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Interproximal contact loss at implant sites: a retrospective clinical study with a 10-year follow-up

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Abstract

Aim: To assess the frequency and quantity of interproximal contact loss (ICL) between implant restorations and adjacent teeth after at least 10 years of follow-up (FU).

Methods: Thirty-nine patients (median age 57.3 years) with 80 implants were re-examined at least 10 years after insertion of final restorations (single crowns or fixed dental prostheses (FDPs)). Baseline (insertion of the restorations) and FU examinations encompassed the following: Stone casts were scanned and superimposed for metric assessment of tooth movements, radiographs, and clinical measurements. Outcome measures at implant sites were as follows: the extent of tooth movement and the frequency of interproximal contact loss [ICL], peri-implant marginal bone levels [MBLs], and clinical measurements (plaque control record [PCR], Bleeding on Probing [BOP], and probing depth [PD]). Data were analyzed statistically with generalized regression modeling with robust standard errors to account for within-patient clustering at 5%.

Results: Interproximal contact loss for at least one contact point after 10 years was observed in 50% of all implants (with open interproximal spaces up to 1.64 mm). Mesial contact points were significantly more prone to ICL than distal ones (relative risk [RR] = 1.79; 95% confidence interval [CI] = 1.07–2.99; $p = .03$). The type of restoration had a significant effect on ICL, with FDPs of 2 implants being significantly more prone to mesial ICL than single crowns (RR = 1.52; 95% CI = 1.02–2.25; $p = .04$). ICL was also associated with a significant increase in PD (+0.46 mm (95% CI = 0.04–0.88 mm; $p = .03$)) compared to implant sites without ICL. BOP, MBLs, and PCR were not significantly influenced by ICL.

Conclusion: Interproximal contact loss was a common finding in 50% of the implant sites and was significantly associated with an increase in PD.

KEYWORDS
digital measurement, implant–tooth gap, interproximal contact, tooth movement

1 | INTRODUCTION

Since their introduction in the 1970s, dental implants are a common and reliable treatment option to replace missing teeth. The reported survival rate of implants 10 years after loading amounts to 95.2% (Jung et al., 2012). The scientific literature also provides data on the respective complications rates consisting of three categories: 1. biological complications, 2. technical complications, and 3. esthetic complications (Albrektsson et al., 2012; Wittneben et al., 2014). Biological and technical complications are frequently reported in the literature. Esthetic complications mainly include the following: recession of the mid-facial margo mucosae, discoloration of the peri-implant mucosa, exposure of the endosseous implant part, and loss of papillae (Cosyn et al., 2017). Esthetic scores (pink esthetic score) (Furhauser et al., 2005), white esthetic score (Belser et al., 2009), and implant crown esthetic index (Meijer et al., 2005) are the most common indices to objectively describe esthetic outcomes.

Infraposition (IP; vertical changes) and missing contact points (MCP; horizontal changes) of implants to their adjacent teeth are described as esthetic complications and may as well favor biological complications (Jernberg et al., 1983), hard and soft tissue deficiencies around dental implants (Hammerle & Tarnow, 2018), and patient dissatisfaction (Jeong & Chang, 2015). Consequently, recommendations were made to postpone implant placement in young adult to limit esthetic failures (Thilander & Lekholm, 2001). Furthermore, spontaneous drifts in the mesiodistal direction have been found as well repeatedly in several studies (French et al., 2019; Jo et al., 2019; Papageorgiou et al., 2018).

The underlying reasons for horizontal and vertical changes between implants and adjacent teeth are to be found in the physiology of the human dentoalveolar bone growth and the physiologic differences between teeth and implants. Teeth are suspended by the periodontal ligament (PDL) and therefore allow a certain amount of movement during lifetime (Dager et al., 2008). Implants in contrast exhibit a direct contact to bone once the implant is osseointegrated showing a similar condition to ankylosed teeth (Roberts et al., 1984). Therefore, contrary to implants, natural teeth show a physiologic tooth migration (PTM). Physiologic tooth migration describes naturally occurring tooth movements that take place during and after tooth eruption. This includes tooth eruption itself, the tipping of the functioning tooth in its socket, and the lifelong ability to adapt to functional demands and therefore to shift their position throughout the alveolar ridge. Each tooth has a physiologic ability to move in horizontal, vertical, and rotational directions and usually preserves it during a lifetime (Oesterle & Cronin, 2000; Ten Cate et al., 1976; Thilander et al., 1999). PTM might be essential to maintain stomatognathic form and function (Fields et al., 2018).

