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Marginal Bone Loss and Peri-Implant Health Around One-Piece and Two-Piece Tissue-Level Zirconia Implants: A Multicenter Retrospective Cohort Study With 5 to 11 Years of Follow-Up

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Abstract

Purpose

To compare marginal bone loss (MBL) and peri-implant health between one-piece and two-piece tissue-level zirconia implants in routine practice under different placement and loading protocols.

Methods

This retrospective multicenter cohort included 470 implants in 137 patients, placed between 2014 and 2020 in three private practices. MBL was measured at mesial and distal sites on serial radiographs and analyzed with linear mixed-effects models using a piecewise time structure, random effects at implant and patient level, and covariate adjustment. Peri-implant parameters were assessed cross-sectionally at the last follow-up.

Results

Mean radiographic follow-up was 6.3 ± 1.6 years. MBL occurred mainly during the first year (− 0.88 mm, 95% CI -0.955 to -0.801; P = < 0.001) and was near-stable thereafter (− 0.018 mm/year; 95% CI − 0.044 to 0.007; P = 0.152). Mean MBL at the last radiograph was − 1.01 ± 1.02 mm, and 22.9% of implants showed bone loss exceeding 2 mm. Bone level trajectories did not differ between designs; the 95% CI of the interaction after the first year limited the plausible divergence to − 0.13 to 0.18 mm over five years. Immediate placement was associated with greater first-year loss in an exploratory analysis (P = 0.039) but not with overall MBL (P = 0.282). Peri-implantitis affected 1.5% of implants and 5.1% of patients. Bleeding on probing was more frequent at two-piece implants (adjusted OR 1.75; 95% CI 0.97 to 3.13). Five-year complication-free survival exceeded 98% in both designs.

Conclusions

One-piece and two-piece tissue-level zirconia implants of this system showed comparable marginal bone maintenance, with most bone remodeling occurring during the first year.

1. Background

Zirconia dental implants have emerged as an alternative to titanium implants over the past two decades, driven by esthetic demand in sites with thin peri-implant mucosa and by a growing patient preference for implant supported rehabilitation(1, 2). Long term evaluations of contemporary zirconia implant systems have shown clinical performance comparable to titanium (3, 4).Five year survival rates of 95–98% support the use of zirconia dental implants in various indications(5, 6).

Over the past decade, zirconia implant systems have evolved from predominantly one-piece designs toward broader availability of two-piece, screw-retained and cement retained configurations intended to increase prosthetic flexibility. In titanium implantology, a stable and undisturbed transmucosal abutment connection has been shown to be important for the preservation of marginal bone, with the location of the implant abutment microgap influencing the extent of crestal bone remodeling(7–9). Whether an analogous relationship applies to zirconia implant systems, including tissue-level two-piece designs in which the implant-abutment interface is located above the bone crest, and whether one-piece and two-piece zirconia designs differ meaningfully in long term marginal bone maintenance, remains incompletely characterized. Reported survival rates for zirconia implants vary across the published literature. Recent clinical outcomes for one-piece zirconia implants are supported by prospective cohort data, including five year survival in the range of approximately 95 to 98 percent with modest marginal bone changes in appropriately selected cases(10, 11). For two-piece zirconia implants, particularly screw retained concepts, longer follow-up data remain comparatively limited and published results are heterogeneous(12, 13).

Peri-implant soft tissue behavior represents a second area of clinical relevance. Studies evaluating peri-implant biomarkers have characterized the inflammatory mediator profile around zirconia implants, although direct comparisons with titanium remain limited and inconsistent(14, 15). Multiple studies and reviews indicate that zirconia surfaces may exhibit equal or reduced bacterial and biofilm accumulation compared with titanium, which could be relevant for peri-implant soft tissue stability(16–19). Despite these favorable characteristics, zirconia implants remain susceptible to peri-implant disease, and reported outcomes vary considerably across the literature depending on implant design and follow-up duration(20–22)

Accordingly, long-term, multicenter data that account for the hierarchical clustering of implants within patients and patients within centers are needed to clarify whether marginal bone remodeling and peri-implant soft tissue outcomes differ meaningfully between one-piece and two-piece zirconia implant designs under routine clinical conditions. The present retrospective multicenter cohort study evaluated marginal bone loss and peri-implant soft tissue parameters in a large cohort of zirconia dental implants followed for a minimum of five, up to eleven years across three private dental practices, with particular attention to the influence of implant design, immediate versus delayed placement, and immediate versus delayed loading on long term outcomes.

2. Methods

2.1 Patient Population and Ethics

This retrospective observational cohort study evaluated the clinical and radiographic outcomes of zirconia dental implants placed in three private dental practices. A total of 470 implants were placed in 137 patients between June 2014 and November 2020. Every case had to be completely documented by the date of November first 2025 to ensure the retrospective nature of this study. The mean patient age at

implant placement and the sex distribution are reported in Table 1. Clinical and radiographic data were extracted from existing patient records at each participating center and transferred anonymized via secure data transfer. The study is reported in accordance with the STROBE statement (Additional file 2).

All clinical and radiographic data had been recorded during routine care before the study was conceived. The study was approved by the Ethics Committee of the Medical Chamber of Rhineland-Palatinate on 20 August 2026 (reference 2026–18860). Data extraction and anonymization were performed after approval had been granted. Given the retrospective analysis of anonymized routine data, the requirement for individual informed consent was waived.

2.2 Implant Systems and Distribution

All implants were manufactured by Swiss Dental Solutions (Kreuzlingen, Switzerland). One-piece implants (SDS 1.0, SDS 1.1 and SDS 1.2) and a two-piece, tissue-level implant (SDS 2.0) were included. All included designs are placed at tissue level with a transmucosal portion. The implant-abutment connection of the two-piece SDS 2.0 is located above the bone crest, so that neither design has an implant-abutment interface at bone level. The distribution of implants by system and center is presented in Table 1.

2.3 Eligibility Criteria

2.3.1 Inclusion Criteria

Each center was instructed to screen its patient records in reverse chronological order, starting from a cut-off date of November 2020, and to include consecutive implants fulfilling the documentation requirements until a target of approximately 120 implants per center was reached. Because all eligible implants of an included patient were recorded, the final number of implants per center deviated from this target (C1, 133; C2, 247; C3, 90). Documentation requirements comprised at least three radiographs (at implant placement, at prosthetic loading and at a follow-up visit at least five years after placement) and a peri-implant probing chart recorded at a routine maintenance visit at least five years after placement. No patient was recalled for the purpose of this study and all data were extracted from existing records. The earliest included implant was placed in June 2014. The number of records screened and the reasons for non-inclusion were not documented. Implants that had undergone reoperation due to implant loss or complications e.g fractures during follow-up were included if the documentation requirements were met.

2.3.2 Exclusion Criteria

Implants were excluded in the case of incomplete baseline data, missing radiographic time points, compromised radiographic quality, or an incomplete patient chart. Further exclusion criteria for implant therapy comprised severe uncontrolled systemic disease at the time of implant insertion, decompensated diabetes mellitus (HbA1c greater than 9 percent), immunosuppressive therapy, systemic corticosteroid therapy, antiresorptive therapy, active malignancy or a history of radiotherapy to the jaw or facial region, and pregnancy at the time of insertion.

2.4 Surgical Protocol and Timing

Implant placement was performed according to site specific clinical indications and healing conditions. In each Center, the implants were placed by one surgeon with experience of more than ten years in implant dentistry. Immediate implant placement was defined as placement immediately after extraction. Immediate loading was defined as loading within the first 48 hours after placement. The distribution of immediate versus delayed placement and immediate versus delayed loading by center is presented in Table 1.

Augmentation procedures, where performed, including sinus augmentation and guided bone regeneration. The distribution of augmentation procedures and preoperative bone quality by center is presented in Table 1.

