



This is an author produced version of a paper published in Clinical Oral Implants Research. This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the published paper:

Löfgren, Niklas; Larsson, Christel; Mattheos, Nikos; Janda, Martin. (2016). Influence of misfit on the occurrence of veneering porcelain fractures (chipping) in implant-supported metal-ceramic fixed dental prostheses. Clinical Oral Implants Research, vol. 28, issue 11, p. null

URL: <https://doi.org/10.1111/clar.12997>

Publisher: Wiley

This document has been downloaded from MUEP (<http://muep.mah.se>).

Nils Löfgren  
 Christel Larsson  
 Nikos Mattheos   
 Martin Janda

# Influence of misfit on the occurrence of veneering porcelain fractures (chipping) in implant-supported metal-ceramic fixed dental prostheses: an *in vitro* pilot trial

## Authors' affiliations:

Nils Löfgren, Martin Janda, Department of Prosthodontics, Centre for Specialist Dental Care, Public Dental Care, Lund, Sweden  
 Christel Larsson, Department of Materials Science and Technology, Faculty of Odontology, Malmö University, Malmö, Sweden  
 Nikos Mattheos, Martin Janda, Department of Implant Dentistry, Faculty of Dentistry, The University of Hong Kong, Hong Kong SAR, China

## Corresponding author:

Nikos Mattheos, DDS/PhD  
 Department of Implant Dentistry, Faculty of Dentistry, The University of Hong Kong, 434 Hospital Road, Sai Ying Pun Hong Kong, Hong Kong SAR, China  
 Tel.: +852 2859 0411  
 Fax: +852 2858 6114  
 e-mail: nikos@mattheos.net

**Key words:** chipping, complication, FDP, implant, metal-ceramic

## Abstract

**Objective:** Technical complications such as veneer fractures are more common in implant-supported than tooth-supported restorations. The underlying causes have not been fully identified. The aim of this study was to evaluate whether misfit between the restoration and the implant may affect the risk of veneer fractures.

**Materials and methods:** Twenty standardized five-unit implant-supported metal-ceramic fixed dental prostheses (FDPs) were manufactured and fixed in acrylic blocks. The test group consisted of ten FDPs fixed with a 150- $\mu$ m misfit at the distal abutment. The remaining ten FDPs were fixed without misfit and acted as a control group. All FDPs underwent cyclic loading for a total of 100,000 cycles at 30-300 N. The FDPs were checked for cracks or chip-off fractures regularly. After cyclic load, the retorque value of all abutment screws was checked.

**Results:** Cracks within the veneering porcelain were noted in nine FDPs in the test group and one FDP in the control group. This difference was statistically significant ( $P < 0.001$ ). Fractures of the veneering porcelain occurred in three FDPs in the test group. No fractures occurred in the control group. This difference was not statistically significant. There were no significant differences in retorque values neither between the groups nor between different abutment positions in the FDPs.

**Conclusions:** Within the limitations of this *in vitro* pilot trial, it is suggested that misfit between a restoration and the supporting implant may increase the risk of cracking and/or chipping of the veneering porcelain for metal-ceramic FDPs.

Restoring missing teeth with the aid of dental implants has become a predictable treatment option offering several advantages. Implant-supported restorations help improve masticatory function, esthetics, and overall quality of life (Yao et al. 2014). Satisfaction after treatment with dental implants appears to be evident in a number of studies (Yao et al. 2014). Long-term follow-up studies show excellent survival of both the supporting implants and the suprastructures (Pjetursson et al. 2014).

Despite excellent survival rates and continuous improvements, implant treatment is not completely free of problems (Pjetursson et al. 2014). Technical and biological complications in implant-supported fixed dental prostheses (FDPs) are more than twice as common compared to tooth-supported FDPs, 38.7% compared to 15.7% after 5 years

(Pjetursson et al. 2007). Although the overall cost-effectiveness of dental implant treatment has been found to be sound and comparable to that of conventional tooth-supported restorations, a review concluded that the differences in complication rate will likely have implications for long-term costs (Vogel et al. 2013). Reducing complications will be beneficial from the point of view of patients and caregivers as well as society in general.

The most frequent technical complications are fractures of the veneer material, abutment or screw loosening, and loss of retention (Pjetursson et al. 2007). Fractures of the veneering porcelain were three times as common in the implant-supported group. Fractures appear at a rate of 13.5% for small-span implant-supported FDPs after 5 years and have been reported to reach 33.3% and 66.6% for full-arch implant-supported FDPs

## Date:

Accepted 25 October 2016

## To cite this article:

Löfgren N, Larsson C, Mattheos N, Janda M. Influence of misfit on the occurrence of veneering porcelain fractures (chipping) in implant-supported metal-ceramic fixed dental prostheses: an *in vitro* pilot trial. *Clin. Oral Impl. Res.* 00, 2016, 1–7  
 doi: 10.1111/clr.12997

at 5 and 10 years, respectively (Papaspri-dakos et al. 2012; Pjetursson et al. 2012). The reported rate of chipping is even higher when the substructure is ceramic (Larsson & Wennerberg 2014; Le et al. 2015; Pjetursson et al. 2015; Sailer et al. 2015).