It has been highlighted by three recent consensus conferences (American Academy of Periodontology and European Federation of Periodontology 2017 World Workshop, the XIII European Workshop on Periodontology in 2018 (Roccuzzo et al., 2018) and the 5th EAO Consensus Conference 2018) as well as by a systematic review (Ramanauskaite et al., 2018) that research should be directed to further elucidate the magnitude and the potential implications of adverse effects of osseointegrated implants functioning among natural teeth. In order to do so, monitoring the clinical situation of the dentition and the implant restoration by means of precise and repeatable methods (full-arch digital scans) was recommended (Hammerle & Tarnow, 2018; Papageorgiou et al., 2018).

The aim of the present study was therefore to assess the frequency and quantity of interproximal contact loss (ICL) between implant restorations and adjacent teeth after at least 10 years of follow-up.

2 | MATERIALS AND METHODS

2.1 | Study design

The present study is part of a non-interventional follow-up of patients previously enrolled to compare clinical, esthetic, and radiographic outcomes of implants and the respective implant-supported restorations (Thoma et al., 2014). Sixty-eight patients were included. Clinical data for the present study were extracted after 10, 12, and 15 years in conjunction with impressions, clinical photographs, and radiographic images. The present study was approved by the local ethics committee (PB_2020-00019) and performed at the Clinic of Reconstructive Dentistry, Center of Dental Medicine, University of Zurich, Switzerland, between August 2019 and November 2020.

Patients had been treated with dental implants between June 2002 and January 2008. For the selection of the present study material, the following study-specific inclusion and exclusion criteria were applied:

2.2 | Inclusion criteria

1. Male and female patients, older than 18 years;
2. Patients had received implants and implant-supported fixed restorations;
3. Follow-up examination >10 years after insertion of final restorations; and
4. Ability to fully understand the nature of the proposed non-interventional long-term follow-up study and the ability to sign the informed consent form.

2.3 | Exclusion criteria

1. Severe trauma to implant site or adjacent teeth;
2. Known or suspected noncompliance, drug, or alcohol abuse;
3. Orthodontic treatment in the same quadrant;
4. Restorations were removed because of failure or further therapy needed;
5. Patients with a removable reconstruction (ball attachment, bars);
6. Stone cast models that showed imprecisions in the region of interest (ROI) or could not be aligned because of quality issues; and
7. Patients with missing radiographs, stone casts, or clinical records of PD, PCR, and BOP.

2.4 | Baseline and follow-up examinations

All follow-up examinations were performed by a blinded examiner not involved in the therapeutic phase and thereby unaware of the treatment the patients had received.

The following information was collected:

- Clinical parameters (assessed at 6 sites at each implant site)
  a. Probing depth (PD);
  b. Bleeding on Probing (BOP); and
  c. Plaque control record (PCR)
- Clinical photographs
- Hydrocolloid imprint of the dental arch with the implant(s)
- Standardized periapical radiographs using a rim holder (long-cone paralleling technique).

2.5 | Outcome measures

2.5.1 | Measurement of tooth movement

Impressions were taken using a hydrocolloid material. The latest existing dental stone casts were scanned in order to obtain STL (stereolithography) files using a laboratory scanner (IScan L1 series, Imetric 3D SA, Courgenay, Switzerland) (Figure 1a).

A metrology software (Geomagic Control X, 3D Systems Inc., Rock Hill, SC, USA) was used to perform the measurements. For that purpose, the palatal and buccal surface of the implant restoration was aligned by a best-fit algorithm. When alignment was satisfactory, a color-coded map was calculated and visualized any alterations. Distances between 100µm and 2mm were shown in different colors. A plane was defined parallel to the occlusal plane. The occlusal plane was placed at the height of the proximal contact points. This allowed measuring the ICL (Figure 1b).

Each implant crown/cantilever/bridge was measured independently at its mesial and distal contact points. In case two implants supported a splinted restoration (bridge), the measurement was "not applicable" both distally of the anterior implant and mesially of the posterior implant. If the adjacent distal tooth was missing, the measurement was as well "not applicable." The threshold for the measurements was 0.1 mm. Measurements < 0.1 mm were therefore considered as "closed contact point."

2.5.2 | Radiologic examination of marginal bone loss

Marginal bone loss was recorded by measuring the first bone to implant contact (fBIC) at the mesial and distal aspects of each implant at the last time point available. FBIC was measured using a software program (ImageJ 1.51; Wayne Rasband, National Institutes of Health, Bethesda, MD, USA) on periapical radiographs obtained with a long-cone paralleling technique. The known pitch distance between three threads of the implants was used to calibrate the apical–coronal measurements on each radiographic image. The reported fBIC was measured at the mesial and distal sites separately for each single implant (Figure 1c).