2.5 Prosthetic Protocol

Restorations comprised single crowns, splinted single crowns, and three unit fixed dental prostheses. Prosthetic materials included lithium disilicate, monolithic zirconia, and veneered zirconia. Restorations were either cement retained or, in a subset of cases, adhesively retained. The distribution of prosthetic restoration type, material, and retention type by center is presented in Table 2.

2.6 Radiographic Assessment of Marginal Bone Levels

Marginal bone level was assessed on standardized periapical radiographs and panoramic radiographs at the mesial and distal aspect of each implant, measured from a defined implant reference point to the first visible bone to implant contact. Marginal bone loss was calculated relative to the radiographic baseline obtained at implant placement and was expressed in millimeters, with negative values indicating bone loss. Measurements were obtained using ImageJ (version 1.51n; National Institutes of Health, Bethesda, Maryland). Implant length was obtained using reference points on the implant body provided by the manufacturer. The consecutive measurements were then calibrated via the implant length of each implant. All radiographic measurements were performed by a calibrated examiner (PH) who was not involved in the clinical treatment of the patients. Prior to radiographic analysis, the examiner underwent a calibration procedure consisting of repeated measurements on a subset of radiographs not included in the final analysis. To assess inter-examiner reliability, a randomly selected 25% of the radiographs were re-evaluated by a second examiner (SMP) under identical conditions. Reliability was assessed using the intraclass correlation coefficient (ICC), which demonstrated excellent inter-examiner agreement (ICC = 0.92) Because one-piece and two-piece implants are distinguishable on radiographs, the examiner could not be blinded to implant design.

2.7 Soft Tissue Assessment

Peri implant soft tissue parameters were assessed at the final available follow up visit and included probing depth and recession, each recorded at six sites per implant using a calibrated periodontal probe. Bleeding on probing was recorded as present or absent; suppuration was not consistently documented

across centers and was therefore not used. Peri-implantitis was classified at implant level based on the case definition of the 2017 World Workshop on the Classification of Periodontal and Peri-Implant Diseases and Conditions(23). As clinical data were available from a single examination only, a modified definition was applied: bleeding on probing, probing depth ≥ 6 mm at one or more sites, and radiographic marginal bone loss > 2 mm relative to the baseline radiograph at implant placement. The criterion "increased probing depth compared with previous examinations" could not be applied. Implants were assigned to mutually exclusive categories: peri-implant health (no bleeding on probing, bone loss ≤ 2 mm), peri-implant mucositis (bleeding on probing, bone loss ≤ 2 mm), Periimplantitis (bleeding on probing with bone loss > 2 mm and probing depth ≥ 6 mm) and absence of bleeding on probing with bone loss > 2 mm. Bone loss referred to the worst site measured from implant placement. Two sensitivity definitions were applied: bleeding on probing with bone loss > 2 mm irrespective of probing depth, and bleeding on probing with bone loss > 2 mm after prosthetic loading. Prevalence was reported at implant and patient level.

2.8 Outcome Measures

2.8.1 Primary Outcomes

The primary outcome was the change in marginal bone level from implant placement to the last available radiographic follow up. In addition, marginal bone level change was described from implant placement to prosthetic loading and from definitive prosthetic loading to the last radiograph, together with the proportions of implants and patients with bone loss exceeding 1, 2 and 3 mm. A second primary outcome was the peri-implant health status at the long-term follow-up visit, classified according to the categories defined in section 2.7.

2.8.2 Secondary Outcomes

Secondary outcomes included bleeding on probing, non-inflammatory buccal recession phenotypes and vertical peri implant bone defects, as well as complication free survival, defined as freedom from implant loss, fracture, or reoperation.

2.9 Statistical Analysis

Marginal bone level change was analyzed with linear mixed-effects models including all mesial and distal measurements over time. Because the unadjusted LOESS curves and model comparison indicated a biphasic course, time since placement was modeled as a piecewise linear term with one segment for the first year and one for the period thereafter. The primary model included a random intercept per implant and a random slope for time after the first year per patient, accounting for repeated measurements within implants and for the clustering of implants within patients. The random-effects structure was selected by the Bayesian information criterion. Fixed effects comprised implant site, implant system, implant diameter, implant length, treatment center, immediate placement, immediate loading, patient age, sex and smoking status. Unadjusted estimates were obtained from models containing the respective predictor and the two time terms. Interactions of implant system and of

immediate placement with both time segments were tested in separate models. The placement interaction was considered exploratory. The previous specification (linear time with patient-level random effects) and an intermediate specification are reported as sensitivity analyses (Additional file 1, Table S1). Multicollinearity was assessed with variance inflation factors.

Bleeding on probing was analyzed using logistic generalized estimating equations with an exchangeable working correlation clustered by patient, adjusted for center, age, sex and smoking status. Because of the small number of events, peri-implantitis was analyzed with Firth's penalized logistic regression, adjusted for center only. Recession was analyzed using linear mixed-effects models with a patient-level random intercept. Complication-free survival was estimated with the Kaplan-Meier method and compared between implant systems by the log-rank test; the hazard ratio for hard complications was estimated using a Cox proportional hazards model with robust standard errors clustered by patient.

The primary analysis was based on complete cases. Continuous variables are presented as mean ± standard deviation and categorical variables as frequency and percentage. Statistical significance was set at $P < 0.05$. A priori sample size calculation was performed using a precision-based approach accounting for the clustering of implants within patients (expected MBL 1.0 ± 0.8 mm, mean 5.5 implants per patient, ICC = 0.15, design effect = 1.67)(24–26). A minimum of 184 implants was required to estimate mean MBL with a precision of ± 0.15 mm (95% CI half-width). Under the same assumptions, the final cohort of 470 implants provided a precision of ± 0.093 mm.(3, 24, 25).All analyses were performed in R (version 4.5.3; R Foundation for Statistical Computing, Vienna, Austria) using the packages lme4, lmerTest, geepack, logistf, survival and performance, run in RStudio (version 2026.01.1 + 403; Posit Software, PBC, Boston, MA).

3. Results

A total of 470 implants placed in 137 patients from three centers (C1, C2 and C3) were included in the analyses.

3.1 Cohort Characteristics

Table 1 summarizes the demographic and implant characteristics of the study cohort. The number of patients and implants varied by center, with C2 contributing the largest proportion of the study population. Mean radiographic follow-up was 6.3 ± 1.6 years (center means 5.7 to 7.8 years), with the longest observation period in C3. 465 implants had a clinical examination at least five years after placement. Implant diameter and length were generally comparable across centers, although C2 placed slightly wider and longer implants than C1 and C3. One-piece implants represented the majority of implants in all centers (59–68%), while two-piece implants accounted for 32–41% of cases. Immediate implant placement and immediate loading were frequently performed, with immediate placement ranging from 75% to 86% and immediate loading from 64% to 74% across centers. Augmentation procedures and bone quality distributions differed substantially among centers. Sinus augmentation was

performed more frequently in C2 and C3 than in C1, whereas guided bone regeneration (GBR) procedures were relatively uncommon. Bone quality also demonstrated center-specific variation, with D2 bone predominating in C1, while C2 primarily included D3 and D4 bone. Bone quality was not recorded for 41 implants in C2.

Table 1
Patient demographics and implant site characteristics by center.

