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Multicenter 14-year follow-up of fibula vascular grafts of mandibles and maxillae restored with short and extra-short implants

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A R T I C L E I N F O

Keywords:
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A B S T R A C T

Purpose: This multi-center retrospective study evaluated the survival and success of extra-short and short locking-taper dental implants placed in both maxillary and mandibular fibula grafts.
Methods: A total of 37 patients were treated across five study sites and received 146 implants in fibula grafted sites. Out of those patients, 23 received prostheses, and they received 25 prostheses in total. Kaplan-Meier survival analysis was used to assess the survival and success rates of both implants and prostheses. Multivariate Cox regression and manifold learning were used to correlate study covariates to implant survival outcomes. Marginal bone levels surrounding implants supporting full arch prostheses were measured and correlated with the lengths of distal extensions.
Results: The overall thirteen-year implant survival rate was 86.9 % (95 % confidence interval: 75.5–93.2 %), while the implant success rate was 80.2 % (95 % confidence interval: 66.8–88.7 %.) The prosthesis survival rate at 13 years after prosthesis insertion was 90.0 % (95 % confidence interval: 65.6–97.4 %); while the prosthetic success rate was 78.9 % (95 % confidence interval: 56.2–90.7 %.) Hypertension, implant placement in the mandible, tooth loss from tumor, patient age, and lateral augmentation were correlated with reduced implant survival; while maxillary implant placement, osteoporosis and antiresorptive drug use, chemotherapy before implant surgery, and tooth loss from trauma were correlated with improved survival. Marginal bone levels around implant immediately adjacent to distal extensions were positively correlated with the lengths of distal extensions ($R^2 = 0.74$).
Conclusion: Extra short and short locking-taper dental implants presented high survival and success rates when used to restore the dentition of patients receiving fibula grafts for maxillary or mandibular reconstruction.

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1. Introduction

Complex orofacial defects impact the form and function of the face and require reconstruction. Defects can result from trauma, infection, congenital defects, or more frequently, tumors (Akinbami, 2016). To reconstruct such maxillofacial defects, various options including vascularized flaps, non-vascularized autogenous grafts, or allografts can be used, with the vascularized graft being the preferred option due to its superior outcomes and versatility (Gangwani et al., 2022). In particular, the fibula free flap (FFF), a revascularized free flap technique, has been regarded as the gold standard for mandibular and maxillary reconstructions, owing to the adequate bone stock, ideal vascular pedicle, sufficient skin flap, and wide cortical bone diameter enabling the support of dental implants (Nguyen et al., 2020; Sozzi et al., 2017; Hidalgo, 1989; Taylor et al., 1975). In addition to the reconstruction of maxillary and mandibular bone and soft tissues, the restoration of masticatory function, speech, and aesthetics relies heavily on dental prostheses.

Research has been performed on the outcomes of implants placed in FFF. A systematic review and meta-analysis estimated the technique is highly successful, with an annual implant failure rate of 0.02 (Gangwani et al., 2022). Another recent study, which investigated other vascular bone flaps in addition to FFF, calculated a 92.2 % implant survival rate at a median follow-up of 36 months (Panchal et al., 2020). The study also concluded that radiation significantly increased the risk of implant failure (risk ratio: 4.74). Another systematic review concluded that implants placed in vascularized mandibular fibula bone grafts presented success rates similar to those in native mandibular bone rehabilitations (Ardisson et al., 2022), while contrasting results suggested that implants placed in fibula grafts had a 2.91 times higher failure rate compared to those placed in natural bones (Tahmasebi et al., 2023).

Although the osseointegration of dental implants is commonly predictable in healthy individuals, past investigations on dental implants in FFF have revealed high complication rates. In a 3-year follow-up study, the authors indicated that peri-implant bone stability in FFF could not be expected on the long-term (Kniha et al., 2017). A different 6-year follow-up of screw designed implants placed in FFF also revealed a high prevalence of peri-implantitis, which impacted 29 % of implants and 96 % of patients (Lombardo et al., 2023).

Notably, past research on dental implants in FFF have not assessed the performance of plateau-root form implants, which have presented high implant and prosthetic survival rates in a variety of challenging clinical scenarios (Cheng et al., 2023, 2024; Ewers et al., 2021), owing to its unique osseointegration pathways (Baldassarri et al., 2012; Bonfante et al., 2019; Gil et al., 2015). Besides being less invasive, short and extra-short plateau-root form dental implants are placed subcrestally in bone microvascular free flaps because more bone remodeling should be expected around implants in such flaps when compared to implants placed in native bone (Ardisson et al., 2022). Plateau-root form implants are promising candidates for improving the outcomes of dental implant in FFF – while individual successful cases have been documented (Ewers et al., 2023), long-term evaluation of their performance in FFF is warranted. Therefore, this study aims to investigate the survival and success of plateau-root form implants placed in FFF, and identify factors that influence implant outcomes.

Previous work have shown that short implants have higher failure rates than standard-size implants (10 mm or longer) and consequently it has been suggested that fibula vascular graft reconstructions should employ surface-treated implants with a minimum length of 10 mm (Kim and Ghali, 2011; Smith Nobrega et al., 2016). However, such studies have used screw-root form implants which present substantially different initial and long-term osseointegration pathways compared to plateau-root form implants (Berglundh et al., 2003; Coelho et al., 2010; Coelho and Jimbo, 2014). In the latter implant design, initial stages of osseointegration are characterized by direct contact of osteogenic cells with implant treated surfaces within the healing chambers and rapid bone formation, whereas in screw-root form implants interfacial bone remodeling occurs first due to the implant's tight fit with the osteotomy walls which is then followed by bone formation (Coelho et al., 2015).

2. Method of research

2.1. Study population

Five study sites were included in this study: the Department of Maxillofacial Surgery at F. D. Roosevelt University Hospital, Banská Bystrica, Slovak Republic; the Clinic for Maxillofacial Surgery at the University of Belgrade School of Dental Medicine, Serbia; the Clinic for Oral and Maxillofacial Sugery at the University Hospital Carl Gustav Carus Dresden, Germany; the Department of Oral and Maxillofacial Surgery at University Hospitals Leuven, Belgium; and the University Hospital for Cranio-Maxillofacial and Oral Surgery, Vienna, Austria (abbreviated BB, BG, DD, LV, and VI, respectively.) Data from all study sites were collected according to the Declaration of Helsinki and the Good Clinical Practice guidelines. Ethical approval numbers included No. 018/2011 from the Medical University of Vienna, and No. February 2020 from the F. D. Roosevelt University Hospital, Banská Bystrica.