The cause of veneer fractures is not entirely clear and is probably multifactorial (Pang et al. 2015). Inappropriate thickness of veneering porcelain and/or poor design with unsupported porcelain as a result has been suggested. Residual stresses may originate from differences in thermal expansion coefficients between veneer and framework as well as from inappropriate cooling rates. Clinical factors such as occlusal forces, wear, and microcracks from cyclic sliding contacts during chewing have also been discussed (Rekow et al. 2011; Pang et al. 2015). Such factors, however, could not sufficiently account for the differences in frequency observed between natural teeth and implant-supported FDPs. The lack of periodontal proprioception is often hypothesized as the main reason for this difference (Brägger et al. 2001). Yet, the impact of misfit of the reconstruction is poorly understood. Natural teeth can soon "neutralize" misfit of an FDP through orthodontic movement and adjustment to the occluding forces (Poyser et al. 2005) but not the ancylic implants.

Misfit between a restoration and the implant/abutment is not uncommon (Abduo et al. 2011). Teeth and implants differ in many ways, and one of the most important is that the implant is in direct, rigid contact with alveolar bone, whereas the tooth is supported by periodontium (Lindhe et al. 2008a). This gives the tooth the ability to migrate in response to applied force, for example, adjusting to an ill-fitting framework (Cho & Chee 1992; Garcia & Oesterle 1998; Sahin & Cehreli 2001). As the implant lacks this ability (Lindhe et al. 2008b), any misfit will result in stresses within the implant-reconstruction complex (Watanabe et al. 2000; Sahin & Cehreli 2001; Karl et al. 2004; Abduo et al. 2010). Ceramics are brittle materials and ill-equipped to tolerate tensile forces (Anusavice 2012). If misfit occurs and leads to tensile forces within the restoration, it is likely that the veneering porcelain will act as the weak link and fracture. This factor may influence the occurrence of veneer fractures, and there seems to be no difference between cement and screw-retained implant FDP (Sailer et al. 2015). There are, however, few studies available that examine the possible effect of misfit on risk of veneer fractures.

## Aim

The aim of this study was to investigate whether misfit between a restoration and the supporting implant may affect the risk of veneer fractures in screw-retained implant-supported metal-ceramic FDPs.

The hypothesis was that misfit would increase the risk of veneering porcelain fractures in metal-ceramic implant-supported FDPs.

## Materials and Methods

Twenty five-unit implant-supported metal-ceramic FDPs were manufactured, all with the same simplified design and geometry. The FDPs were screw-retained on implant level (Nobel Brånemark System RP, Göteborg, Sweden).

A mastermodel with implant analogs set up in plaster (Vel-Mix Stone, Kerr Nordic, Tranås, Sweden) at standardized distance for a five-unit FDP with premolar-sized teeth was made. The implants were placed to act as two anterior end abutments and one posterior end abutment with two pontics in-between. A simplified framework design was then built up on the mastermodel using a resin material (Dura-Lay; Reliance Dental MFG Co, Worth, IL, USA) and wax-up sleeves (Nobel Biocare AB, Göteborg, Sweden). The design was scanned in a NobelProcera 2G scanner (Nobel Biocare AB), and 20 identical milled titanium frameworks (NobelProcera Implant Bridge Titanium, Nobel Biocare AB) were ordered. To achieve a reproducible, uniform veneering porcelain layer, a two-piece putty mold (Provil Novo Putty, Heraeus Kulzer GmbH, Hanau, Germany) was constructed to guide the dental technician. The veneering porcelain (GC Initial Ti, GC Europe, Leuven, Belgium) was built up in five layers: one bonder, two opaquer layers, and two dentine layers according to the manufacturer's instruction and fired under vacuum in a ceramic furnace (Ivoclar

Programat P500; Ivoclar Vivadent AG, Schaan, Liechtenstein). The same dental technician performed all steps in the process and produced all FDPs. No *in vitro* study could be found with adequate relevance to provide data for a power calculation, given the fact that the settings and design of this study are rather unique (prosthesis design, implant distribution, and microgap size), as well as the studied outcome (microcracks, chipping). Nevertheless, extrapolating from Pjetursson et al. 2012, we assumed that an approximate incidence of veneer fractures in similar FDPs for a clinical load period corresponding to 2 million cycles is around 10%. Assuming that an incidence of 45% in the test group (misfit) would constitute a clinically important difference, the necessary sample size of the test group was calculated to be 8 (alpha 0.05, beta 0.2, power 0.8).

After construction, the FDPs were randomized into two groups, one test group and one control group (Fig. 1). To achieve a completely passive fit between implant and FDP in the control group, implant dummies (Nobel Brånemark System Groovy Mk III RP 3.75 × 13 mm, Nobel Biocare AB) were first connected to the FDPs with original abutment screws (Abutment Screw Brånemark System RP, Nobel Biocare AB) using hand force. The implant dummies were then fixed in pre-drilled PMMA (Plexlite Plastprodukter AB, Malmö, Sweden) blocks with epoxy (EpoFix, Struers, Copenhagen, Denmark) and left to cure for 24 h. The same procedure was repeated in the test group with the exception that spacers cut from a 150- $\mu$ m steel sheet were placed between the FDPs and implant analogs at position 5 (Fig. 2). After curing, all FDPs were dismantled and inspected. In the test group, the spacers were removed and the misfits created at position 5 were controlled to be 150 ± 5  $\mu$ m by visual inspection (Fig. 3) in light microscopy (Wild M3, Wild Heerbrugg, Switzerland). All FDPs were then remounted to the models with a torque of 35

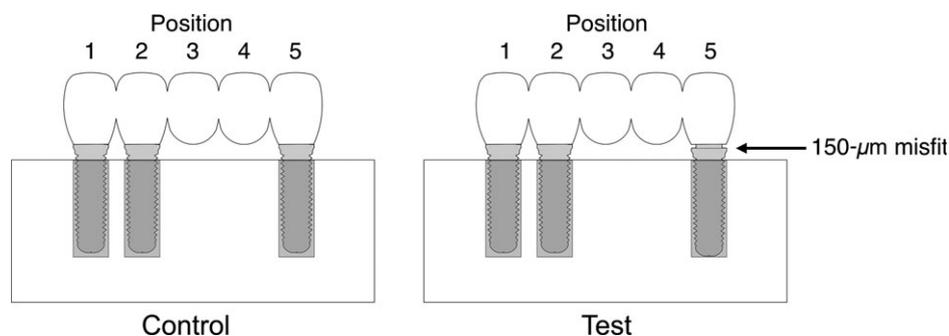


Fig. 1. The test and control arrangement of the implant-supported prosthesis.