Variable	C1	C2	C3	Total
Patients, n	32	92	13	137
Implants, n	133	247	90	470
Follow-up, last radiograph (years), mean ± SD	6.34 ± 1.40	5.71 ± 1.25	7.76 ± 1.73	6.28 ± 1.59
Age at surgery (years), mean ± SD	48.91 ± 12.78	55.24 ± 13.16	58.81 ± 9.84	54.10 ± 13.08
Sex: female	22 (68.8%)	37 (40.2%)	8 (61.5%)	67 (48.9%)
Sex: male	10 (31.2%)	53 (57.6%)	5 (38.5%)	68 (49.6%)
Sex: not recorded	0 (0.0%)	2 (2.2%)	0 (0.0%)	2 (1.5%)
Smoking: ever	2 (6.2%)	8 (8.7%)	0 (0.0%)	10 (7.3%)
Smoking: never	30 (93.8%)	84 (91.3%)	13 (100.0%)	127 (92.7%)
Diabetes (documented): none	32 (100.0%)	92 (100.0%)	13 (100.0%)	137 (100.0%)
Implant diameter (mm), mean ± SD	4.55 ± 0.49	4.66 ± 0.49	4.23 ± 0.50	4.54 ± 0.52
Implant length (mm), mean ± SD	12.76 ± 1.85	13.45 ± 2.14	12.13 ± 2.09	13.00 ± 2.11
System: one-piece	79 (59.4%)	168 (68.0%)	60 (66.7%)	307 (65.3%)
System: two-piece	54 (40.6%)	79 (32.0%)	30 (33.3%)	163 (34.7%)
Immediate placement:	100 (75.2%)	212 (85.8%)	77 (85.6%)	389 (82.8%)
Immediate loading: yes	85 (63.9%)	181 (73.3%)	67 (74.4%)	333 (70.9%)
Augmentation: GBR/lateral	11 (8.3%)	4 (1.6%)	2 (2.2%)	17 (3.6%)
Augmentation: none	101 (75.9%)	179 (72.5%)	55 (61.1%)	335 (71.3%)
Augmentation: sinus	21 (15.8%)	64 (25.9%)	33 (36.7%)	118 (25.1%)
Bone quality: D2	131 (98.5%)	1 (0.4%)	50 (55.6%)	182 (38.7%)
Bone quality: D3	2 (1.5%)	138 (55.9%)	40 (44.4%)	180 (38.3%)
Bone quality: D4	0 (0.0%)	67 (27.1%)	0 (0.0%)	67 (14.3%)
Bone quality: not recorded	0 (0.0%)	41 (16.6%)	0 (0.0%)	41 (8.7%)

3.2 Prosthetic and Clinical Characteristics

Table 2 summarizes the prosthetic, inflammatory, and systemic characteristics of the study cohort by center. Considerable variation in prosthetic rehabilitation was observed among the participating centers. Single crowns were the predominant restoration in C1, whereas splinted single crowns represented the majority of restorations in C2 and C3. Prosthetic materials also differed by center, with zirconia monolithic restorations primarily used in C1 and C2, while zirconia-veneered restorations were almost exclusively used in C3. Most restorations were cement-retained, although adhesively retained restorations were observed only in C2. Preoperative inflammatory status also varied among centers; chronic inflammation was the most common indication in C1 and C2, whereas a greater proportion of implants in C3 were placed in sites without active inflammation. Previous titanium implant explantation was documented for seven implants, all in C2, and was not recorded for 19 implants. Systemic cardiovascular disease was infrequent and was recorded exclusively among patients treated at C2. These variables demonstrated marked center-specific distributions and were therefore not included as covariates in the pooled multivariable analyses because of substantial center confounding.

Table 2
Prosthetic, inflammatory and systemic characteristics by center.

Variable	C1	C2	C3	Total
Restoration: three-unit FDP	0 (0.0%)	20 (8.1%)	3 (3.3%)	23 (4.9%)
Restoration: single crown	133 (100.0%)	98 (39.7%)	14 (15.6%)	245 (52.1%)
Restoration: splinted single crowns	0 (0.0%)	129 (52.2%)	73 (81.1%)	202 (43.0%)
Material: lithium disilicate	39 (29.3%)	60 (24.3%)	1 (1.1%)	100 (21.3%)
Material: monolithic zirconia	94 (70.7%)	186 (75.3%)	0 (0.0%)	280 (59.6%)
Material: veneered zirconia	0 (0.0%)	0 (0.0%)	89 (98.9%)	89 (18.9%)
Retention: adhesively retained	0 (0.0%)	62 (25.1%)	0 (0.0%)	62 (13.2%)
Retention: cement retained	133 (100.0%)	185 (74.9%)	90 (100.0%)	408 (86.8%)
Preoperative inflammation: acute	0 (0.0%)	12 (4.9%)	2 (2.2%)	14 (3.0%)
Preoperative inflammation: chronic	129 (97.0%)	171 (69.2%)	32 (35.6%)	332 (70.6%)
Preoperative inflammation: none	1 (0.8%)	64 (25.9%)	48 (53.3%)	113 (24.0%)
Preoperative inflammation: retained root tip	3 (2.3%)	0 (0.0%)	8 (8.9%)	11 (2.3%)
Previous titanium implant explanted: no	133 (100.0%)	221 (89.5%)	90 (100.0%)	444 (94.5%)
Previous titanium implant explanted: yes	0 (0.0%)	7 (2.8%)	0 (0.0%)	7 (1.5%)
Systemic disease (patients): autoimmune	1 (3.1%)	0 (0.0%)	0 (0.0%)	1 (0.7%)
Systemic disease (patients): cardiovascular	0 (0.0%)	6 (6.5%)	0 (0.0%)	6 (4.4%)
Systemic disease (patients): other	1 (3.1%)	0 (0.0%)	0 (0.0%)	1 (0.7%)

3.3 Marginal Bone Level Change

Marginal bone level changes are summarized in Table 3. From implant placement to the last radiograph (mean 6.3 ± 1.5 years), mean bone level change was − 1.01 ± 1.02 mm (median − 0.81 mm; IQR − 1.50 to − 0.38) for the mean of mesial and distal sites and − 1.25 ± 1.11 mm for the worst site. Bone loss

exceeded 1 mm at 235 of 468 implants (50.2%), 2 mm at 107 implants (22.9%) and 3 mm at 36 implants (7.7%); at patient level, 59 of 137 patients (43.1%) had at least one implant with bone loss exceeding 2 mm. Most of the change occurred between placement and loading (− 0.77 ± 0.88 mm after a mean of 0.62 years), whereas the change from loading to the last radiograph was − 0.35 ± 0.76 mm; 21 implants (6.9%) lost more than 2 mm after loading.

Table 3
Marginal bone level change and threshold distribution by implant system and center.

Variable	Overall	One-piece	Two-piece	C1	C2	C3
Time placement to loading (years), mean ± SD	0.62 ± 0.30	0.64 ± 0.31	0.57 ± 0.27	0.66 ± 0.30	0.49 ± 0.23	0.85 ± 0.28
Placement to loading, mean of sites (mm), mean ± SD	-0.77 ± 0.88	-0.78 ± 0.90	-0.76 ± 0.82	-0.54 ± 0.77	-0.95 ± 0.80	-0.73 ± 1.09
Placement to loading, worst site (mm), mean ± SD	-0.98 ± 0.99	-0.99 ± 1.01	-0.97 ± 0.93	-0.75 ± 0.90	-1.10 ± 0.88	-1.08 ± 1.24
Implants with last radiograph, n	468	305	163	133	246	89
Time placement to last radiograph (years), mean ± SD	6.31 ± 1.54	6.40 ± 1.53	6.14 ± 1.55	6.34 ± 1.40	5.74 ± 1.20	7.85 ± 1.53
Placement to last radiograph, mean of sites (mm), mean ± SD	-1.01 ± 1.02	-1.06 ± 1.09	-0.91 ± 0.86	-0.90 ± 0.96	-1.16 ± 0.97	-0.74 ± 1.17
Placement to last radiograph, mean of sites (mm), median [IQR]	-0.81 [-1.50; -0.38]	-0.82 [-1.71; -0.41]	-0.78 [-1.32; -0.36]	-0.84 [-1.50; -0.11]	-0.83 [-1.44; -0.52]	-0.60 [-1.65; 0.07]
Placement to last radiograph, worst site (mm), mean ± SD	-1.25 ± 1.11	-1.28 ± 1.18	-1.19 ± 0.97	-1.20 ± 1.10	-1.32 ± 1.04	-1.15 ± 1.29
Loading to last radiograph, mean of sites (mm), mean ± SD	-0.35 ± 0.76	-0.37 ± 0.75	-0.31 ± 0.77	-0.36 ± 0.92	-0.49 ± 0.43	-0.11 ± 0.82
Loading to last radiograph, worst site (mm), mean ± SD	-0.59 ± 0.85	-0.60 ± 0.84	-0.57 ± 0.89	-0.65 ± 1.07	-0.62 ± 0.49	-0.45 ± 0.91
Bone loss > 1 mm since placement, implants n (%)	235 (50.2%)	151 (49.5%)	84 (51.5%)	71 (53.4%)	119 (48.4%)	45 (50.6%)
Bone loss > 2 mm since placement, implants n (%)	107 (22.9%)	74 (24.3%)	33 (20.2%)	32 (24.1%)	50 (20.3%)	25 (28.1%)