2.6 | Blinding in data collection, data analyses, and outcome assessment

Follow-up clinical examinations (Thoma et al., 2014) were performed by a blinded and calibrated examiner neither involved in the surgical and prosthetic phase of the study nor in the present study. Extraction of clinical data and measurements of STL data and radiographs were performed by a further blinded examiner (TG) that was involved neither in the therapeutic phase nor in the data collection during the follow-up appointments of the original study.

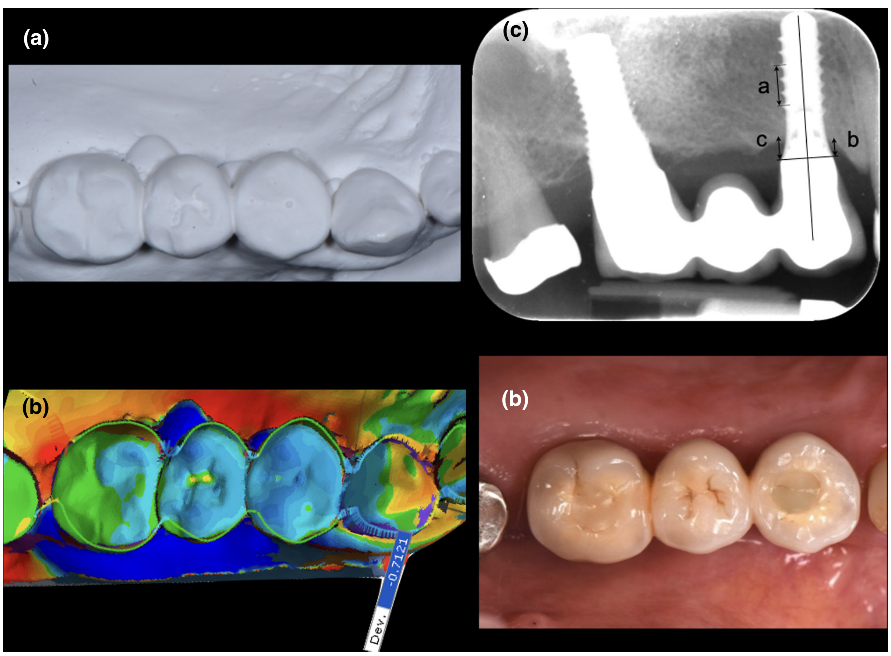

FIGURE 1 (a) Stone cast model at baseline; (b) superimposed baseline and follow-up model. Color-coded mapping indicates differences between the two models. Anterior movement of tooth 13 and lost contact point toward implant in position 14; (c) radiograph of follow-up time point with performed measurements; and (d) clinical photograph of follow-up time point with lost contact between implant 14 and tooth 13

2.7 | Inter-rater and intra-rater reliability

The first 10 models and radiographic measurements were independently analyzed by two of the authors (TG & DT) and then discussed to aim for congruence. Subsequently, all measurements were performed by one calibrated examiner (TG). In case of doubts or difficulties, a further examiner was involved (DT). One calibrated examiner performed all measurements three times at three different time points (TG). The obtained values were then averaged.

2.8 | Potential error of methods

All analyses were performed bearing in mind some potential of error. This included the use of alginate impressions (error of method reported to be within 0.2%) (Rohanian et al., 2014); scanning of models (potential error of method reported to be within 0.01–0.03 mm) (Mandelli et al., 2017) (Song et al., 2017); radiographs (potential error of method for intra-rater interproximal bone height measurements reported to be 0.37 mm (SD ± 0.76) and 0.55 mm (SD ± 0.68); and interrater discrepancies mostly below 0.5 mm (Afrashtehfar et al., 2020).

2.9 | Statistical analysis

Descriptive statistics were calculated, including absolute/relative frequencies and medians with interquartile ranges (IQRs) for continuous outcomes, after checking for normality with the Shapiro–Wilk test. Crude differences in frequencies were assessed with the chi-squared test. Generalized linear regression modeling was used to explore the effect of various factors on the outcomes of (a) binary contact point loss (ICL) (with <0.1 mm as cutoff), (b) marginal bone level (MBL), and (c) probing depth (PD), after accounting for within-patient clustering with robust standard errors. Relative risks (RRs) for ICL and unstandardized regression coefficients (b) were used as effect sizes, including their 95% confidence intervals (CIs), while regression models were built both for contact points overall and separately for mesial or distal contact points. The post hoc differences in MBL and PD were compared between implant sites with ICL > 0.1 mm and implant sites with retained contact points applying the Kruskal–Wallis test. All analyses were run in Stata version 14.0 (Stata-Corp LP, College Station, TX, USA) by one author (SNP) with a two-sided test with $\alpha = 5\%$. The dataset is publicly available (Gasser et al., 2021).