Fig. 2. 150- $\mu$ m steel sheet was placed between the FDPs and implant analogs at position 5.

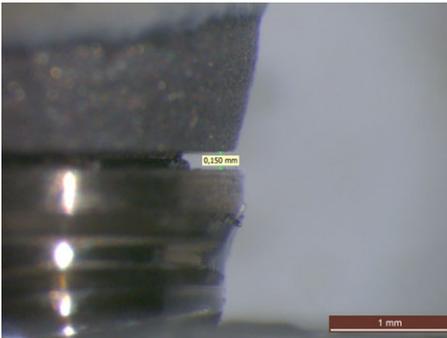


Fig. 3. Misfit at position 5 was controlled by visual inspection in light microscopy.

Ncm using a manual torque wrench (Manual Torque Wrench Prosthetic, Nobel Biocare AB). Sheffield test approach was followed (Jemt 1991). The cast framework was carefully seated on the implants by first tightening down completely the terminal gold screw on the opposite side of the misfit (positions 1, 2). A poor fit was revealed as a gap opening between the framework and the terminal implant on the other side (position 5). Screw access holes were closed with silicon string (Kuntze & Co AB, Hägersten, Sweden) and dental restorative composite (Tetric Evo-Ceram, Ivoclar Vivadent AG, Schaan, Liechtenstein). The same operator performed all steps in the process. Standardized digital periapical radiograph with optimal parallelity was taken before and after tightening of the position 5 abutment screw (Fig. 4a,b). The images were analyzed with ImageJ (National Institute of Health, USA) to investigate possible framework distortion. Measurements were conducted after calibrating the images with the known length in mm of the implant shoulder. A straight line was drawn from the shoulder of the implant in position 5 and a parallel line passing from the most apical point of the bridge pontic in position 4 for both radiographs. The distance between the two lines was measured before (a) and after (b) the complete seating of the bridge (Fig. 5a,b).

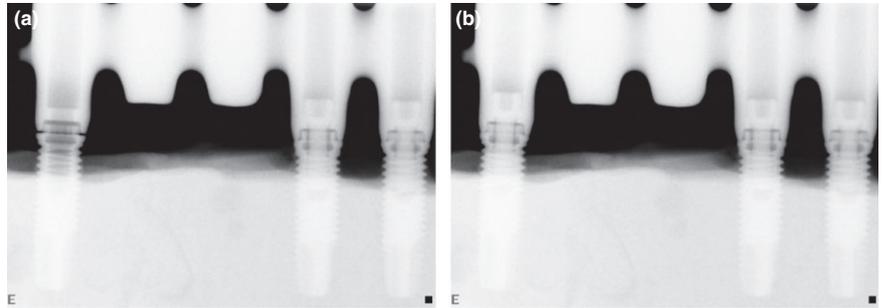


Fig. 4. (a) Standardized digital periapical radiograph before tightening of the position 5 abutment screw. (b) Standardized digital periapical radiograph after tightening of the position 5 abutment screw.

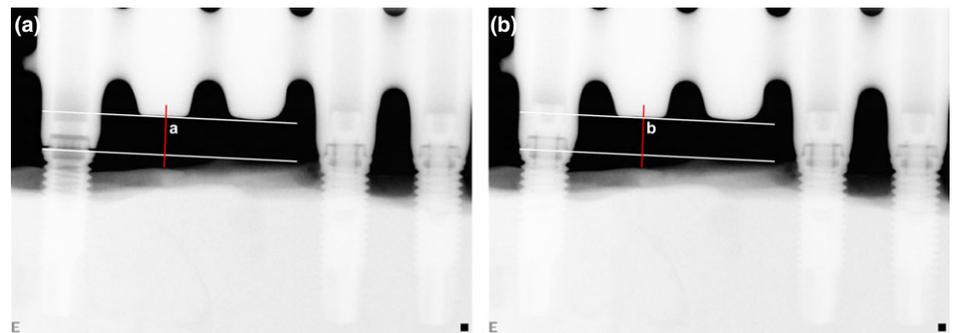


Fig. 5. (a) Standardized measurements on periapical radiograph before tightening of the position 5 abutment screw. (b) Standardized measurements at the periapical radiograph after tightening of the position 5 abutment screw.