Note. Marginal bone level change in mm; negative values denote bone loss. Worst site, the more negative of the mesial and distal values.

Variable	Overall	One-piece	Two-piece	C1	C2	C3
Bone loss > 3 mm since placement, implants n (%)	36 (7.7%)	28 (9.2%)	8 (4.9%)	7 (5.3%)	25 (10.2%)	4 (4.5%)
Bone loss > 1 mm since placement, patients n (%)	100 (73.0%)	72 (74.2%)	50 (63.3%)	27 (84.4%)	64 (69.6%)	9 (69.2%)
Bone loss > 2 mm since placement, patients n (%)	59 (43.1%)	45 (46.4%)	24 (30.4%)	16 (50.0%)	36 (39.1%)	7 (53.8%)
Bone loss > 3 mm since placement, patients n (%)	28 (20.4%)	22 (22.7%)	7 (8.9%)	4 (12.5%)	21 (22.8%)	3 (23.1%)
Bone loss > 1 mm since loading, implants n (%)	59 (19.5%)	41 (20.5%)	18 (17.5%)	29 (25.4%)	13 (11.2%)	17 (23.3%)
Bone loss > 2 mm since loading, implants n (%)	21 (6.9%)	13 (6.5%)	8 (7.8%)	14 (12.3%)	3 (2.6%)	4 (5.5%)
Bone loss > 1 mm since loading, patients n (%)	33 (36.3%)	26 (40.0%)	12 (23.5%)	16 (59.3%)	11 (20.4%)	6 (60.0%)
Bone loss > 2 mm since loading, patients n (%)	14 (15.4%)	10 (15.4%)	6 (11.8%)	8 (29.6%)	3 (5.6%)	3 (30.0%)

Note. Marginal bone level change in mm; negative values denote bone loss. Worst site, the more negative of the mesial and distal values.

The results of the unadjusted and adjusted linear mixed-effects models are presented in Table 4. The model showed a biphasic course: bone level decreased by − 0.878 mm during the first year (95% CI − 0.955 to − 0.801; P < 0.001) and by − 0.018 mm per year thereafter (95% CI − 0.044 to 0.007; P = 0.152), indicating stable bone levels after initial remodeling. Implant system, implant site, implant diameter, implant length, treatment center, immediate placement (β = −0.076 mm; 95% CI − 0.214 to 0.062; P = 0.282), immediate loading, age, sex and smoking were not significantly associated with marginal bone level change after adjustment (all P > 0.05). The model showed a conditional R^2 of 0.618 and a marginal R^2 of 0.212. Compared with the previous specification with linear time and patient-level random effects only, the primary model had a substantially lower Akaike information criterion (6176.8 versus 7042.8; Additional file 1, Table S1).

Table 4
Linear mixed-effects model for marginal bone level change (piecewise time).

Predictor	Unadjusted β (95% CI)	Unadjusted P	Adjusted β (95% CI)	Adjusted P
Time, first year (per year)	-0.876 (-0.952 to -0.800)	< 0.001	-0.878 (-0.955 to -0.801)	< 0.001
Time, after first year (per year)	-0.021 (-0.046 to 0.004)	0.105	-0.018 (-0.044 to 0.007)	0.152
Site: distal vs mesial	0.017 (-0.026 to 0.060)	0.434	0.016 (-0.027 to 0.059)	0.468
Two-piece vs one-piece	0.024 (-0.086 to 0.133)	0.674	0.056 (-0.175 to 0.287)	0.634
Implant diameter (per mm)	-0.107 (-0.207 to -0.007)	0.037	-0.078 (-0.188 to 0.031)	0.163
Implant length (per mm)	-0.010 (-0.035 to 0.015)	0.432	-0.000 (-0.027 to 0.027)	0.998
Immediate vs delayed placement	-0.083 (-0.220 to 0.053)	0.230	-0.076 (-0.214 to 0.062)	0.282
Immediate vs delayed loading	-0.011 (-0.126 to 0.104)	0.848	0.032 (-0.207 to 0.271)	0.792
Age (per year)	-0.002 (-0.007 to 0.002)	0.270	-0.002 (-0.007 to 0.003)	0.451
Male vs female	-0.076 (-0.185 to 0.032)	0.168	-0.050 (-0.163 to 0.063)	0.387
Smoking: ever vs never	0.122 (-0.127 to 0.370)	0.338	0.190 (-0.062 to 0.441)	0.140

Linear mixed-effects model with a random intercept per implant and a random slope for time after the first year per patient. Time split at one year.

In the unadjusted analyses, marginal bone level change did not differ significantly between one-piece and two-piece implants (β = 0.024 mm; P = 0.674; Fig. 1), between immediate and delayed loading (β = −0.011 mm; P = 0.848; Fig. 2), or between immediate and delayed placement (β = −0.083 mm; P = 0.230; Fig. 3). Figures 1 to 3 show unadjusted LOESS curves and are descriptive.

3.4 Implant Design and Placement Protocol over Time

To determine whether the course of marginal bone level change differed between designs, interaction terms between implant system and both time segments were added to the primary model (Table 5). Neither interaction was statistically significant (first year: β = 0.059 mm; 95% CI − 0.098 to 0.217; P = 0.462; after the first year: β = 0.005 mm/year; 95% CI − 0.026 to 0.035; P = 0.768; joint likelihood-ratio test

P = 0.468). The confidence interval of the long-term interaction limits the plausible divergence between designs to − 0.13 to 0.18 mm over five years after the first year. Model-based marginal bone level change at the mean follow-up of 6.3 years was − 1.06 mm for one-piece and − 1.01 mm for two-piece implants. In an exploratory analysis, immediate placement was associated with greater bone loss during the first year (interaction β = −0.213 mm; 95% CI − 0.416 to − 0.011; P = 0.039) but not thereafter (β = 0.022 mm/year; P = 0.214; joint likelihood-ratio test P = 0.114).

Table 5
Interactions of implant system and immediate placement with time on marginal bone level change.