This study included patients who received free fibula flaps due to the following indications: tumor, trauma, or extreme atrophy. Exclusion criteria for this study, and for FFF treatment in general, included the current use of antiresorptive medications, smoking of more than 20 cigarettes a day, alcoholism, and poor oral hygiene. Notably, patients without current antiresorptive use, but have either a history of antiresorptive use or initiated antiresorptive treatment after implant surgery were included in the study. Patients were evaluated for rehabilitation and for inclusion in this study by the surgeon in cooperation with the prosthodontist.

After an angiogram was used to confirm sufficient blood supply to the native fibula, patients who were included in the study received FFF. Vestibuloplasties were performed to manage the skin island, if necessary. Subsequently, patients were evaluated for dental rehabilitation. Patients with tumors were to be recurrence free for one year and be in good general health to be eligible. Additionally, patients with Type II diabetes should have HbA1c values under 6.0.

For dental rehabilitation, short and extra-short locking-taper implants with hydroxyapatite coatings (Integra-CP™, Bicon LLC, Boston, USA) were inserted into the graft following the manufacturer's two-stage protocol, under local anesthesia. The hydroxyapatite coating, combined with the plateau-root form shape of the implant, has been shown to induce the formation of lamellar bone with Haversian-like morphology (Coelho et al., 2010b). Typically, four to five implants are placed in each patient for full-arch rehabilitation. As the fibula generally contains 4.0–5.0 mm of cortical bone, implants with diameters of 4.0, 4.5, or 5.0 mm were used. The lengths of implants used ranged from 5.0 mm to 11.0 mm. Most commonly used implant dimensions were 4.0 × 5.0 mm implants (Fig. 1) in attempt to promote less invasive osteotomies. After implant insertion, titanium temporary abutments with low profiles (Thin Crestal Temporary Abutments, Bicon LLC) were inserted into the implants' locking-taper wells and covered with soft tissue to allow for implant osseointegration.

Implants were allowed to heal for four to six months before they were uncovered and restored with prostheses. Prosthesis types included single unit crowns, as well as both fixed and removable, partial and full-arch prostheses. Prostheses were secured to implants using cement, screws, bars, or telescopic attachments. Notably, some prostheses were fabricated using a Computer-aided design and Computer-aided manufacturing (CAD/CAM) fiber-reinforced composite (FRC) framework (TRINIA®, Bicon LLC), while others consisted of metal, acrylic, or metal ceramic materials. During the course of this study, it was ensured that by the time prosthetic rehabilitation was complete, the opposing dentition would also be present. Some patients retained their natural teeth on the opposite jaw, and others received prostheses as part of rehabilitation. Not all patients met the criteria for prosthetic

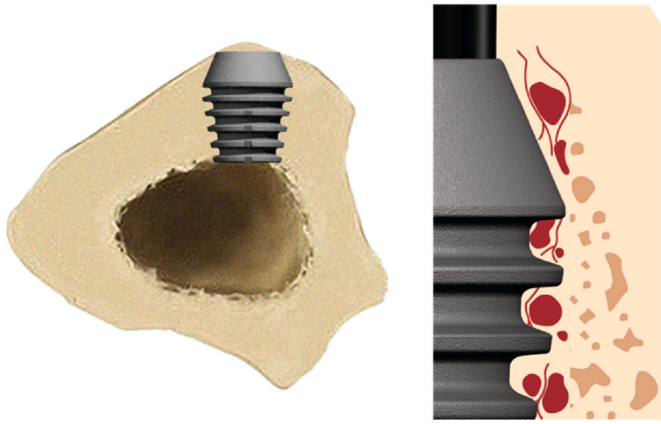

Fig. 1. Representative graphics of implant placement and implant surface. Left: representative placement of a 4.0 × 5.0 mm implant in a fibula graft. Right: enlarged graphic of the interface between an implant and surrounding vascularized bone.

rehabilitation, and some were lost to follow up. At the time of this writing, the number of patients who received prostheses was 22, with 27 prostheses in total.

2.2. Representative workflow

The workflow and outcomes of using short and extra short implants to restore dental function and aesthetics in two patients, who received fibula grafts, are shown below. One patient underwent rehabilitation of the maxilla, and the other of the mandible.

The first patient was a 52-year-old female, who presented with squamous cell carcinoma of the premaxilla and hard palate (T2/T3N0Mx). Bilateral neck dissection (levels I-III) was performed, as well as resection of the maxilla with all teeth except for #15. Subsequently, the maxilla was reconstructed with a fibula free flap, with the donor site closed with a split-thickness skin graft. The postoperative pathology staging was pT4apN0pMX. For two months following the grafting procedure, 40Gy of adjuvant radiotherapy was performed. A postoperative panoramic radiograph and a computed tomography (CT) scan are shown in Fig. 2A and B.

18 months after surgery, reduction of the skin flap was performed intraorally, and the osteosynthesis plates were partially removed. Six months after that, four 4.0 × 6.0 mm short implants were placed in regions 3, 6, 10, and 12 (Bicon LLC, Boston, USA.) Fifteen months after implant surgery, the implants were uncovered, and in the same session an impression was taken, followed by the placement of healing abutments (Fig. 2C–D). A prosthesis with ten teeth in total containing four abutments and six pontics was fabricated using a CAD/CAM milled FRC framework (TRINIA™, Bicon LLC, USA), as depicted in Fig. 2E. Two years after implant placement, the prosthesis was loaded (Fig. 2F–H.)

The second patient was a 59-year-old male with a history of smoking and hypertension, who presented with squamous cell carcinoma of the anterior floor of the mouth (pT4a pN0 (0/65) L0 V0 R0 G3) with osseous infiltration. A preoperative radiograph is shown in Fig. 3A. After tumor surgery, 66.0 Gy of radiotherapy for 2 months as well as 100 mg/m^2 Cisplatin was administered. Then, bony and soft tissue reconstruction was performed using FFF (Fig. 3B–D).