3 | RESULTS

3.1 | Study sample

A total of 39 patients (62% female) with a median age of 57.3 years (IQR 43.5–63.4 years; range 22.0–77.0 years) participated in the study with only a minority being bruxers (n = 2; 5%) or smokers (n = 5; 13%) (Table 1). The patients had received 80 implants restored either with implant-supported single crowns (SCs; n = 26; 67%) or with fixed dental prostheses (FDPs; n = 13; 33%). The median follow-up time was 12.0 years (IQR 11.7–12.1 years; range 8.2–14.1 years). Forty-nine implants (61.3%) were placed in the maxilla and 13 (16.3%) in the esthetic zone (central incisor to canine). The number of contact points assessable for analysis was 57 (to a mesially positioned natural tooth; 71.3%) or 33 (to a distally positioned natural tooth; 41.3%) (Table 2).

3.2 | Assessment of interproximal contact loss (ICL)

At the implant level (with 90 assessed interproximal contact points), the distance between the implant and the neighboring tooth measured <0.1 mm in 50% of the sites (n = 45), between 0.1 and 0.2 mm in 17.8% (n = 16), between 0.2 and 0.3 mm in 12.2% (n = 11), between 0.3 and 0.4 mm in 8.9% (n = 8), and more than 0.4 mm in

TABLE 1 Characteristics of included patient population

Level	Variable	N (%)	Median (IQR)	Range
Patient level	Age	39 (100%)	57.3 (43.5–63.4)	22.0–70.0
	Male	15 (38%)		
	Female	24 (62%)		
	Follow-up	39 (100%)	12.0 (11.7–12.1)	8.2–14.1
	Smokers	5 (13%)		
	Bruxers	2 (5%)		
	Single crown	26 (67%)		
	FDP	13 (33%)		
Implant level	Maxilla	49 (61.3%)		
	Mandible	31 (38.8%)		
	Anterior	13 (16.3%)		
	Posterior	67 (83.8%)		

Note: FDP, multi-unit fixed dental prosthesis; IQR, interquartile range.

11.1% (n = 10) (Table 3). Considering a threshold of 0.1 mm, ICL was observed in 50% of the sites (n = 45) during the follow-up period. At the patient level, 56.1% (n = 23) of the implants with one assessable contact point presented an interproximal contact loss of >0.1 mm. The respective figures for implants with two assessable contact points were 41.7% (n = 10) with one ICL and 25.0% (n = 6) with two ICL > 0.1 mm.

3.3 | Clinical and radiologic examination

The median marginal bone levels were located more coronally than the implant reference point (implant shoulder/transition between rough and smooth surface) with +0.77 mm at baseline (IQR 0.42 to 1.04 mm). At the follow-up, the median MBL was located below the reference point with −0.54 mm (IQR −1.1 to 0 mm) (Table 4). The median peri-implant probing depth demonstrated a slight increase from baseline (3.0 mm (IQR 2.5 to 3.5 mm)) to the follow-up (3.5 mm (IQR 3.0 to 4.0)). Plaque control records at baseline (median 0; IQR 0 to 0) and at the follow-up (median 0; IQR 0 to 0.5) and Bleeding on Probing at baseline (median 0; IQR 0 to 0.5) and at the follow-up (median 0.5; IQR 0 to 1.0) were stable over time.

TABLE 2 Number and percentages of implant contact points assessed

Category	Mesial	Distal	p (x^2)
Assessable	57 (71.3%)	33 (41.3%)	<.001
Not assessable	23 (28.8%)	47 (58.8%)	

3.4 | Regression analyses

Mesial contact points were significantly more prone (+79%) to ICL than distal CPs (RR = 1.79; 95% CI = 1.07 to 2.99; p = .03). Furthermore, multi-unit implant-supported FDPs were significantly more prone (+52%) to ICL than single crowns at the mesial contact point (RR = 1.52; 95% CI = 1.02 to 2.25; p = .04) (Table 5).