Term	Unadjusted β (95% CI)	Unadjusted P	Adjusted β (95% CI)	Adjusted P
Two-piece vs one-piece (at placement)	0.003 (-0.121 to 0.126)	0.968	0.022 (-0.217 to 0.261)	0.857
Two-piece x time, first year	0.037 (-0.119 to 0.193)	0.643	0.059 (-0.098 to 0.217)	0.462
Two-piece x time, after first year	0.003 (-0.027 to 0.034)	0.827	0.005 (-0.026 to 0.035)	0.768
Immediate vs delayed (at placement)	-0.021 (-0.176 to 0.135)	0.795	-0.001 (-0.159 to 0.156)	0.987
Immediate x time, first year	-0.164 (-0.365 to 0.036)	0.108	-0.213 (-0.416 to -0.011)	0.039
Immediate x time, after first year	0.014 (-0.021 to 0.049)	0.438	0.022 (-0.013 to 0.058)	0.214
Note. Models as in Table 4 *plus the respective interaction terms*				

3.5 Complication-Free Survival

During follow-up, eight hard complications were recorded, comprising seven reoperations and one fracture of a one-piece implant in C2. All events occurred within five years of placement, corresponding to event rates of 1.6% for one-piece and 1.8% for two-piece implants. Among implants with at least five years of documented function, the Kaplan-Meier estimates of five-year complication-free survival were 98.4% (95% CI 97.0 to 99.8) for one-piece and 98.2% (95% CI 96.1 to 100.0) for two-piece implants (Fig. 4). No significant difference was observed between implant systems by the log-rank test (P = 0.862) or in the Cox model with patient-clustered standard errors (hazard ratio 1.14; 95% CI 0.27 to 4.69; P = 0.861; Table 7).

3.6 Peri-Implant Soft Tissue Parameters

Peri-implant soft tissue parameters are presented in Table 6. Of 465 implants with complete clinical and radiographic data, 297 (63.9%) were classified as healthy, 62 (13.3%) as peri-implant mucositis and 7 (1.5%) as peri-implantitis; a further 79 implants (17.0%) showed bone loss exceeding 2 mm without

bleeding on probing, and 20 (4.3%) showed bleeding on probing with bone loss exceeding 2 mm but probing depths below 6 mm. At patient level, peri-implantitis affected 7 patients (5.1%). Without the probing depth criterion, 27 implants (5.8%) and 19 patients (14.0%) met the definition. Mean probing depth was 1.87 ± 0.66 mm and mean recession 0.50 ± 0.84 mm. Bleeding on probing was recorded at 43 two-piece implants (26.5%) and 46 one-piece implants (15.1%) (unadjusted OR 1.81; 95% CI 1.01 to 3.23; P = 0.047; adjusted OR 1.75; 95% CI 0.97 to 3.13; P = 0.061; Table 7). Peri-implantitis did not differ significantly between designs (OR 2.44; 95% CI 0.59 to 11.02; P = 0.214). Mean recession was not associated with implant system (adjusted P = 0.201), and no significant correlation was found between recession and worst-site marginal bone loss at the final follow-up (Spearman's ρ = 0.069, P = 0.135).

Table 6
Peri-implant soft tissue parameters and disease categories (cross-sectional).

Parameter	Overall	One-piece	Two-piece	C1	C2	C3
Implants with clinical examination, n	465	303	162	133	247	85
Probing depth, mean per implant (mm), mean ± SD	1.87 ± 0.66	1.79 ± 0.58	2.03 ± 0.77	1.84 ± 0.55	1.88 ± 0.70	1.91 ± 0.69
Implants with PD ≥ 6 mm, n (%)	37 (7.9%)	20 (6.6%)	17 (10.5%)	9 (6.8%)	21 (8.5%)	7 (8.0%)
Recession, mean per implant (mm), mean ± SD	0.50 ± 0.84	0.49 ± 0.81	0.51 ± 0.89	0.55 ± 0.82	0.55 ± 0.94	0.26 ± 0.41
Implants with recession > 0 mm, n (%)	176 (37.7%)	118 (38.7%)	58 (35.8%)	56 (42.1%)	80 (32.4%)	40 (46.0%)
BOP-positive implants, n (%)	89 (19.1%)	46 (15.1%)	43 (26.5%)	29 (21.8%)	39 (15.8%)	21 (24.1%)
BOP-, bone loss ≤ 2 mm (peri-implant health)	297 (63.9%)	197 (65.0%)	100 (61.7%)	83 (62.4%)	165 (66.8%)	49 (57.6%)
BOP-, bone loss > 2 mm	79 (17.0%)	60 (19.8%)	19 (11.7%)	21 (15.8%)	43 (17.4%)	15 (17.6%)
BOP+, bone loss ≤ 2 mm (peri-implant mucositis)	62 (13.3%)	33 (10.9%)	29 (17.9%)	18 (13.5%)	32 (13.0%)	12 (14.1%)
BOP+, bone loss > 2 mm, PD < 6 mm	20 (4.3%)	10 (3.3%)	10 (6.2%)	9 (6.8%)	4 (1.6%)	7 (8.2%)
BOP+, PD ≥ 6 mm, bone loss > 2 mm (Peri-implantitis)	7 (1.5%)	3 (1.0%)	4 (2.5%)	2 (1.5%)	3 (1.2%)	2 (2.4%)
Peri-implantitis, patient level, n (%)	7 (5.1%)	3 (3.1%)	4 (5.1%)	2 (6.2%)	3 (3.3%)	2 (16.7%)
Sensitivity: BOP + and bone loss > 2 mm (no PD criterion), implants	27 (5.8%)	13 (4.3%)	14 (8.6%)	11 (8.3%)	7 (2.8%)	9 (10.6%)
Sensitivity: BOP + and bone loss > 2 mm (no PD criterion), patients	19 (14.0%)	10 (10.3%)	12 (15.4%)	7 (21.9%)	7 (7.6%)	5 (41.7%)
Sensitivity: BOP + and bone loss > 2 mm after loading, implants	9 (3.0%)	4 (2.0%)	5 (4.9%)	8 (7.0%)	0 (0.0%)	1 (1.4%)
Sensitivity: BOP + and bone loss > 2 mm after loading, patients	6 (6.7%)	3 (4.6%)	4 (8.0%)	5 (18.5%)	0 (0.0%)	1 (11.1%)

Table 7
Binary and time-to-event endpoints: two-piece versus one-piece implants.

Endpoint	Events / n	Model	Unadjusted OR/HR (95% CI)	Unadjusted P	Adjusted OR/HR (95% CI)	Adjusted P
Bleeding on probing	89 / 467	GEE logistic	1.81 (1.01 to 3.23)	0.047	1.75 (0.97 to 3.13)	0.061
Peri-implantitis (primary definition)	7 / 465	Firth logistic	2.44 (0.59 to 11.02)	0.214	2.42 (0.58 to 10.93)	0.220
BOP + and bone loss > 2 mm (sensitivity)	27 / 465	Firth logistic	2.10 (0.97 to 4.58)	0.059	2.00 (0.92 to 4.39)	0.081
Hard complications (reoperation, fracture, loss)	8 / 470	Cox, patient-clustered	1.14 (0.27 to 4.69)	0.861	not estimated (few events)	

4. Discussion

4.1 Marginal bone level change

Marginal bone level change in this cohort followed a biphasic course, with − 0.88 mm during the first year and near-stable levels thereafter (− 0.018 mm per year), resulting in a mean change of − 1.01 ± 1.02 mm at the last radiograph after a mean of 6.3 years. This is consistent with the range reported for zirconia implants in the current literature, where a recent systematic review by Moraschini et al. found generally modest and stable peri-implant bone levels across studies with variable follow-up durations(22). Monzavi et al., evaluating 275 zirconia implants over eleven years, described a pooled first year loss of 0.49 mm followed by 0.12 mm annually thereafter(5). The biphasic pattern observed here corresponds to this trajectory. The larger first-year change in the present cohort may partly reflect the high proportion of immediately placed implants and measurement from the placement radiograph rather than from prosthetic loading.