Twenty months after tumor resection, guided dental implant insertion was performed in regions 33, 35, 41, 43, and 45 (Fig. 3E–F) using 4.0 × 5.0 mm extra short implants. Thin crestal temporary abutments were used to prevent the implants from falling into the marrow space. The skin island of the fibula flap was refixed intraorally after implant insertion (Fig. 3G–H). Six months after implant surgery, the implants were uncovered and a vestibuloplasty was performed. Five months after uncovering, a prosthesis fabricated using a metal framework was cemented in place (Fig. 3I–J) Radiographs and intraoral photos taken four years after prosthesis insertion demonstrate maintenance of marginal bone levels and soft tissue health (Fig. 3K–L).

2.3. Data collection

For each patient, their gender and age at the time of implant surgery, as well as their use of medications, including antibiotic use, were recorded. The presence of systemic conditions that may potentially affect dental implant therapy, namely, diabetes mellitus; osteoporosis/osteopenia; smoking; history of antiresorptive treatment, were recorded. The reason underlying each patient’s tooth loss was also recorded. For patients who experienced tooth loss due to tumors, the use of irradiation or chemotherapy before or after implant surgery was recorded.

For each implant, the diameter, length, position in the mouth, the duration between FFF and implant surgery, as well as the duration between implant surgery and uncovering were recorded. The use of lateral bone augmentation was also recorded. For each prosthesis, the date of prosthesis installation, type of prosthesis, type of retention, framework material, as well as the material of the opposing arch were recorded.

The outcomes of this study were: implant survival, implant success, prosthesis survival, and prosthetic success. Implant survival was assessed by whether the implant was explanted; while implant success was defined as the absence of surgical morbidity and any complication, including implant mobility, pain, parasthesia, and infection, as suggested by Albrektsson et al. (1986) Prosthesis survival was defined by the prosthesis remaining in situ; and prosthetic success was defined by the prosthesis being in situ without any modification (ten Bruggenkate et al., 1990; Tonetti et al., 2023). Patients were followed up regularly for recall.

For each full arch prosthesis, the marginal bone levels surrounding implants were recorded. Marginal bone levels (MBL) were measured from panoramic radiographs, and calibrated using the length and diameter of the nearest implant. MBL was defined as the average distance between the height of crestal bone and the top of the implant, between the mesial and distal aspects of each implant. Bone levels were measured first at the time of prosthesis insertion, and then at the most recent follow-up. Additionally, the lengths of distal extensions of each prosthesis were measured in a similar fashion.

2.4. Statistical analysis

Study outcomes including implant survival, implant success, prosthesis survival, and prosthetic success were evaluated with Kaplan-Meier (K-M) survival analysis, using the lifelines 0.26.0 software package in Python. Log-rank tests were used to test for significant differences between Kaplan-Meier survival curves.

Multivariate Cox regression, clustered using the robust variance estimator to account for multiple implants being placed in the same patient, was used to correlate study covariates with implant survival. Study covariates included: patient age at the time of implant surgery; gender; the presence of systemic conditions other than cancer; antibiotic premedication; smoking; diagnostic reason for tooth loss; irradiation and chemotherapy before and after implant surgery; antiresorptive treatment before or after implant surgery; implant length; implant diameter; implant location (anterior vs. posterior, maxilla vs. mandible); and the use of bone regenerative techniques.

To investigate the relationship between distal extension lengths and MBL, the Real Statistics software package in Microsoft Excel was used to perform linear regression and t tests. Furthermore, manifold learning using Uniform Manifold Approximation and Projection (UMAP) was applied to study covariates to identify potential local similarities within sub-populations of implants.

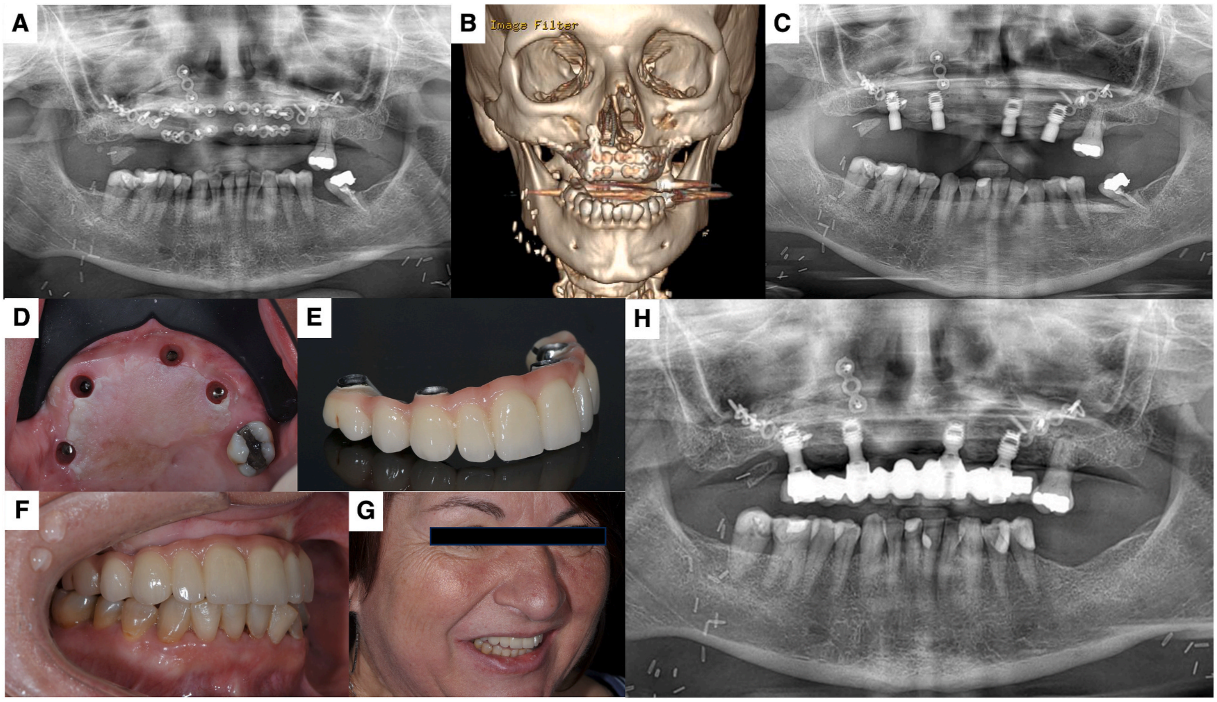

Fig. 2. Representative case of maxillary fibula flap. A) Panoramic radiograph and B) CT scan of a 52-year-old female patient with squamous cell carcinoma of the premaxilla and hard palate with revascularized fibula graft stabilized by several mini osteosynthesis plates and screws. C) Panoramic radiograph taken after implant surgery, after the placement of healing abutments. D) Photograph taken after the implants were uncovered, and before healing abutments were inserted. E) The prosthesis, which was fabricated using a FRC framework. F) Photograph of the prosthesis at the time of initial loading. G) Photograph and H) radiograph of the patient at the time of initial loading.