Marginal bone-level changes (Table 6) were associated with patient gender. Implants in male patients demonstrated a greater marginal bone loss than in female patients (b = −0.69 mm; 95% CI = −1.35 to −0.02 mm; p = .04). This was predominantly observed at mesial contact points (b = −0.87 mm; 95% CI = −1.62 to −0.16 mm; p = .02) compared with distal CPs (b = −0.49 mm;

TABLE 3 Contact point measurements at follow-up

Level	Variable	N (%)
Implant level	Assessed interproximal contacts	90 (100%)
	ICL < 0.1 mm	45 (50.0%)
	0.1 mm ≤ ICL < 0.2 mm	16 (17.8%)
	0.2 mm ≤ ICL < 0.3 mm	11 (12.2%)
	0.3 mm ≤ ICL < 0.4 mm	8 (8.9%)
	ICL ≥ 0.4 mm	10 (11.1%)
	Interproximal contact present	45 (50.0%)
	Interproximal contact lost	45 (50.0%)
Patient level	Implants with 1 CP (n = 41): lost one CP	23 (56.1%)
	Implants with 1 CP (n = 41): lost no CPs	18 (43.9%)
	Implants with 2 CPs (n = 24): lost one CP	10 (41.7%)
	Implants with 2 CPs (n = 24): lost two CPs	6 (25.0%)
	Implants with 2 CPs (n = 24): lost no CPs	8 (33.3%)

Note: ICL, interproximal contact loss; CP, contact point.

TABLE 4 Clinical and radiographic measurements at baseline and at the follow-up

Level	Variable	Median (IQR)	Range
Marginal bone level (mm)	Baseline (n = 86)	0.77 (0.42, 1.04)	−1.25, 2.61
	Follow-up (n = 82)	−0.54 (−1.1, 0)	−5.02, 4.09
Probing depth (mm)	Baseline (n = 86)	3.0 (2.5, 3.5)	1.5, 6.0
	Follow-up (n = 88)	3.5 (3.0, 4.0)	2.0, 6.5
Plaque control record	Baseline (n = 86)	0 (0, 0)	0, 1.0
	Follow-up (n = 88)	0 (0, 0.5)	0, 1.0
Bleeding on Probing	Baseline (n = 86)	0 (0, 0.5)	0, 1.0
	Follow-up (n = 88)	0.5 (0, 1.0)	0, 1.0

Note: IQR, interquartile range.

TABLE 5 Regression analysis for interproximal contact loss (>0.1 mm) for all implants

		Overall		Mesial contact points		Distal contact points	
Factor	**Category**	**RR (95% CI)**	***p***	**RR (95% CI)**	***p***	**RR (95% CI)**	***p***
Age	Per year	1.00 (0.98, 1.02)	.91	1.00 (0.99, 1.02)	.74	0.98 (0.95, 1.02)	.31
Gender	Female	Reference					
	Male	1.09 (0.67, 1.78)	.72	1.20 (0.77, 1.88)	.42	1.13 (0.38, 3.33)	.83
Follow-up	Per year	1.18 (0.97, 1.45)	.10	1.11 (0.87, 1.42)	.40	1.28 (0.88, 1.87)	.20
Smoker	No	Reference					
	Yes	1.10 (0.47, 2.60)	.82	1.23 (0.62, 2.44)	.55	0.73 (0.10, 5.10)	.75
Bruxer	No	Reference					
	Yes	0.79 (0.54, 1.15)	.22	1.13 (0.67, 1.90)	.66	No CPL for bruxers	
Reconstruction	Single crown	Reference					
	Multi-unit bridge	1.52 (0.97, 2.37)	.07	**1.52 (1.02, 2.25)**	**.04**	1.00 (0.19, 5.24)	1.00
Jaw	Mandible	Reference					
	Maxilla	1.00 (0.62, 1.61)	1.00	1.06 (0.68, 1.65)	.79	1.00 (0.30, 3.37)	1.00
Region	Posterior	Reference					
	Anterior	1.00 (0.50, 1.98)	1.00	0.69 (0.26, 1.84)	.46	2.69 (0.80, 9.05)	.11
Implant level	Distal	Reference		-	-	-	-
	Mesial	**1.79 (1.07, 2.99)**	**.03**	-	-	-	-
Marginal bone level at baseline	Per mm	0.86 (0.59, 1.25)	.43	[a]0.40 (0.13, 1.29)	.13	1.03 (0.49, 2.18)	.93
Probing depth at baseline	Per mm	0.85 (0.66, 1.11)	.23	1.11 (0.93, 1.32)	.24	0.52 (0.22, 1.20)	.12

Note: CI, confidence interval; RR, relative risk.