Both FDP groups were then subjected to a cyclic loading test of 30–300 N at 2 Hz for 100,000 cycles in a cyclic loading machine (MTI Engineering AB, Lund/Pamaco AB, Malmö, Sweden). The load was applied by a 2.5-mm stainless steel ball in the middle of the occlusal surface at position 3. A thin plastic foil was placed between the indenter and the restoration surface (PE-Baufolie, Probau, Mannheim, Germany). The FDPs were mounted at a 10° angle to the force direction and were covered by water during loading (Fig. 6). To record visible veneer cracks and chip-off fractures, all FDPs were controlled with the aid of a LED white light source (Ronvig Dental Mfg, Daugaard, Denmark) at five occasions: before loading and after 10, 10,000, 50,000, and finally after 100,000 cycles. FDPs that presented chip-off fractures at any occasion were excluded from further testing. Fixed dental prostheses that presented with cracks were kept in testing to check for further crack propagation and/or chipping. Composite plugs were removed after completion of cyclic loading, and all screws were controlled for loosening by retorquer with a retorquer meter (Tohnichi digital torque gauge model BTGE-G, Tohnichi MFG Co, Tokyo, Japan). The same operator performed all registrations during the process.

#### Statistical analysis

The difference between test and control group regarding occurrence of visible cracks and chip-off fractures at the different intervals was analyzed by Fisher's exact probability test. The difference between test and control group regarding retorquer value was analyzed by independent groups *t*-test of the means at the different positions. Calculations were made in collaboration with a statistician. The SPSS software (SPSS 18.0; SPSS Inc, Chicago, IL, USA) was used to perform calculations. Differences were considered statistically significant at  $P < 0.05$ .

#### Results

No immediate cracks or chip-off fractures occurred at the start of cyclic load and the 10-cycle check. Visible cracks within the porcelain veneer occurred significantly more often in the test group compared to the control group: at 10,000 ( $P < 0.033$ ), 50,000 ( $P < 0.003$ ), and 100,000 ( $P < 0.001$ ) cycles. After 100,000 cycles of loading, nine of ten FDPs in the test group presented with visible cracks, compared to one of ten in the control group. (Figs 7 and 8).

The location of the cracks differed between test and control group. Although most cracks

occurred between implant position 2 and the pontic, cracks in the test group were also found in various other positions (Fig. 9a,b). In one of the test bridges, two cracks occurred in positions 1 and 5.

Three chip-off fractures were recorded in the test group, none in the control group. (Fig. 10) This difference was not statistically significant. One fracture occurred at 50,000 cycles. This FDP was excluded from further testing.

The difference in mean retorque value was greatest at the position of introduced misfit, position 5. No statistically significant differences were, however, found neither between the groups nor between positions. Mean values, calculated on the nine FDPs that underwent 100,000 load cycles, were recorded as follows: position 1: 27.11 Ncm (test) and 26.44 Ncm (control); position 2: 24.71 Ncm (test) and 25.22 Ncm (control); position 5: 24.00 Ncm (test) and 25.77 Ncm (control) (Fig. 11).

The measurements on the radiographs confirmed the bending of the framework with (a) being 3.40 mm while (b) was 3.29 mm. Microscope photograph of the implant in position 5 showed an uneven seating of the reconstruction, with the external side seating

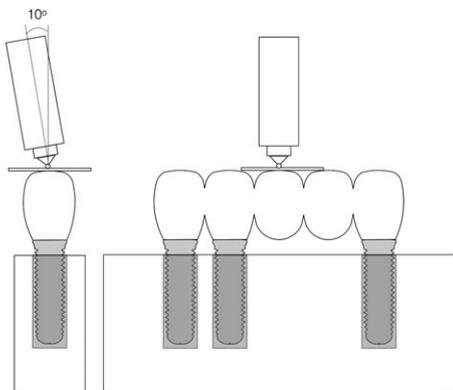


Fig. 6. Schematic illustration of the test set-up for cyclic loading.

in tight contact but a gap of 20 µm in the internal side (Fig. 12).

## Discussion

The results from the present study suggest that misfit between a restoration and the supporting implant significantly affects the occurrence of fractures of the porcelain veneer. The most likely explanation is the fact that implant framework misfit alters the biomechanical situation (Abduo & Judge 2014). The rigid connection of the implants to the bone means that stress is transferred to the implant components and/or built up within the frameworks (Abduo & Judge 2014). It is likely that compressive as well as tensile stress develops. For metal-ceramic FDPs, areas where tensile stress is concentrated are potential crack-initiation sites and prone to fracture, as ceramics are ill-equipped to tolerate tensile forces (Anusavice 2012).

Implant-supported restorations rarely exhibit perfect passive fit (Abduo et al. 2011). When producing an implant-supported FDP, there are numerous steps where the fit can be affected: from the impression to final

production and adjustment, and it is well known that a certain amount of misfit is unavoidable, irrespective of production technique. (Abduo et al. 2011). The potential influence of misfit on technical complications such as veneer fractures should therefore not be overlooked.

Several authors have discussed the levels of misfit and attempted to define passive fit or an acceptable level of fit (Brånemark 1983; Jemt 1991; Sahin & Cehreli 2001; Karl et al. 2004; Abduo et al. 2010). One suggestion has been to define any distance between abutment and FDP as misfit. A distance ranging from 10 µm up to 150 µm has been discussed, while other authors define passive fit as no space between abutment and FDP (Brånemark 1983; Jemt 1991; Watanabe et al. 2000). Another definition of passive fit is no tension within the framework, after delivery (Sahin & Cehreli 2001). However, all proposed definitions are hypothetical (Abduo et al. 2010). In the present study, misfit was set as a distance of 150 µm between implant and FDP. This is in the higher range of what is discussed in the studies mentioned above, and stress increases with increasing misfit (Abduo et al. 2010). It is, however, evident from clinical reports that misfit of this magnitude exists (Jokstad & Shokati 2015). It has also been proven in laboratory studies that discrepancies of up to 500 µm will disappear after screw tightening (Clelland et al. 1995). In the present study, it was possible to close the 150-µm gap by tightening the bridge screws purely by hand before using the torque wrench. This finding is in accordance with another study that demonstrated that misfits could be closed by tightening prosthetic screws to 10 Ncm (Clelland et al. 1995).