Comparative data support the equivalence of zirconia to titanium in this respect. Payer et al. observed no material related difference at 24 months in a randomized two piece comparison, with mean bone levels of 1.43 mm for titanium and 1.48 mm for zirconia(26). Zuercher et al. reported near identical MBL stability at one year in a within subject randomized design(27). A recent meta-analysis by Pachiou et al., pooling nine studies, found marginal bone loss to favour titanium at one year but detected no significant difference at three years or beyond five years(2). The stable bone levels after the first year observed here are consistent with the convergence these authors describe, although no titanium comparison was included in the present study.

4.2 Implant design

Within the system studied, both designs are placed at tissue level, and the two-piece implants have no implant-abutment interface at bone level. In this setting, the current study found no difference in marginal bone level change between one-piece and two-piece implants, and the confidence interval of the design-by-time interaction limits the plausible divergence to − 0.13 to 0.18 mm over five years after the first year. Existing literature has been unable to address the question directly. Neugebauer et al., in a systematic review designed specifically to compare the two designs, found the evidence base for two piece systems sparse(6). Moraschini et al. reported that fourteen of nineteen included studies evaluated one piece designs and only four evaluated two piece designs(22). Pachiou et al. identified two of nine studies addressing two piece implants(2). In each case the absence of a demonstrated design effect reflects the absence of data.

Cionca et al. reported six year outcomes for 49 two piece implants and Brunello et al. followed two piece implants over nine years, while Kohal et al. and Balmer et al. documented three and five year outcomes for one piece systems, none of which produced evidence of systematically inferior bone maintenance(10, 28–30).The microgap at the implant abutment interface provides a coherent mechanical rationale for a design effect,(31). However, this rationale could not be tested here, because the implant-abutment interface of the two-piece implants in this system is located supracrestally. Differences in the design of zirconia implants could therefore impose differences in outcomes that were not captured. Especially the maintenance of MBL in bone-level zirconia implant systems should be further explored, since micromovements can occur and disturb the biological width and consecutively the bony adaptation at the implant-abutment interface.

Bleeding on probing was more frequent at two-piece implants (26.5% versus 15.1%; adjusted OR 1.75; P = 0.061), and the sensitivity definition of peri-implantitis showed a similar tendency (OR 2.10; P = 0.059). Although not statistically significant after adjustment, further research is needed to clarify the reason for higher BOP, as the connection of observed tissue level two-piece implants impose no micromovement or microgap within the soft tissue.

4.3 Immediate placement

In the primary model, immediate placement was not significantly associated with overall marginal bone level change (β = −0.076 mm; 95% CI − 0.214 to 0.062; P = 0.282). An exploratory interaction analysis suggested that immediately placed implants lost more bone during the first year (β = −0.213 mm; 95% CI − 0.416 to − 0.011; P = 0.039) but not thereafter, indicating that any difference is confined to the initial remodeling phase. In the previous model specification without an implant-level random effect, immediate placement had appeared significant (β = −0.124 mm; P = 0.004; Additional file 1, Table S1). Immediate loading showed no association. The same directional pattern of higher bone remodelling in immediate placement, has been reported for titanium implants and is therefore not specific to zirconia materials. Initial resorption after immediate placement occurs in both types of implants(32, 33). What these data do establish is that any additional remodeling after immediate placement is small in absolute terms, lies within the range of radiographic measurement error, and occurs within a protocol that avoids the post-extraction healing interval in which the documented resorption takes place. Further research

focusing on buccal soft- and hard-tissue preservation, including papilla stability, is warranted, as the success and advantages of immediate implant placement cannot be judged by radiographic bone parameters alone.

Kiechle et al., in an eight-year follow-up of 67 one-piece implants, reported a significantly higher bone crest around immediately placed implants (P = 0.0120) together with more favourable pink esthetic scores (P = 0.0002)(34). Grassi et al. documented five-year radiographic outcomes for immediately loaded one-piece implants without evidence of accelerated loss(35).

Interpretation requires attention to the reference frame of the outcome variable. Marginal bone loss in this study, as in those cited above, was measured from the time of implant placement. Any dimensional change of the alveolar ridge occurring between tooth extraction and implant placement therefore lies outside the measurement window by construction. For delayed protocols that interval contains a period of post-extraction healing, for immediate protocols it does not. The two groups consequently enter the measurement window at different points along the post-extraction timeline. This is a property of the measurement definition and applies symmetrically to studies reporting effects in either direction. The magnitude of the change occurring within the healing phase is well documented. Tan et al. reported horizontal ridge reduction of 29 to 63 per cent and vertical reduction of 11 to 22 per cent within six months of extraction, with the steepest changes in the first three to six months(36). Couso-Queiruga et al., in a meta-analysis of unassisted socket healing, reported mean radiographic ridge reduction in non-molar sites of 2.54 mm horizontally and 1.65 mm at the mid-facial aspect, and in molar sites of 3.61 mm and 1.46 mm respectively(37). Aimetti et al., in ungrafted maxillary extraction sockets with four intact walls, observed 1.2 mm of vertical buccal resorption and 3.2 mm of bucco-palatal width reduction at three months(38).

4.4. Clinical consequences

Implant design may be selected on prosthetic and site-specific findings, rather than on an expectation of differing bone maintenance. Across centers with mean follow-up of 5.7 to 7.8 years, one-piece and two-piece zirconia implants showed equivalent behaviour with respect to marginal bone level change and complication-free survival, whereas bleeding on probing tended to be more frequent at two-piece implants. Under the case definitions applied, peri-implantitis was recorded at 1.5% of implants and mean probing depths were below 2 mm. Because no titanium control was included, these data do not allow inferences about the relative susceptibility of zirconia to peri-implant disease.

4.5 Peri-implant tissues

Peri-implantitis prevalence of 1.5 per cent at implant level and 5.1 per cent at patient level lies at the low end of the published range, although direct comparison is limited by differing case definitions. Moraschini et al. reported pooled implant level estimates of 2 per cent for follow-up up to three years, 2 per cent for three to five years, and 8 per cent beyond five years.(22) Mean probing depth in this cohort (1.87 mm) was lower than the pooled mean of 2.98 mm reported in the review by Moraschini et al., and bleeding on probing at 19.1 per cent of implants fell below the reported mean of 28.4 per cent(22).

Recession showed no association with implant design and no correlation with marginal bone loss (ρ = 0.069).

These findings should be interpreted against experimental and clinical data on soft tissue behaviour at zirconia surfaces, which are not uniform. Clever et al. found interleukin 1β significantly elevated around titanium compared with zirconia implants and natural teeth under experimental mucositis(39). Cionca et al. reported significantly lower plaque index at zirconia implants than at contralateral teeth(14). Roehling et al. observed significantly less crestal bone loss around zirconia than titanium implants following ligature induced peri-implantitis, with no zirconia failures(40). Esplin et al. found comparable peri-implantitis induction around both materials, but greater radiographic defect fill after regenerative treatment at titanium implants(41). A scoping review by Lee et al. concluded that zirconia implants perform comparably to titanium in survival and peri-implant tissue health, with possible additional benefit in mucosal margin stability and resistance to bacterial accumulation(18).

4.6 Limitations

The current study has several limitations. First, its retrospective design precludes randomized exposure allocation, and residual confounding by indication cannot be excluded, particularly for immediate implant placement, where socket integrity may influence case selection. No patient had documented diabetes, so that diabetes could not be evaluated as a potential risk factor. In addition, the cohort included only a single zirconia implant manufacturer, which limits the generalizability of the findings regarding implant design to other zirconia implant systems. Bone quality distribution also differed markedly between centers, with D2 bone predominating at one center while being largely absent at another, introducing additional heterogeneity across the study population.