[a]Odds ratio used instead of relative risk due to issues with model convergence.

Bold values are indicates statistically significant.

p = .15). In addition, significantly more MBL was observed at the mesial side of multi-unit implant-supported FDPs compared with single crowns (b = −0.65 mm; 95% CI = −1.28 to −0.03; p = .04). Significantly more MBL was observed in the maxilla compared with the mandible (b = −0.52 mm; 95% CI = −1.03 to −0.02 mm; p = .04) at the distal aspect of the implants. However, marginal bone differences between the mesial and distal aspects of the implant-supported restoration are of small magnitude and must be viewed with caution due to the moderate sample size of the present study.

The peri-implant probing depth (PD) was significantly associated with the patient's jaw (Table 6) with higher PD values in the maxilla than in the mandible (b = 0.59 mm; 95% CI = 0.25 to 0.93 mm; p = .001). This discrepancy was more evident at the mesial side (b = 0.71 mm; p = .001) than at the distal side (b = 0.48; p = .007) of the implant restorations. Finally, ICL had a significant effect on peri-implant PD. At interproximal areas with ICL > 0.1 mm, significantly higher PD values were observed (b = 0.46 mm; 95% CI = 0.04 to 0.88; p = .03) compared to sites with retained contact points. This pertained mostly to mesial interproximal sites (b = 0.58 mm; 95% CI = 0.03 to 1.13 mm; p = .04) and not distal sites (b = 0.17 mm; p = .71).

4 | DISCUSSION

The present retrospective analysis assessed the long-term status of interproximal contacts and peri-implant tissue health of 80 implants placed in 37 patients and followed for at least 10 years post-insertion of final restorations. The main finding of the study revealed 50% of the implant sites with a lost contact point. It is known that dental implants placed in patients in their late teens or even early adulthood might be unable to follow the constant adaptation of the teeth and jaws that continues even until late adulthood (Behrents, 1985; Bjork & Skieller, 1972; Dager et al., 2008; Solow, 1980). Consequently, adverse effects due to their osseointegrated nature might be seen. This is mostly observed as loss of the interproximal contact points or infraposition relative to the neighboring natural teeth (Papageorgiou et al., 2018). The findings of the present study indicating that half of the contact points were lost are in line with previous studies reporting rates of over 50% (Brahem et al., 2017; Byun et al., 2015; Fukunishi et al., 2016; Pang et al., 2017; Varthis et al., 2016; Wong et al., 2015), while a meta-analysis reported an average rate of 46.3% (Papageorgiou et al., 2018). The large heterogeneity observed in between the various studies might be attributed to different follow-up periods (Bompolaki et al., 2020) or different methods of measuring

TABLE 6 Regression analysis on (a) marginal bone level at follow-up, (b) probing depth at follow-up (with baseline level as covariate) for all implants

		Overall		Mesial contact points		Distal contact points	
Factor	Category	b (95% CI)	*p*	b (95% CI)	*p*	b (95% CI)	*p*
(a)							
Age	Per year	0.01 (−0.01, 0.03)	.15	0.02 (0, 0.04)	.10	0.01 (−0.01, 0.03)	.30
Gender	Female	Reference		Reference		Reference	
	Male	**−0.69 (−1.35, −0.02)**	**.04**	**−0.87 (−1.62, −0.16)**	**.02**	−0.49 (−1.15, 0.17)	.15
Follow-up	Per year	0.27 (−0.14, 0.68)	0.20	0.27 (−0.20, 0.74)	.26	0.27 (−0.13, 0.66)	.19
Reconstruction	Single crown	Reference		Reference		Reference	
	Multi-unit bridge	−0.48 (−1.04, 0.07)	.09	**−0.65 (−1.28, −0.03)**	**.04**	−0.31 (−0.87, 0.25)	.27
Jaw	Mandible	Reference		Reference		Reference	
	Maxilla	−0.45 (−0.99, 0.09)	.10	−0.38 (−1.03, 0.27)	.25	**−0.52 (−1.03, −0.02)**	**.04**
Region	Posterior	Reference		Reference		Reference	
	Anterior	−0.42 (−1.20, 0.36)	.29	−0.46 (−1.29, 0.36)	.27	−0.38 (−1.16, 0.41)	.35
Implant side	Distal	Reference		-	-	-	-
	Mesial	0.09 (−0.15, 0.32)	.47	-	-	-	-
Contact point	Retained	Reference		Reference		Reference	
	Lost	−0.02 (−0.73, 0.69)	.96	0.12 (−0.86, 1.11)	.81	−0.20 (−1.16, 0.76)	.69
(b)							
Age	Per year	0 (−0.02, 0.01)	.56	0 (−0.02, 0.01)	.63	0 (−0.02, 0.01)	.55
Gender	Female	Reference		Reference		Reference	
	Male	−0.02 (−0.39, 0.34)	.90	0.04 (−0.45, 0.53)	.87	−0.10 (−0.47, 0.27)	.59
Follow-up	Per year	−0.12 (−0.39, 0.15)	.38	−0.10 (−0.42, 0.23)	.57	−0.16 (−0.45, 0.13)	.28
Reconstruction	Single crown	Reference		Reference		Reference	
	Multi-unit bridge	−0.24 (−0.65, 0.16)	.24	−0.10 (−0.60, 0.41)	.71	−0.37 (−0.78, 0.04)	.08
Jaw	Mandible	Reference		Reference		Reference	
	Maxilla	**0.59 (0.25, 0.93)**	**.001**	**0.71 (0.29, 1.13)**	**.001**	**0.48 (0.13,.82)**	**.007**
Region	Posterior	Reference		Reference		Reference	
	Anterior	0.30 (−0.15, 0.75)	.19	0.26 (−0.27, 0.79)	.34	0.38 (−0.16, 0.93)	.17
Implant level	Distal	Reference		-	-	-	-
	Mesial	0.16 (−0.06, 0.38)	.15	-	-	-	-
Contact points	Retained	Reference		Reference		Reference	
	Lost	**0.46 (0.04, 0.88)**	**.03**	**0.58 (0.03, 1.13)**	**.04**	0.14 (−0.60, 0.89)	.71