The implant placement and distribution were adapted to clinical situations. It may be preferable to distribute the load of the restoration on more than two implants when making a five-unit FDP. It is not uncommon to find anatomical limitations in the posterior parts of the jaws – therefore, two anterior implants were placed and one posterior. To place the misfit at the distal abutment in the test group could be said to represent a “worst case scenario,” whereas the control group represents the ideal situation. *In vitro* studies have shown the distal abutment to be the area of the maximum distortion in implant-supported FDPs (Mitha et al. 2009). It is possible that a centrally placed misfit might not have created deflection and tensile stress of a similar extent. The clinical situation may present misfit at any position. Future studies

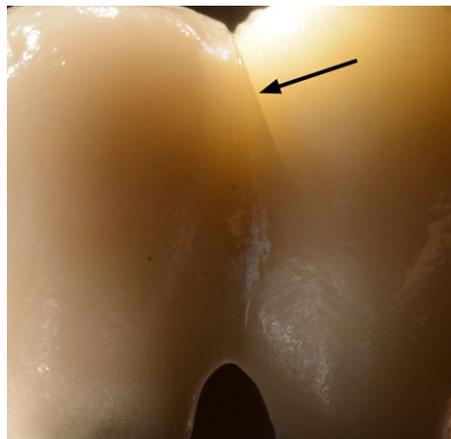


Fig. 8. Visualisation of a veneer crack.

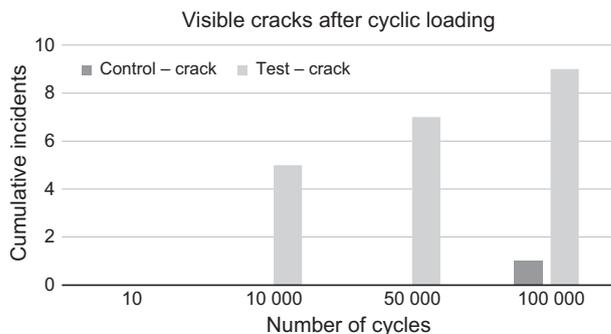


Fig. 7. Number of visible cracks after loading cycles.

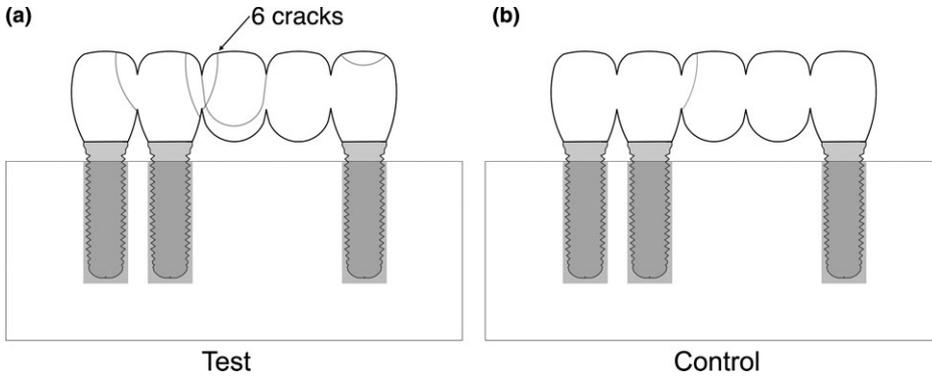


Fig. 9. Illustration of location of cracks at test (a) and control (b) FDPs.

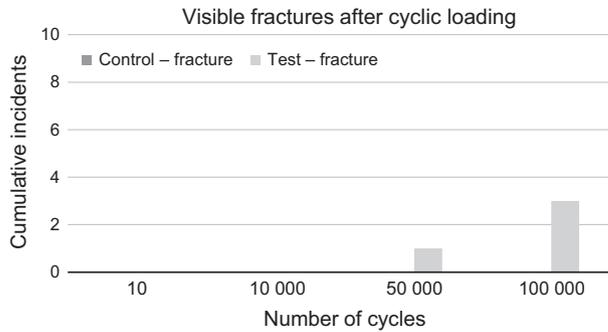
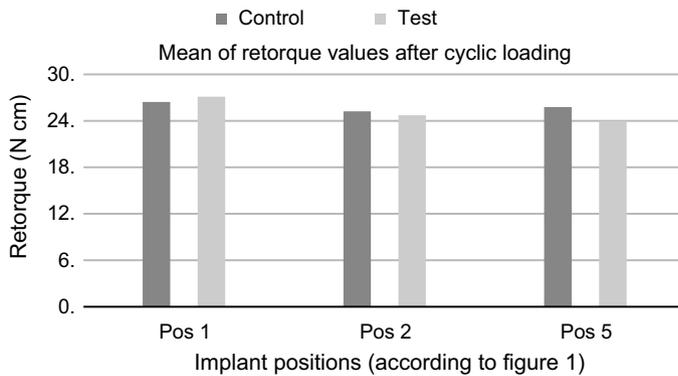


Fig. 10. Chip-off fractures in the test group after 50 and 100 thousand loading cycles.



