rack, A. Rack, K. Nelson: Rev. Sci. Instrum. 81 (2010) 103703.

[30] T. Rack, S. Zabler, A. Rack, H. Riesemeier, K. Nelson, submitted J. Dent. Res. (2011).

[31] A. Rack, S. Zabler, B. R. Müller, H. Riesemeier, G. Weidemann, A. Lange, J. Goebbels, M. Hentschel, W. Görner: Nucl. Instrum. & Meth. Phys. Res. A 586 (2008) 327.

[32] A. Mirone, R. Wilcke, A. Hammersley, C. Ferrero: PyHST – High Speed Tomographic Reconstruction (2010) http://www.esrf.eu/UsersAndScience/Experiments/TBS/SciSoft/

[33] University of Wisconsin: Octave Homepage http://www.octave.org

[34] Dittmer, S., Dittmer, M. P., Kohorst, P., Jendras, M., Borchers, L., Stiesch, M., J. Prosthodont. 00 (2011) 1-7.

[35] N. Broggini, L. M. McManus, J. S. Hermann, R. Medina, R. K. Schenk, D. Buser, D. L. Cochran: J. Dent. Res. 85 (2006) 473.

[36] M. Taira, T. Kagiya, H. Harada, M. Sasaki, S. Kimura, T. Narushima, T. Nezu, Y. Araki: J. Mater. Sci.: Mater. Med. 21 (2010) 267.

Correspondence address:

Dr. Simon Zabler

Fakultät für Physik und Astronomie - LRM
Universität Würzburg
Am Hubland
97074 Würzburg
Germany

simon.zabler@physik.uni-wuerzburg.de

Table 1:

Sample	**Manufacturer**	**Dimensions of implant and IAC ° [mm] / L [mm]**	**Cone half-angle [°]**	**Material (I: Implant, A: Abutment, S: Screw)**	**Torque [Ncm]**
An01, An02 (tested)	Ankylos c/x (indexed) Friadent	Implant: 3.5 (3.0) / 14.0 IAC: 2.5 / 1.8	Taper: 5.7 Lever: 57.8	I: cp-Ti gr. 4 A: Ti-64 gr. 5 S: Ti-64 gr. 5	15
Anp01, Anp02 (tested)	Ankylos Friadent	Implant: 3.5 (3.0) / 14.0 IAC: 2.5 / 2.2	Taper: 5.7 Lever: 51.8	I: cp-Ti gr. 4 A: Ti-64 gr. 5 S: Ti-64 gr. 5	15
Ch01, Ch02 (tested)	Astratech	Implant: 4.5 (3.5) /13.0 IAC: 3.8 / 2.4	Taper: 11.2 Lever: 66.0	I: cp-Ti gr. 4 A: cp-Ti gr. 4 S: Ti-64 gr. 5	25
St01, St02 (tested)	Bone Level Straumann AG	Implant: 4.1 / 14.2 IAC: 3.3 / 0.7	Taper: 16.0 Lever: 92.5	I: cp-Ti gr. 4 A: cp-Ti gr. 4 S: Ti-6Al-7Nb	35

Captions

Table 1: Samples, manufacturers, geometric parameters and the torque values for fastening the abutment screws of the four investigated dental implant systems.

Fig. 1: Schematic drawing of the three designs of the different implants systems, each comprising the I. Implant body, II. Abutment and III. Abutment screw. The inset shows a magnified view of the implant-abutment connection in the Ankylos implant marking the taper angle as well as the lever angle (for an applied 30° extra-axial force vector).

Fig. 2: Assembly of the implant systems (this figure: Straumann Bone Level) for fatigue testing. The latter is explained by a sketch from the ISO 14801:2003 standard for whom a stress ratio of $R = 0.1$ is applied with 120 N maximal compression repeated at 15 Hz frequency.

Fig. 3: Scheme showing the flow of data processing: Series of 1800 phase contrast radiographs are recorded whereby the sample rotates in 0.1° incremental steps. The total set of projections is reconstructed into a 3D volume image (tomogram) from which cylindrical normal projection maps are extracted, thus mapping the interferences over the entire IAC.

Fig. 4: Max-min projection maps for samples 'Anp01' (virgin, a) and 'Anp02' (tested, b) along with magnified regions of interest shown in (c). Each of the three regions corresponds to an area of approx. 0.98 mm x 0.56 mm size. Symbols indicate the coordinates for the extraction of radial profiles which are depicted in Fig. 9.

Fig. 5: Max-min projection maps for samples 'An01' (virgin, a) and 'An02' (tested, b) along with magnified regions of interest shown in (c). Each of the three regions corresponds to an

area of approx. 0.98 mm x 0.56 mm size. Symbols indicate the coordinates for the extraction of radial profiles which are depicted in Fig. 10.

Fig. 6: Max-min projection maps for samples 'Ch01' (virgin, a) and 'Ch02' (tested, b) along with magnified regions of interest shown in (c). Each of the three regions corresponds to an area of approx. 0.98 mm x 0.56 mm size. Symbols indicate the coordinates for the extraction of radial profiles which are depicted in Fig. 11.

Fig. 7: Max-min projection maps for samples 'St01' (virgin, a) and 'St02' (tested, b) along with magnified regions of interest shown in (c). Each of the three regions corresponds to an area of approx. 0.98 mm x 0.56 mm size. Symbols indicate the coordinates for the extraction of radial profiles which are depicted in Fig. 12.

Fig. 8: Surface plot showing the results of the numerical forward simulations: the intensity is plotted versus radial coordinate x [mm] and gap width [mm], the latter ranging from 0.05 to 30 µm.

Fig. 9: Radial profiles extracted from the stack of cylindrical normal projections of samples 'Anp01' (a) and 'Anp02' (b), ranging from the abutment to the implant and mapping the radial interference fringes locally. Prior to the profile extractions a Gauss-filter with radius 3 pixels was applied to the projection maps. The circular symbol marks the profile which is extracted from the brightest region in Fig. 4, the bulk square marks the adjacent region of intermediate brightness and the hollow square indicates the profile at a supposed 'contact point'.

Fig. 10: Radial profiles extracted from the stack of cylindrical normal projections of samples 'An01' (a) and 'An02' (b), ranging from the abutment to the implant and mapping the radial interference fringes locally. Prior to the profile extractions a Gauss-filter with radius 3 pixels was applied to the projection maps. The circular symbol marks the profile which is extracted from the brightest region in Fig. 5, the bulk square marks the adjacent region of intermediate brightness and the hollow square indicates the profile at a supposed 'contact point'.

Fig. 11: Radial profiles extracted from the stack of cylindrical normal projections of samples 'Ch01' (a) and 'Ch02' (b), ranging from the abutment to the implant and mapping the radial interference fringes locally. Prior to the profile extractions a Gauss-filter with radius 3 pixels was applied to the projection maps. The circular symbol marks the profile which is extracted from the brightest region in Fig. 6, the bulk square marks the adjacent region of intermediate brightness and the hollow square indicates the profile at a supposed 'contact point'.

Fig. 12: Radial profiles extracted from the stack of cylindrical normal projections of samples 'St01' (a) and 'St02' (b), ranging from the abutment to the implant and mapping the radial interference fringes locally. Prior to the profile extractions a Gauss-filter with radius 3 pixels was applied to the projection maps. The circular symbol marks the profile which is extracted from the brightest region in Fig. 7, the bulk square marks the adjacent region of intermediate brightness and the hollow square indicates the profile at a supposed 'contact point'.