Note: b, unstandardized regression coefficient; CI, confidence interval.
Bold values are indicates statistically significant.

a lost contact point (e.g., visual inspection, dental floss, and digital superimposition methods) (Brahem et al., 2017).

As far as contact point loss is concerned, the mesial sites of implant-supported restorations were considerably more affected than the distal sides in the present study. This is in agreement with previous studies reporting significantly higher rates of contact point loss for the mesial aspect of the implant-supported restoration compared with its distal aspect (Bompolaki et al., 2020; Byun et al., 2015; Varthis et al., 2016). A possible explanation that has been proposed for this is that the restorations were placed in the free-end edentulous ridge and therefore had only one contact to the mesial aspect and no contact to the distal aspect. However, post hoc exploratory analyses of the original overall effect (RR = 1.79) indicated robustness when limiting to implants placed up to the position of the 1st molar (RR = 1.93), up to the 2nd premolar (RR = 1.86), or up to the 1st premolar (RR = 1.50). This observation therefore contradicts the implant's position at the last free-standing end of the dentition as a possible explanation for the predilection of contact point loss at the mesial sides. A way more likely explanation for this observation might be the mesial migration of the remaining natural teeth (Jo et al., 2019), which is closely associated with the anterior force component of mastication (Southard & Behrents, 1990; Vardimon et al., 2007). Mesial migration is a natural phenomenon thought to counteract the attrition of interproximal contact points, which become more flattened, so that a stable continuity of the dental arch exists and increases proportionally with the magnitude of bite force (Komiyama et al., 2012; Southard & Southard, 1990). It is therefore possible that the natural teeth at the mesial aspect of the implants were still free to migrate, while the mesial migration of natural teeth at the distal aspect of the implants was impeded by the osseointegrated implants not undergoing any adaptation and/or remodeling. Even though more mesial contact points might be lost due to migration, the distal aspect of implant-supported restorations should not be neglected, as several distal contact points were also lost in the present study (11/33; 33%).