Control	Position 1	Position 2	Position 5
Mean	26.44	25.22	25.77
Median	26.65	25.7	25.75
SD	1.66	1.83	1.89

Test	Position 1	Position 2	Position 5
Mean	27.11111111	24.71111111	24
Median	27.1	23.7	25.1
SD	3.00	3.08	1.96

Fig. 11. Mean, Median and standard deviation of retorque values, for the nine FDPs that underwent 100,000 load cycles, for each of the implant positions.

should include alternative designs of the sub-groups.

The localization of cracks differed between test and control groups where cracks in the

test group occurred in various places. This is not easy to interpret, but is likely attributed to the misfit causing a shift from linear stress distribution to more complex stress

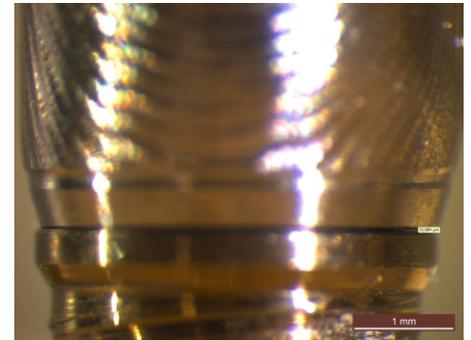


Fig. 12. Illustration of tight contact at external side seating and 20µm gap at internal side seating.

patterns (Glantz et al. 1984). The present study was not meant to tackle the issue of stress distribution. Future studies, for example, finite element analysis, could enhance our understanding.

The consequences of stress are exacerbated by dynamic loading (Sahin & Cehreli 2001). The present study therefore chose to load the FDPs cyclically. A thin plastic foil was used between indenter and FDP to ensure even distribution of load on the surface of the restoration (Kelly 1999). No thermocycling was performed. It is often used when evaluating effects on the cement and risk of loss of retention, whereas this study evaluated screw-retained restorations (Gale & Darvell 1999). It may, however, also affect fracture resistance of ceramic FDPs *in vitro*, at least at temperatures of 50°C (Rosentritt et al. 2006). No concrete evidence that failures in clinical practice occur because of thermal stresses exists though (Gale & Darvell 1999). Water was, however, present during cyclic load as it is considered to aggravate stress corrosion and lead to strength degradation (Jung et al. 2000).

The choice of 30- to 300-N loads is within what has previously been used for *in vitro* tests (Rosentritt et al. 2008). *In vivo* mean masticatory forces generally range between 20 and 70 N, and a 50- to 200-N test load has been established to create cracking and fracture of porcelain veneer (Rosentritt et al. 2008) (Jung et al. 2000).

One Lakh cycles were performed. There is no consensus on what number of cycles is adequate. One regularly cited study claims that as much as 800,000 chewing cycles may be performed per year (Rosentritt et al. 2006). If this estimate is true, it would mean that 100,000 cycles are the equivalent of a couple of months of chewing. The authors did, however, not perform any measurements; instead, a provisory survey was made among dental students and assistants. The validity and reliability of those results may be unreliable.

Another study found significant degradation of porcelain to occur already at 10,000 cycles (Jung et al. 2000).

In the present study, the differences concerning the occurrence of cracks within the veneer were clearly significant already after 50,000 cycles. This is in accordance with a statement that ceramic failure is predicted to occur mostly within the first days after insertion and should therefore be able to be detected at early stages of cyclic loading (Kelly 1999). It cannot, however, be ruled out that the prevalence of fractures within the veneer might differ with increasing number of cycles, as a fracture in the control group only occurred at the end of the test. Future studies should increase the number of cycles performed. There were no significant differences in retorque values of the abutment screws. Other investigators have showed that misfit significantly decreases the loosening torque values of implant FDP prosthetic screws after cyclic loading of 1,000,000 cycles (Farina et al. 2012). It might be possible that the abutment screws would have loosened in the present study if cyclic load had been continued beyond 100,000 cycles.

Differences between the groups are unlikely to be attributed to the veneering technique. All feasible efforts to standardization of the manufacturing process have been taken. The restorations were standardized and produced in the same way throughout, by one and the same dental technician. The technique has been previously used and displays predictable results (Mahmood et al. 2016). It is anticipated that randomization would eliminate any risks from any inevitable diversity. Further studies with slicing of the reconstructions and/or micro-CT analysis

might be helpful to reveal further cracks and indicate the patterns of stress/strain induced.

The present study is a pilot trial comprising relatively few FDPs. The number of specimens might also influence whether differences noted reach statistical significance or not – as, for example, concerning the occurrence of chip-off fractures which differed numerically between groups. Further studies are necessary and should include an increased number of specimens.

As technical complications are more common in implant-supported than tooth-supported restorations, it is of great interest to evaluate possible factors behind complications in order to gain knowledge and understanding on how to prevent complications. Future studies should also include and compare different materials. Less stiff materials, such as titanium used in the present study, or high-noble alloys, exhibit less stress within the frameworks compared to stiffer framework materials, such as cobalt–chromium and zirconia (Abduo et al. 2012). On the other hand, stiffer frameworks cause less stress within the ceramic veneer.

From a clinical point of view, one might wonder if a misfit of 150 µm would be detectable in clinical settings in a similar reconstruction. After seating of the reconstruction with 35 Ncm, the gap appears to close, so clinical detection through, for example, probing appears impossible. Nevertheless, in the *in vitro* settings, an optimally parallel periapical radiograph (Fig. 8) indicates the presence of the misfit. Whether such an optimal parallelism and contrast, however, are likely to be achieved in clinical settings is questionable.