3. Results

3.1. Patient demographics

This study included 37 patients who received 146 implants in total. The patients were followed up for an average of 54.2 months (SD: 39.3 months). The patients' mean age at the time of implant surgery was 50.7 years old (SD: 16.8 years), with a maximum of 76.5 years, and a minimum of 15.2 years. All patients received antibiotic premedication prior to implant surgery, except for one patient who had allergies. Eleven patients were smokers, though not over the exclusion criterion of 20 cigarettes a day.

The diagnosis that indicated fibula graft treatment was a tumor in 32 patients, trauma in four patients, and extreme atrophy in one patient. Of the patients with tumors, thirteen received irradiation and ten received chemotherapy prior to implant surgery. Ten patients received irradiation after implant surgery due to recurrence of cancer, while none received chemotherapy after. Four patients received antiresorptive medications, though not at the time of implant surgery as per the exclusion criteria – three patients had histories of using oral bisphosphonates, four, ten, and seventeen years before implant surgery, respectively; while another patient started receiving denosumab injections one year after implant surgery. A detailed list of patient characteristics is provided in Table 1. The average implant length was 5.7 mm (SD: 1.3 mm), and detailed information on implant dimensions is provided in Table 2. The average duration between FFF surgery and implant surgery was 20.3 months (SD: 37.4 months). Out of the 146 implants, 33 implants were placed on the same day as FFF surgery, 88 implants were placed within the first year after FFF, and 117 implants were placed within the first two years.

3.2. Implants and prostheses succeed at high rates for over ten years

Kaplan-Meier survival analysis revealed that over a period of 161 months, the 146 implants that were placed in 37 patients survived at a rate of 86.9 % (Fig. 4A, blue line, 95 % confidence interval: 75.5–93.2 %.) The implant success rate for the same 161-month period was 80.2 % (Fig. 4A, orange line, 95 % confidence interval: 66.8–88.7 %.) Out of eleven implants that did not survive for the entire duration of the study, three were explanted at the time of uncovering, while the remainder were explanted after prosthesis insertion. We attributed the earlier failures to implant non-integration and the latter ones to peri-implantitis. Of the 135 implants that survived for the entire duration of the study, three developed periimplantitis, 0.3, 5.5, and 5.5 years after implant insertion, respectively. All three were treated successfully. One implant had to undergo additional surgery five months after implant insertion to remove a fibroma over the abutment, before it could be restored.

Additionally, Kaplan-Meier survival analysis revealed that all the implants that did not survive were placed in the mandible. When analyzed separately, the 128 implants placed in the mandibles of 33 patients had a 161-month survival rate of 85.8 % (Fig. 4B, orange line, 95 % confidence interval: 74.2–92.4 %), while the 18 implants placed in the maxillae of 6 patients had a 96-month survival rate of 100 % (Fig. 4B, blue line). The implants placed in maxillae have shorter follow-up durations compared to implants placed in mandibles, due to the fact that the earliest few cases in this study were all examples of mandibular rehabilitation. Due to the small number of implants placed in the maxilla, there was no significant difference between maxillary and mandibular implant survival according to the log-rank test ($P = .23$). Log-rank tests also revealed no significant differences in the survival of implants placed less than 20 months after FFF, compared to implants placed more than 20 months after FFF ($P = .25$). There was also no significant difference in the survival of implants placed on the same day as FFF surgery, compared to those that were placed later ($P = .94$).

For the 25 prostheses that were used to restore implants placed in FFF, the Kaplan-Meier survival rate at 156 months after prosthesis insertion was 90.0 % (Fig. 5, 95 % confidence interval: 65.6–97.4 %);