Further limitations must be considered. Inclusion required documentation at least five years after placement, so that early failures that were not retreated were excluded by design. The peri-implantitis case definition deviated from the 2017 World Workshop, because previous probing data were unavailable and suppuration was not consistently recorded. Soft tissue parameters were assessed at a single cross-sectional visit, which precludes statements on incidence or stability. No titanium control group was included, and periodontal history, plaque scores and the width of keratinized mucosa were not recorded. Periapical and panoramic radiographs were used. Because implants were placed by one surgeon per center, surgeon and center effects cannot be separated. Finally, both designs studied are tissue-level implants, and the findings cannot be extrapolated to bone-level two-piece zirconia implants.

5. Conclusions

In this multicenter cohort of 470 zirconia implants of a single system with a mean radiographic follow-up of 6.3 years, marginal bone loss averaged approximately 1 mm, occurred predominantly during the first year and was near-stable thereafter. One-piece and two-piece tissue-level designs showed comparable marginal bone level change, with a plausible divergence of less than 0.2 mm over five years. Immediate placement was associated with greater remodeling during the first year in an exploratory analysis, but

not with overall bone level change. Peri-implantitis prevalence was low, but this estimate is conditioned on long-term survival and maintenance attendance, and bleeding on probing tended to be more frequent around two-piece implants.

Abbreviations

BOP
Bleeding on probing
CI
Confidence interval
FDP
Fixed dental prosthesis
GBR
Guided bone regeneration
GEE
Generalized estimating equations
HR
Hazard ratio
ICC
Intraclass correlation coefficient
IQR
Interquartile range
LOESS
Locally estimated scatterplot smoothing
MBL
Marginal bone loss
OR
Odds ratio
PD
Probing depth
SD
Standard deviation

Declarations

Ethics approval and consent to participate:

The study was approved by the Ethics Committee of the Medical Chamber of Rhineland-Palatinate (reference 2026–18860, 20 August 2026). Given the retrospective analysis of anonymized routine data, the requirement for individual informed consent was waived.

Competing Interests

Competing interests are fully disclosed in the manuscript. One co-author (UV) is the founder of the implant manufacturer but held no shares in and had no affiliation with the company at the time the study was conducted. Three co-authors have received lecture fees from related implant manufacturers. One co-author (BAN) is a member of the journal's Editorial Board.

Competing interests:

See Declarations.

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Author Contribution

PH : Conceptualization, Methodology, Investigation, Writing - Original Draft, Statstic analyses SMP: Conceptualization,Investigation, Writing - Review & Editing, Statistic analyses JN: Conceptualization, Writing - Review & Editing, Supervision, Preparation of Figures 1-3 GHL: Conceptualization, Investigation, Writing - Review & Editing, Supervision, Statistic analyses UV: Conceptualization, Writing - Review & EditingAS: Conceptualization, Writing - Review & EditingMK: Conceptualization, Data Collection, Investigation, Writing - Review & EditingRB: Conceptualization, Data Collection, Investigation, Writing - Review & EditingGH: Conceptualization, Data Collection, Investigation, Writing - Review & Editing BAN: Conceptualization, Investigation, Writing - Review & Editing, Supervision

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The first author (PH) and second author (SMP) declare a shared first authorship.

Data Availability

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

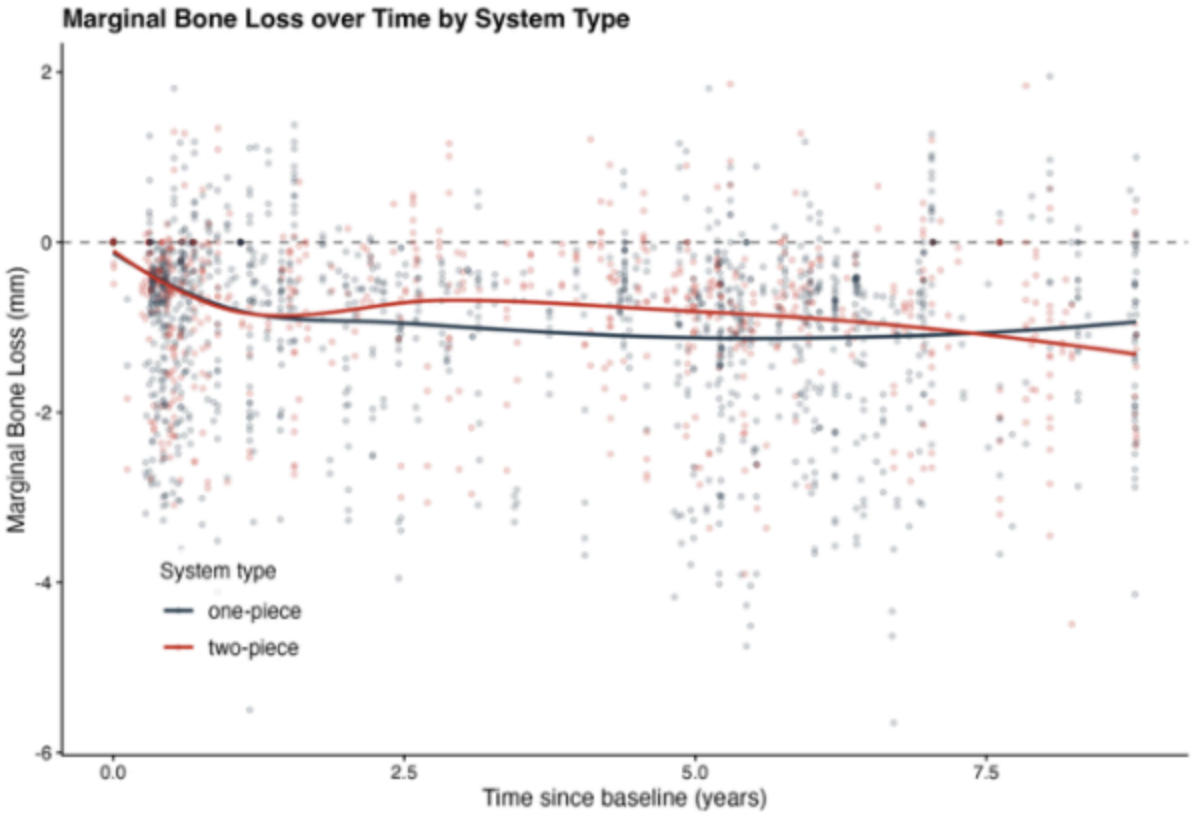


Figure 1

Marginal bone level change over time by implant system. Unadjusted LOESS smoother over individual mesial and distal measurements