The present study used titanium as framework material. The occurrence of veneer

fractures has been reported to be higher on titanium than high-noble alloys but more limited than for zirconia frameworks (Jemt et al. 2003) (Pjetursson et al. 2015). The choice of titanium was made as it is more commonly used today compared to high-noble alloys due to cost, biocompatibility, and modern manufacturing techniques. Future studies should, however, include and compare different materials for the reasons discussed above.

## Conclusion

Within the limitations of this *in vitro* study, it is suggested that misfit between a restoration and the supporting implant may increase the risk of cracking and/or chipping of the veneering porcelain for metal-ceramic FDPs. Further studies are required to investigate possible outcomes for different levels of misfit, increased periods of cyclic load, and different materials.

**Acknowledgements:** The study was supported by a grant from Folkhälsan Skåne AB, Sweden, and partially supported through grant Nr. 775113 by RGC, Hong Kong. Implant components were kindly provided by Nobel Biocare AB, Göteborg, Sweden. Dr. Mattheos reports having received government grants.

## Conflict of interest

The authors declare no conflict of interest.

## References

- Abduo, J., Bennani, V., Waddell, N., Lyons, K. & Swain, M. (2010) Assessing the fit of implant fixed prostheses: a critical review. *International Journal of Oral and Maxillofacial Implants* **25**: 506–515.
- Abduo, J. & Judge, R.B. (2014) Implications of implant framework misfit: a systematic review of biomechanical sequelae. *International Journal of Oral and Maxillofacial Implants* **29**: 608–621.
- Abduo, J., Lyons, K., Bennani, V., Waddell, N. & Swain, M. (2011) Fit of screw-retained fixed implant frameworks fabricated by different methods: a systematic review. *The International Journal of Prosthodontics* **24**: 207–220.
- Abduo, J., Lyons, K., Waddell, N., Bennani, V. & Swain, M. (2012) A comparison of fit of CNC-milled titanium and zirconia frameworks to implants. *Clinical Implant Dentistry and Related Research* **14**(Suppl 1): 20–29.
- Anusavice, K.J. (2012) Dental ceramics. In: Anusavice, K.J., ed. *Phillips' Science of Dental Materials*, 12th edition, 418–473. St.Louis: Saunders.
- Brägger, U., Aeschlimann, S., Bürgin, W., Hammerle, C.H. & Lang, N.P. (2001) Biological and technical complications and failures with fixed partial dentures (FPD) on implants and teeth after four to five years of function. *Clinical Oral Implants Research* **12**: 26–34.
- Brånemark, P.I. (1983) Osseointegration and its experimental background. *Journal of Prosthetic Dentistry* **50**: 399–410.
- Cho, G.C. & Chee, W.W.L. (1992) Apparent intrusion of natural teeth under an implant-supported prosthesis: a clinical report. *Journal of Prosthetic Dentistry* **68**: 3–5.
- Clelland, N.L., Papazoglou, E., Carr, A.B. & Gilat, A. (1995) Comparison of strains transferred to a bone simulant among implant overdenture bars with various levels of misfit. *Journal of Prosthodontics* **4**: 243–250.
- Farina, A.P., Spazzin, A.O., Pantoja, J.M., Consani, R.L. & Mesquita, M.F. (2012) An *in vitro* comparison of joint stability of implant-supported fixed prosthetic suprastructures retained with different prosthetic screws and levels of fit under masticatory simulation conditions. *International Journal of Oral and Maxillofacial Implants* **27**: 833–838.
- Gale, M.S. & Darvell, B.W. (1999) Thermal cycling procedures for laboratory testing of dental restorations. *Journal of Dentistry* **27**: 89–99.
- Garcia, L.T. & Oesterle, L.J. (1998) Natural tooth intrusion phenomenon with implants: a survey. *International Journal of Oral and Maxillofacial Implants* **13**: 227–231.
- Glantz, P.O., Strandman, E., Svensson, S.A. & Randow, K. (1984) On functional strain in fixed