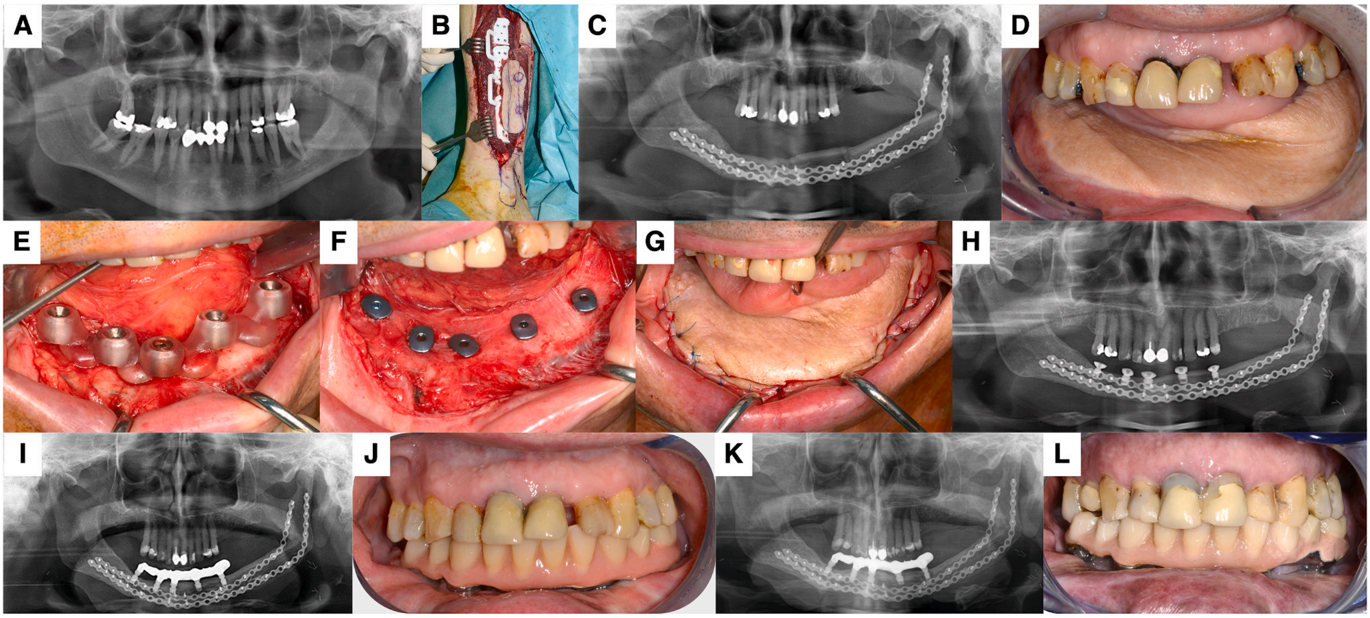

Fig. 3. Representative case of mandibular fibula flap. A) Preoperative radiograph depicting squamous cell carcinoma in the left mandible with osseous infiltration. B) Harvesting the fibula flap. C-D) Radiograph and intraoral photo depicting bony and soft tissue reconstruction of the mandible. E-F) Guided placement of five 4.0 × 5.0 mm implants and thin crestal temporary abutments. G) Refixed skin flap covering the implants. H) Postoperative panoramic radiographs depicting covered implants. I-J) Panoramic radiograph and intraoral photo depicting cemented prosthesis with metal framework on the day of insertion. K-L) Panoramic radiograph and intraoral photo taken four years after prosthesis insertion.

while the prosthetic success rate was 78.9 % (Fig. 5 and 95 % confidence interval: 56.2–90.7 %.) Additionally, 14 prostheses were planned but not installed, in three situations due to nonintegrated implants; in six situations due to loss of follow-up; and in five situations because the patient is pending treatment. No instances of prosthesis breakage or cracking were recorded, and all two events affecting prosthesis survival were caused by implant loss.

Four instances of prosthetic complications were recorded. Two prostheses, both of which were fixed partial dentures, loosened one and seventeen months after prosthesis insertion, respectively. In both cases, this complication was successfully treated by reinsertion. One crown was temporarily removed two months after insertion to facilitate treatment of newly emerged squamous cell carcinoma. One abutment, which was part of a fixed partial denture, fractured seven months after insertion, and was subsequently repaired.

3.3. Patient and implant related covariates are correlated with implant survival

In addition to Kaplan-Meier survival analyses, multivariate Cox regression was used to model the effects of study covariates on implant survival (Fig. 6, Table 3), with *P* values being calculated using a Wald test (Klein and Moeschberger, 2003). The results showed that for implants placed in FFF, those placed in the mandible had less favorable survival outcomes ($P = .003$) while those placed in the maxilla had more favorable survival outcomes ($P = .007$). Hypertension was also significantly correlated with increased risk of implant failure in fibula grafts ($P = .002$.) The use of lateral bone augmentation during implant surgery was also shown as a risk factor ($P = .01$), as well as age ($P = .008$.) Notably, patients who presented with tumors, also experienced increased rates of implant failure ($P = .007$).

Conversely, some covariates were correlated with improved outcomes of implants, in addition to the aforementioned covariate – maxillary location. Osteoporosis, as well as the consequent antiresorptive drug use before or after implant surgery, was correlated with improved outcomes ($P = .01$, $P = .008$, respectively), despite current ongoing antiresorptive use being an exclusion criteria that precludes FFF treatment. Additionally, improved outcomes were also associated with chemotherapy before implant placement ($P = .02$), as well as tooth loss from trauma ($P = .04$).

3.4. Manifold learning reveals profile of implants susceptible to failure and complications

While multivariate analysis can compute hazard ratios for each individual covariate, it cannot ascertain whether a covariate occurs in isolation or coexists with other risk factors. Therefore, nonlinear dimensionality reduction by UMAP was used to investigate whether implants experiencing failure and complications exhibit a specific risk factor profile. UMAP revealed a distinct sub-population of implants that were especially susceptible to complications and failure (Fig. 7A). Those implants have characteristically short follow-up durations consistent with survival analysis results, which indicated that most failed implants failed within the first three years after surgery (Fig. 7B). Overwhelmingly, this sub-population of implants susceptible to failure and complications fit into a homogenous patient profile combining several covariates – a patient over the age of 45, who presented with tooth loss due to tumor, received a fibula flap on the mandible, received radiation after implant surgery, and received a partial fixed dental prosthesis (Fig. 7C–I).

3.5. Longer distal extensions are correlated with peri-implant bone gain

Marginal bone levels of patients with full arch prostheses were regularly monitored using panoramic radiographs. Bone levels at the time of prosthesis delivery were compared with bone levels at the most recent follow-up to determine the average rate of MBL change. The mean duration of follow-up was 30.0 months (SD: 46.9 months.) Linear regression revealed a correlation between distal extension length and bone gain around the implant immediately adjacent to the extension, as shown by the high coefficient of determination ($R^2 = 0.74$). On average, each centimeter increase in the length of a distal extension was

Table 1
Patient characteristics.

Covariate		Number of patients
Patient gender	Male	19
	Female	18
Systemic conditions	Hypertension	7
	Hyperlipidemia	4
	Osteoporosis	4
	Hypothyroidism	3
	Diabetes mellitus	3
Smoking		11
Tooth loss diagnosis	Tumor (squamous cell carcinoma)	16
	Tumor (other carcinoma)	6
	Tumor (ameloblastoma)	5
	Tumor (giant cell)	2
	Tumor (multiple myeloma)	1
	Trauma (car)	2
	Trauma (gun)	2
	Extreme atrophy	1
Irradiation prior to implant surgery		13
Chemotherapy prior to implant surgery		10
Irradiation after implant surgery		10
Antiresorptive medication use		4

Table 2
Implant dimensions.

Implant length (mm)	Implant diameter (mm)	Number of implants
5	4	94
5	5	16
6	5	16
8	5	13
6	4	10
5	4.5	7
8	4.5	5
6.5	4	4
8	4	3
11	4	3
11	4.5	1
8	3	1

associated with a 0.15 mm/month increase in the rate of bone gain. In comparison, distal extension lengths were not correlated with MBL changes around mesial implants ($R^2 < 0.001$), nor with MBL changes around distal implants on the opposite side ($R^2 = 0.28$), as shown by the low coefficients of determination. Statistical comparison of regression slopes using a *t*-test revealed that MBL around implants adjacent to distal extensions has a significantly positive correlation with the lengths of distal extensions ($P = .003$) when compared with mesial implants (Fig. 8.)