Interestingly, the type of the implant-supported restoration seemed to be associated with the loss of the contact point to the adjacent neighboring tooth over 10 years. This is in agreement with a previous study (Byun et al., 2015) reporting that 4.8 years after implant insertion, FDPs were significantly more prone to contact point loss than single implant-supported crowns. The same study also reported that this observation was not influenced by the presence of an adjacent natural tooth at its mesial or distal contact point. In the present study, FDPs and single crowns were similarly placed at the various areas of the corresponding teeth: molars (FDPs, 41%/single crowns, 49%), premolars (FDPs, 46%/single crowns, 32%), canines (FDPs, 8%/single crowns, 2%), and incisors (FDPs, 5%/single crowns, 17%) with no significant differences ($p = .18$ from explorative Fisher's exact test). The increased contact point loss for FDPs was seen only for mesial implant sides (RR = 1.52; $p = .04$) and not for distal implant sides (RR = 1.00; $p = 1.00$). However, controlling for the position of the placed implant had no significant modifying effect on the contact point loss. Still, an increased number of ICL for FDPs were observed at the mesial ($p = .03$ after adjustment) compared with the distal side ($p = .93$ after adjustment). Additionally, limiting the analysis to only implants placed in the position of incisors, canines, and premolars (i.e., excluding 36 of 80 implants placed on the position of the 1st or 2nd molar that might be free-standing) did not influence the results and contact points were lost more often with FDPs overall (RR = 1.58; $p = .05$). The loss of both (mesial and distal) contact points was more often observed in conjunction with FDPs (RR = 1.34 for mesial and RR = 1.56 for distal) rather than single crowns. Finally, no significant differences existed in the follow-up period between FDPs and single crowns ($p = .54$ from the explorative Kruskal–Wallis test), which could act as a confounder. It seems that FDPs might be more prone for ICL than for single crowns, even though a clear explanation for this is missing. This notion is supported at least to some extent by a recent study reporting that after 3.1 years of follow-up, implant-supported restorations with external hexagonal and internal octagonal connections were associated with significantly higher contact point loss than those with internal hexagonal connections (Yen et al., 2020). Differences in terms of micromotion of the abutment (Coppede et al., 2013; Saidin et al., 2012) could influence the interproximal contact stability.

Apart from esthetic- or comfort-related aspects linked to the loss of the implant restoration's contact point to the neighboring tooth, open contact areas might also affect the health of the peri-implant supporting tissues. This is mainly due to the speculation that an open contact point will be more difficult to clean and will lead to more food impaction (Chopra et al., 2019). In the present study, ICL was not found to be associated with the majority of radiographic and clinical outcomes with the exception of probing depth values. Despite similar baseline measurements for probing depth values, implant sites where the contact point had been lost demonstrated a probing depth increase, whereas sites with retained contact points were stable ($p = .02$). These data corroborate with previous clinical studies reporting no correlation of marginal bone loss and ICL, but a trend toward a higher rate of peri-implant mucositis (French et al., 2019; Jernberg et al., 1983), clinical attachment loss (Koori et al., 2010), probing depth (Koori et al., 2010), or caries (Allison & Schwartz, 2003), and no influence on any variables of periodontal/peri-implant tissue conditions in sites with ICL (Bompolaki et al., 2020; Byun et al., 2015). Nevertheless, a higher rate of food impaction and aesthetic impairment especially in the anterior zone might lead to patient dissatisfaction (Jeong & Chang, 2015). On the other hand, the extent of ICL varies individually and over a prolonged time-period, which might reduce the patients 'awareness. It would therefore be recommendable for future research to include patients' perception on interproximal contact loss.

The results of the present study are to some extent limited by: (i) the study design being of a retrospective rather than of a prospective nature; (ii) the use of alginate impressions followed by casts that were scanned; (iii) the reported error of method being estimated to be below 0.1 mm (alginate impression, scanning of models, and error measurement) and, consequently, a threshold of 0.1 mm being chosen; (iv) the absence of further clinical measurements (e.g., using dental floss) that might even underestimate the incidence of ICL; and (v) the potentially low statistical power to formally analyze all parameters; and (vi) the missing patient-reported outcome measures that were not included due to the retrospective nature of the study.

5 | CONCLUSIONS

Interproximal contact loss was a common finding in 50% of the implant sites during a 10-year observation period. Mesial contact points and multi-unit restorations presented a higher risk for ICL than for single crowns and distal contact points. ICL was associated with a significant increase in PD, whereas BOP, MBL, and PCR were stable and not affected.

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CONFLICT OF INTEREST

The authors report no conflict of interests related to the study or products involved.

AUTHOR CONTRIBUTION

Thomas J. W. Gasser: Conceptualization (equal); Data curation (lead); Investigation (lead); Methodology (equal); Software (lead); Visualization (lead); Writing – original draft (lead). **Spyridon N. Papageorgiou:** Conceptualization (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Software (equal); Validation (equal); Writing – original draft (equal). **Theodore Eliades:** Conceptualization (supporting); Resources (supporting); Supervision (supporting); Writing – review & editing (supporting). **Christoph H.F. Hämmerle:** Conceptualization (equal); Resources (equal); Supervision (equal); Writing – review & editing (equal). **Daniel S Thoma:** Conceptualization (lead); Data curation (equal); Formal analysis (equal); Methodology (equal); Project administration (equal); Resources (equal); Supervision (equal); Validation (equal); Writing – review & editing (lead).

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