- mandibular reconstructions. I. An *in vitro* study. *Acta Odontologica Scandinavica* **42**: 241–249.
- Jemt, T. (1991) Failures and complications in 391 consecutively inserted fixed prostheses supported by Brånemark implants in edentulous jaws: a study of treatment from the time of prosthesis placement to the first annual checkup. *International Journal of Oral and Maxillofacial Implants* **6**: 270–276.
- Jemt, T., Henry, P., Linden, B., Naert, I., Weber, H. & Wendelhag, I. (2003) Implant-supported laser-welded titanium and conventional cast frameworks in the partially edentulous jaw: a 5-year prospective multicenter study. *The International Journal of Prosthodontics* **16**: 415–421.
- Jokstad, A. & Shokati, B. (2015) New 3D technologies applied to assess the long-term clinical effects of misfit of the full jaw fixed prosthesis on dental implants. *Clinical Oral Implants Research* **26**: 1129–1134.
- Jung, Y.G., Peterson, I.M., Kim, D.K. & Lawn, B.R. (2000) Lifetime-limiting strength degradation from contact fatigue in dental ceramics. *Journal of Dental Research* **79**: 722–731.
- Karl, M., Winter, W., Taylor, T.D. & Heckmann, S.M. (2004) *In vitro* study on passive fit in implant-supported 5-unit fixed partial dentures. *International Journal of Oral and Maxillofacial Implants* **19**: 30–37.
- Kelly, J.R. (1999) Clinically relevant approach to failure testing of all-ceramic restorations. *Journal of Prosthetic Dentistry* **81**: 652–661.
- Larsson, C. & Wennerberg, A. (2014) The clinical success of zirconia-based crowns: a systematic review. *The International Journal of Prosthodontics* **27**: 33–43.
- Le, M., Papia, E. & Larsson, C. (2015) The clinical success of tooth- and implant-supported zirconia-based fixed dental prostheses. A systematic review. *Journal of Oral Rehabilitation* **42**: 467–480.
- Lindhe, J., Karring, T. & Araujo, M. (2008a) The anatomy of periodontal tissues. In: Lindhe, J., Lang, N.P. & Karring, T., eds. *Clinical Periodontology and Implant Dentistry*, 5th edition, 3–49. Oxford: Blackwell Publishing.
- Lindhe, J., Karring, T. & Araujo, M. (2008b) Osseointegration. In: Lindhe, J., Lang, N.P. & Karring, T., eds. *Clinical Periodontology and Implant Dentistry*, 5th edition, 99–107. Oxford: Blackwell Publishing.
- Mahmood, D.J., Linderth, E.H., Wennerberg, A. & Vult von Steyern, P. (2016) Influence of core design, production technique, and material selection on fracture behavior of yttria-stabilized tetragonal zirconia polycrystal fixed dental prostheses produced using different multilayer techniques: split-file, over-pressing, and manually built-up veneers. *Clinical, Cosmetic and Investigational Dentistry* **8**: 15–27.
- Mitha, T., Owen, C.P. & Howes, D.G. (2009) The three-dimensional casting distortion of five implant-supported frameworks. *The International Journal of Prosthodontics* **22**: 248–250.
- Pang, Z., Chughtai, A., Sailer, I. & Zhang, Y. (2015) A fractographic study of clinically retrieved zirconia-ceramic and metal-ceramic fixed dental prostheses. *Dental Materials* **31**: 1198–1206.
- Papaspyridakos, P., Chen, C.J., Chuang, S.K., Weber, H.P. & Gallucci, G.O. (2012) A systematic review of biologic and technical complications with fixed implant rehabilitations for edentulous patients. *International Journal of Oral and Maxillofacial Implants* **27**: 102–110.
- Pjetursson, B.E., Asgerisson, A.G., Zwahlen, M. & Sailer, I. (2014) Improvements in implant dentistry over the last decade: comparison of survival and complication rates in older and newer publications. *International Journal of Oral and Maxillofacial Implants* **29**(Suppl): 308–324.
- Pjetursson, B.E., Brägger, U., Lang, N.P. & Zwahlen, M. (2007) Comparison of survival and complication rates of tooth-supported fixed dental prostheses (FDPs) and implant-supported FDPs and single crowns (SCs). *Clinical Oral Implants Research* **18**(Suppl 3): 97–113. Review. Erratum in: (2008) *Clin Oral Implants Res* **19**: 326–28.
- Pjetursson, B.E., Sailer, I., Makarov, N.A., Zwahlen, M. & Thoma, D.S. (2015) All-ceramic or metal-ceramic tooth-supported fixed dental prostheses (FDPs)? A systematic review of the survival and complication rates. Part II: Multiple-unit FDPs. *Dental Materials* **31**: 624–639.
- Pjetursson, B.E., Thoma, D., Jung, R., Zwahlen, M. & Zembic, A. (2012) A systematic review of the survival and complication rates of implant-supported fixed dental prostheses (FDPs) after a mean observation period of at least 5 years. *Clinical Oral Implants Research* **23**(Suppl 6): 22–38.
- Poyser, N.J., Porter, R.W., Briggs, P.F., Chana, H.S. & Kelleher, M.G. (2005) The Dahl Concept: past, present and future. *British Dental Journal* **198**: 669–676.
- Rekow, E.D., Silva, N.R.F.A., Coelho, P.G., Zhang, Y., Guess, P. & Thompson, V.P. (2011) Performance of dental ceramics: challenges for improvement. *Journal of Dental Research* **90**: 937–952.
- Rosentritt, M., Behr, M., Gebhard, R. & Handel, G. (2006) Influence of stress simulation parameters on the fracture strength of all-ceramic fixed-partial dentures. *Dental Materials* **22**: 176–182.
- Rosentritt, M., Siavikis, G., Behr, M., Kolbeck, C. & Handel, G. (2008) Approach for valuating the significance of laboratory simulation. *Journal of Dentistry* **36**: 1048–1053.
- Sahin, S. & Cehreli, M. (2001) The significance of passive fit in implant prosthodontics: current status. *Implant Dentistry* **10**: 85–92.
- Sailer, I., Makarov, N.A., Thoma, D.S., Zwahlen, M. & Pjetursson, B.E. (2015) All-ceramic or metal-ceramic tooth-supported fixed dental prostheses (FDPs)? A systematic review of the survival and complication rates. Part I: single crowns (SCs). *Dental Materials* **31**: 603–623.
- Vogel, R., Smith-Palmer, J. & Valentine, W. (2013) Evaluating the health economic implications and cost-effectiveness of dental implants: a literature review. *International Journal of Oral and Maxillofacial Implants* **28**: 343–356.
- Watanabe, F., Uno, I., Hata, Y., Neuendorff, G. & Kirsch, A. (2000) Analysis of stress distribution in a screw-retained implant prosthesis. *International Journal of Oral and Maxillofacial Implants* **15**: 209–218.
- Yao, J., Tang, H., Gao, X.L., McGrath, C. & Mattheos, N. (2014) Patients' expectations to dental implant: a systematic review of the literature. *Health and Quality of Life Outcomes* **29**: 1–14.