4. Discussion

To evaluate the outcomes of short and extra-short plateau root form implants in fibula free flaps, this study evaluated the survival and success of implants and prostheses for a period of up to thirteen years (average of 54.2 months). This study also evaluated the effects of patient and clinical covariates on implant survival. The overall thirteen-year survival rate of implants in this study (86.9 %, 95 % confidence interval: 75.5–93.2 %) was similar to the reported survival rate of other implants at 36 months (92.2 %.)(Panchal et al., 2020) However, considering the ten year difference between the follow-up periods of the two studies, long-term follow-up of screw design implants placed in FFF is needed. Additionally, the thirteen-year success rate of implants in this study (80.2 %) suggested that the performance of locking-taper implants was on par with that of other implants, which had an annual failure rate of 0.02 based on a recent meta-analysis (95 % confidence interval: 0.01–0.03.)(Gangwani et al., 2022)

While other studies on implants placed in FFF reported similarly

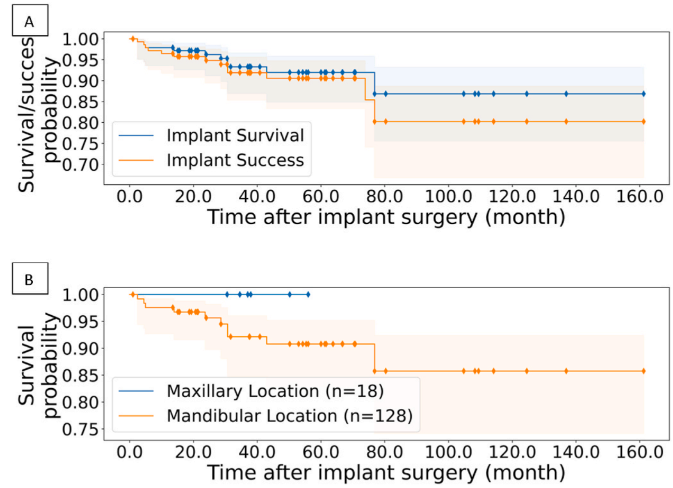

Fig. 4. Kaplan-Meier curves depicting the outcomes of implants placed in fibula grafts. Shaded regions represent 95 % confidence intervals. A) survival and success of implants placed in fibula grafts. The blue line represents implant survival, while the orane line represents implant success. B) survival of implants placed in the maxilla and implants placed in the mandible. The blue line represents implants placed in the maxilla, while the orange line represents implants placed in the mandible. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

desirable implant outcomes, those that reported prosthetic outcomes reported much lower numbers such as 42.9 % in a study of 56 patients and 20 % in a case series, supposedly due to the difficulty of restoring implants placed in such grafts (Anne-Gaëlle et al., 2011; Smolka et al., 2008). In contrast, prostheses in this study presented with relatively high long-term survival and success rates (90.0 % and 78.9 % at 13 years, respectively.) This drastic difference in the rate of prosthetic success may be due to the locking-taper implant's ability to support prostheses in a variety of challenging clinical scenarios, such as cases where discrepancies in the heights of grafted and nongrafted regions lead to high crown-to-implant ratios (Urdaneta et al., 2010). This may be due to several advantages conferred by locking-taper implants: a bacterially sealed implant-abutment interface (Dibart et al., 2005); a short implant design that enables versatile placement while dissipating forces over a large surface area (Chou et al., 2010); and a unique healing mechanism that results in the formation of compact, haversian-like bone (Coelho et al., 2015).

In addition to Kaplan-Meier survival analysis, this study also used multivariate Cox regression to model the effects of study covariates on implant survival. Multivariate analysis revealed that implants placed in the maxilla had slightly higher survival outcomes over those placed in

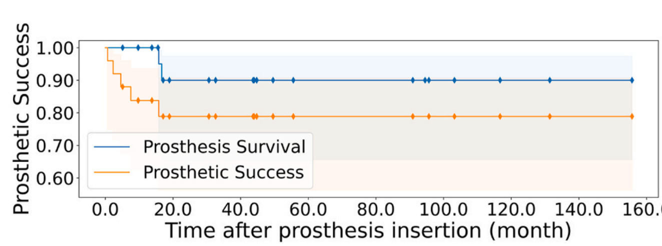

Fig. 5. Kaplan-Meier curves depicting the outcomes of prostheses used to restore implants placed in fibula grafts. Shaded regions represent 95 % confidence intervals. The blue line depicts the probability of prosthesis survival, i.e. the ability of prostheses to remain in situ without failing; while the orange line depicts prosthetic success, a statistic that accounts for not only failed prostheses but also prosthetic complications. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the mandible. Significant differences in Kaplan-Meier survival may be found in larger sample sizes, potentially because the revascularized fibula bone is the same between both arches, but the static load of the maxilla may be more advantageous to survival compared to the dynamic loading nature of the mandible. Also, the effect of mandibular deformation, which occurs during mouth opening (Thongpoung et al., 2022), on the survival of implants placed in FFF is yet to be elucidated. Furthermore, tooth loss from tumor was correlated with reduced implant outcomes, while tooth loss from trauma was correlated with improved implant outcomes.

Multivariate analysis also revealed several other covariates that were correlated with less favorable survival outcomes: patient age, hypertension, and lateral augmentation. Of those factors, advanced patient age has been correlated with reduced marginal bone levels in previous studies involving the same implant system, and could be due to age-related bone loss (Cheng et al., 2022; Cheng et al., 2023); hypertension is traditionally not considered a risk factor in dental implant therapy.

Multivariate analysis also identified some covariates that were correlated with improved outcomes of implants. Notably, osteoporosis and antiresorptive drug use before or after surgery were significantly correlated with improved outcomes – this phenomenon has been previously reported in the same implant system, even though it runs contrary to the general recommendation that even oral antiresorptive drug use be generically treated as an absolute contraindication to dental implant therapy (Cheng et al., 2022b). Additionally, receiving chemotherapy before implant placement was also correlated with improved outcomes, perhaps due to the fact that it is associated with less usage of radiation therapy after implant surgery.

UMAP dimensionality reduction revealed that most implants that developed complications or failed exhibited a similar profile that combined many of the risk factors identified in multivariate analysis. This suggests that the hazards brought on by those risk factors do not act in isolation. Rather, they co-occur in a specific patient population, where significant lowering of implant success rates is observed with the concurrence of multiple risk factors. Outside this cluster, implant complications are extremely rare. As a result of this finding suggests, significant caution should be exercised when treating patients who match this high-risk profile. A comprehensive retrospective study followed up, for a mean 4.9 years, 161 implants and prostheses placed in FFF of 44 patients has shown that tobacco use and irradiation of the FFF were significant predictors for implant failure (Lodders et al., 2021). Authors have also evaluated patients satisfaction, although no detail was provided about the method used.