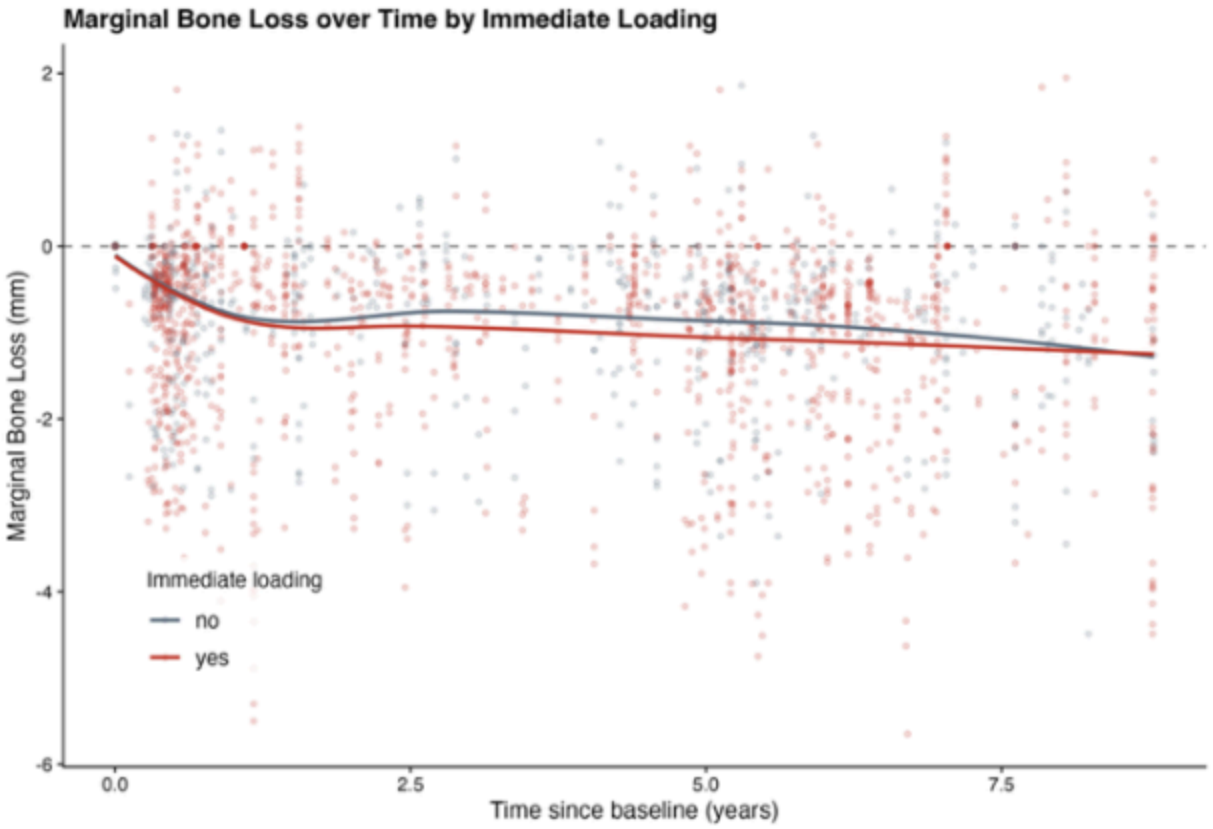


Figure 2

Marginal bone level change over time by loading protocol (immediate versus delayed loading). Unadjusted LOESS smoother

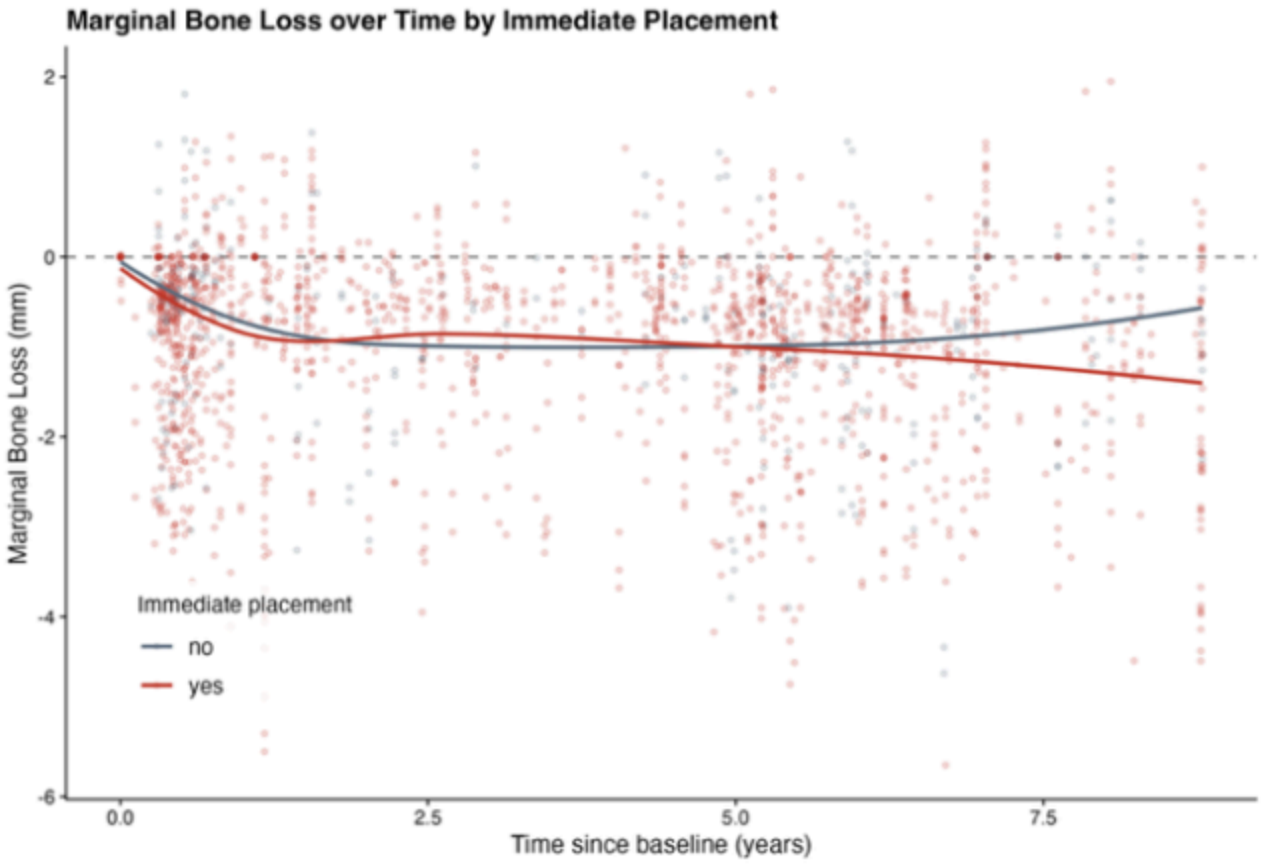


Figure 3

Marginal bone level change over time by placement protocol (immediate versus delayed placement). Unadjusted LOESS smoother

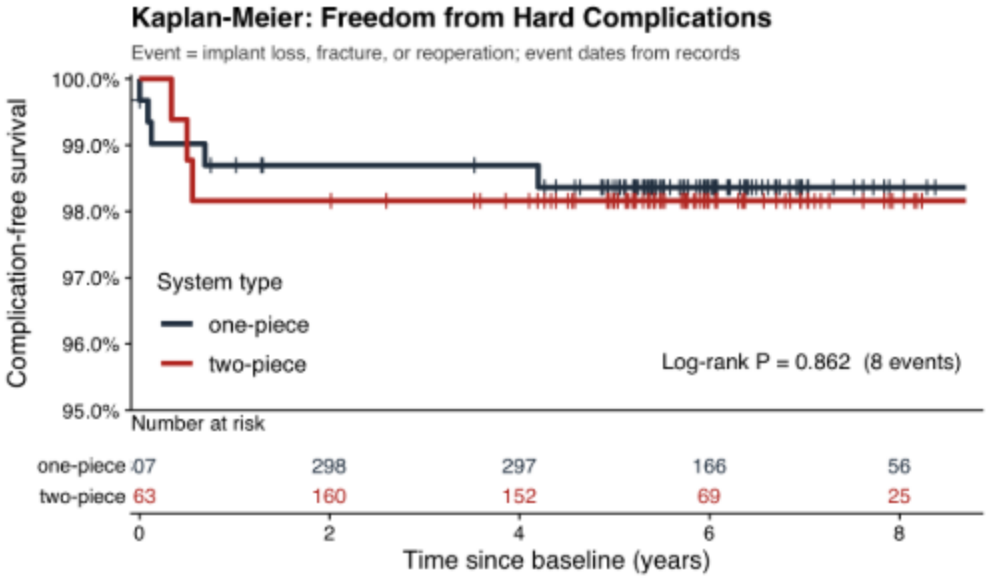


Figure 4

Kaplan-Meier estimates of complication-free survival by implant system.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- STROBEChecklistZirkImplantRetro.docx
- AdditionalTableS1.docx