Table 3
Results of multivariate Cox regression on implant survival.

Covariate	Coefficient	lower 95 % CI	upper 95 % CI	z	*P*
Maxillary location**	−0.29	−0.50	−0.08	−2.70	0.007
Antiresorptive use**	−0.32	−0.56	−0.09	−2.66	0.008
Osteoporosis*	−0.32	−0.58	−0.07	−2.47	0.01
Chemotherapy before implant surgery*	−0.63	−1.17	−0.09	−2.27	0.02
Tooth loss from trauma*	−0.17	−0.34	0.00	−2.01	0.04
Posterior location	−0.14	−0.45	0.17	−0.89	0.37
Antibiotic premedication	−0.03	−0.49	0.43	−0.13	0.90
Smoking	0.01	−0.37	0.38	0.04	0.97
Gender (M:1; F:0)	0.06	−0.31	0.42	0.30	0.77
Anterior location	0.14	−0.17	0.45	0.89	0.37
Irradiation after implant surgery	0.14	−0.11	0.39	1.12	0.26
Diabetes Mellitus	0.41	−0.27	1.08	1.18	0.24
Irradiation before implant surgery	0.20	−0.09	0.50	1.38	0.17
Hyperlipidemia	0.53	−0.16	1.22	1.50	0.13
Hypothyroidism*	0.64	−0.19	1.47	1.51	0.13
Lateral augmentation*	0.68	0.16	1.21	2.55	0.01
Age**	0.56	0.14	0.98	2.63	0.008
Tooth loss from tumor**	0.26	0.07	0.45	2.69	0.007
Mandibular location**	0.32	0.10	0.53	2.93	0.003
Hypertension**	0.61	0.23	0.99	3.16	0.002

One asterisk indicates $P < .05$; two asterisks indicate $P < .01$.

Interestingly, UMAP also revealed that patients with osteoporosis and patients, who had received antiresorptive treatment, do not cluster together. Rather, they are localized into distinct cohorts, with patients, who received antiresorptive treatment but did not have osteoporosis, exhibiting a profile similar to that of the high-risk patient cluster but still demonstrating high success rates. This echoes the multivariate analysis result that antiresorptive treatment may have a protective effect.

Linear regression revealed a correlation between longer distal extension lengths and bone gain – a correlation that is unique to the implant immediately adjacent to the extension. This relationship, which has been previously demonstrated in FRC prostheses supported by three locking-taper implants (Cheng et al., 2023), suggests that the functional loading forces distributed by locking-taper implants adjacent to distal extensions may contribute to local bone gain. The results of this study

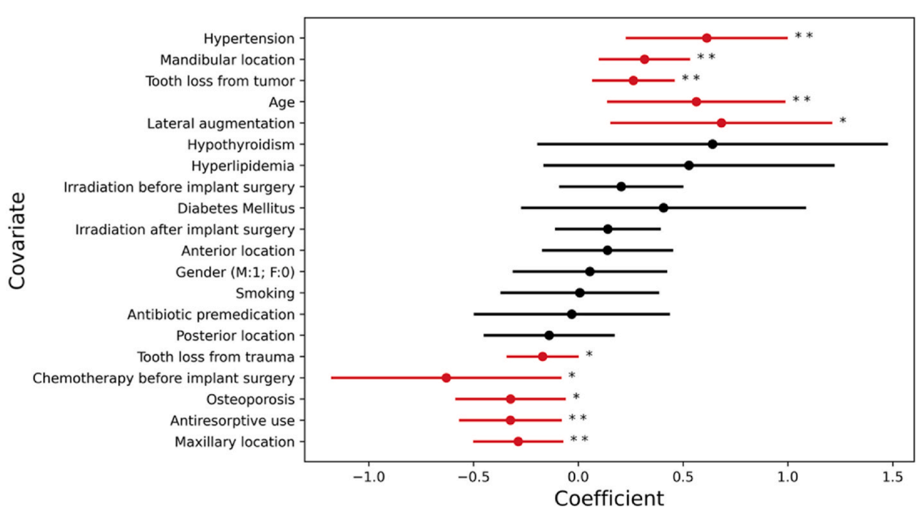

Fig. 6. Hazard plot depicting the Cox regression coefficients of study covariates. Solid lines represent 95 % confidence intervals. Red coloring and an asterisk indicates $P < .05$; two asterisks indicate $P < .01$. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

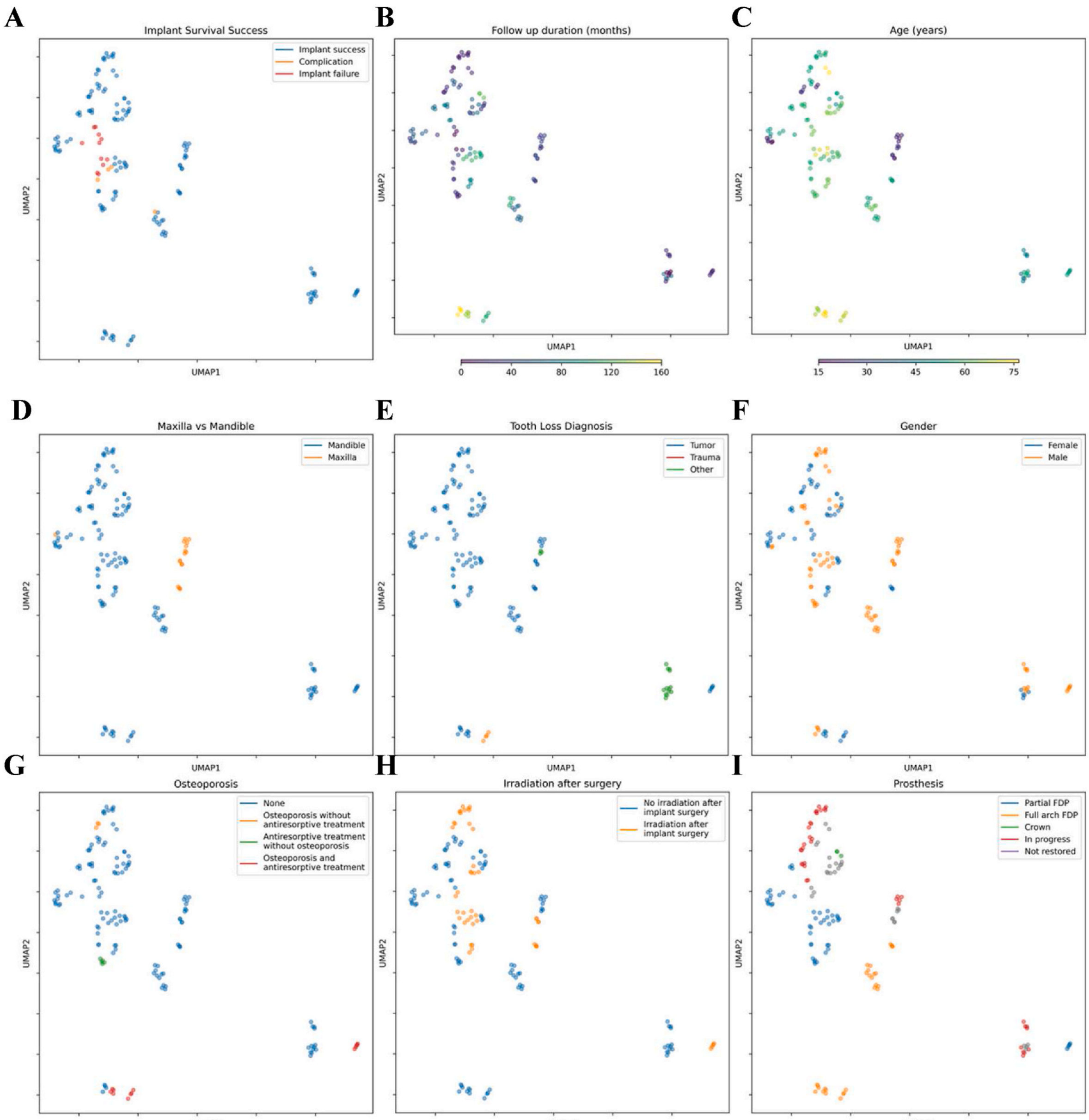

Fig. 7. UMAP nonlinear dimensionality reduction of study covariates. The values of the following parameters were plotted in UMAP space: A) implant outcomes, B) follow-up duration, C) patient age, D) maxillary versus mandibular location, E) tooth loss diagnosis, F) gender, G) osteoporosis and antiresorptive use, H) irradiation after surgery, I) prosthesis.

demonstrate that this bone gain effect applies to grafted fibula bone in addition to native bone (Cheng et al., 2023).

A limitation of the current study is that no specific patient-reported outcome measures were used. A study of patients reconstructed with implants and prostheses placed in FFF showed that out of 33 patients completing the questionnaires, 76 % reported that they could eat hard or soft diets without limitations, 73 % could speak intelligibly, and 23.5 % rated the esthetic result as excellent, 67.7 % evaluated as good, whereas the remaining rated as fair or poor (Attia et al., 2019). In general, reconstructed patients go through a learning curve process for acquainting to chewing, speeching, and other functional activities, while most seem content with the cosmetic presence of the surgical/-prosthetic reconstruction. It is paramount that validated success criteria be developed for the assessment of functional, esthetic and patient-reported outcome measures in dental rehabilitation of patients reconstructed with FFFs due to trauma or head and neck cancer.

Other limitations of this study include its retrospective design, which may lead to selection bias. The small number of patients enrolled in this study also led to some study covariates, such as antiresorptive drug use, not having sufficient statistical power. This study was also limited in that its outcome measures did not include measurements of peri-implant bone height or volume, such that the success of the fibula graft itself could not be measured. The study is also limited to the described two-phase protocol and cannot be extrapolated to primary implant placement. although the promising results warrant further exploration of using short and extra short implants for primary placement in FFF. Lastly, the study included only locking-taper implants, and as a result a direct comparison between locking-taper implants and other implants was not possible. Despite those limitations, this study demonstrated that plateau-root form implants demonstrated high survival and success rates when placed in fibula grafts, and provide a viable solution for the restoration of patients receiving those grafts.

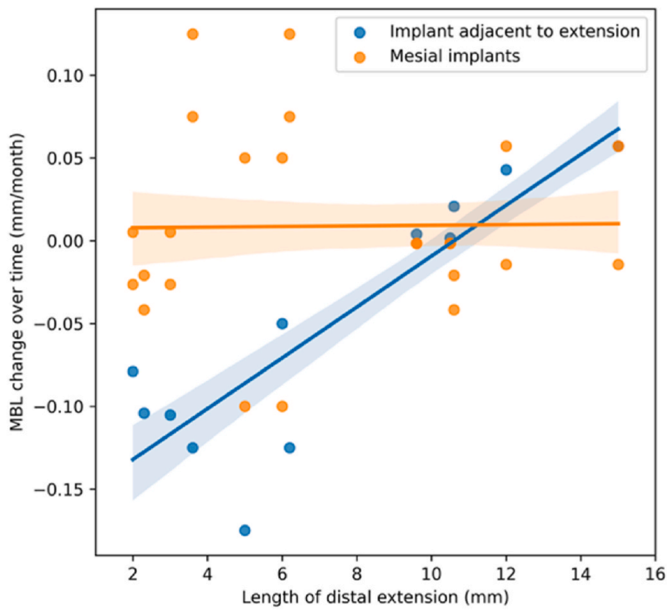

Fig. 8. Linear regression of MBL change rate versus lengths of distal extensions. Shaded regions represent 95 % confidence intervals.

5. Conclusion

Plateau-root form implants placed in fibula free flaps resulted in good long-term survival and success rates for both implants and prostheses. Factors that can negatively affect implant survival include placement in the mandible, hypertension, lateral augmentation, patient age, and tooth loss from tumor; while factors that can positively influence implant survival include maxillary placement, osteoporosis and history of antiresorptive drug use, chemotherapy before implant surgery, and tooth loss due to trauma. Patients who experienced implant complications and failure fit into a profile characterized by the co-occurrence of several higher risk factors. Overall, plateau-root form implants provide a viable solution for patients receiving either maxillary or mandibular fibula free flaps.

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Declaration of competing interest

The authors have no conflict of interest to declare.

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