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A retrospective comparison of the survival of vital teeth adjacent to single, bounded edentulous spaces rehabilitated using implant-supported, resin-bonded, and conventional fixed dental prostheses

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ABSTRACT

Objectives: In this study, we aimed to compare the long-term survival of vital teeth adjacent to bounded edentulous spaces rehabilitated using an implant-supported prosthesis (ISP), a resin-bonded fixed partial denture (RBFPD), or a conventional fixed partial denture (CFPD). The risk factors for complications in teeth adjacent to the edentulous space (TAES) were also investigated.

Methods: We followed-up a consecutive series of 514 patients who underwent rehabilitation of a single bounded edentulous space with vital TAES (ISP: 103; RBFPD: 216; and CFPD: 195) from 2008 to 2017. Cumulative survival rates of prosthesis and TAES, and complication-free rates of TAES, were evaluated using the Kaplan–Meier analysis and log-rank test. Risk factors were evaluated using a Cox proportional hazards model.

Results: Cumulative complication-free rates of TAES showed no significant differences among the three groups. The cumulative survival rate of TAES in CFPD was significantly lower than that of ISP ($p = 0.037$); no significant differences were observed between ISP and RBFPD ($p = 0.513$), and RBFPD and CFPD ($p = 0.076$). Older age ($p = 0.027$) was the only independent significant risk factor for complications in TAES. Installation of CFPD ($p = 0.019$), ceramic prosthesis in edentulous space ($p = 0.026$), and deeper periodontal probing depth ($p = 0.018$) of TAES were significant risk factors for non-surviving TAES.

Conclusions: Rehabilitating a single bounded edentulous space with CFPD could increase the risk for TAES loss compared with ISP. Risk of TAES loss remained similar between ISP and RBFPD, which can minimize the loss of coronal tooth structure during tooth preparation.

Clinical Significance: Teeth adjacent to edentulous space show equivalent longevity when rehabilitating a single bounded edentulous space with resin-bonded fixed partial dentures or single standing implant-supported prosthesis, at least 10 years post-installation.

1. Introduction

When rehabilitating partial edentulism, consideration must be given to prevent further loss of remaining teeth, and provide functional and esthetic recovery. Fixed partial dentures are preferred when replacing a single bounded edentulous space, as they generally acquire a higher degree of patient satisfaction in terms of function, comfort, and esthetics. However, the use of adjacent teeth as abutments when rehabilitating the edentulous space with conventional fixed partial dentures (CFPD) can often cause biological complications [1,2]. Owing to this limitation, single-tooth implant restorations have been widely used in recent clinical settings. This treatment modality can solve the problems caused by CFPD, as it provides a tooth replacement without relying on the surrounding dentition for support [3,4]. However, long-term follow-up of teeth adjacent to an edentulous space (TAES) treated with CFPD, compared to the implant-supported prosthesis (ISP), is extremely rare. Yamazaki *et al.* reported that teeth adjacent to ISPs demonstrate fewer complications than teeth serving as abutments for CFPDs. However, the results of the multivariate analysis indicated that loss of pulpal vitality in TAES was a significant risk factor for tooth complications, whereas the treatment modality was not [5]. Indeed, when the coronal tooth structure of the teeth adjacent to the bounded edentulous area is destroyed and pulpal vitality is lost, patients may opt for replacement with CFPDs. These clinical phenomena may yield a baseline bias in

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prosthesis selection and affect the treatment outcomes. Direct comparisons of ISP and CFPD are of great interest when rehabilitating an edentulous space in which the adjacent teeth still contain vital dental pulp.

As with ISP, resin-bonded fixed partial dentures (RBFPD) have been developed as a minimally invasive treatment option for the replacement of bounded edentulous space. This type of prosthesis is generally recommended in cases where the abutment teeth are healthy vital teeth. The major advantages of RBFPDs are minimal loss of coronal tooth structure during tooth preparation, reduction of pulpal morbidity, and employment of supragingival margins. Thus, compared with CFPDs, RBFPD are thought to prevent biological complications such as caries and periodontal lesions, and preserve the longevity of abutment teeth. However, no study has compared ISP with RBFPD in terms of the long-term prognosis of TAES.

Hence, the objective of this study was to investigate the long-term survival and complication-free rates of TAES in cases rehabilitated using ISP, RBFPD, and CFPD. Because the vitality of dental pulp significantly affects the prognosis, the study targets were restricted to cases where both adjacent teeth contained vital dental pulp. Additionally, we compared the survival rates of each prosthesis during the follow-up period and investigated the risk factors for complications and survival of TAES and the prostheses. The null hypothesis tested in this study is that there is no difference between the three different prostheses on either the long-term consequences of vital TAES or on the survival of the each of the prostheses.

2. Materials and methods

This retrospective clinical study protocol was reviewed and approved by the Ethics Committee of the Okayama University Graduate School of Medicine, Dentistry, and Pharmaceutical Sciences and Okayama University Hospital (K2009-002), in accordance with the Declaration of Helsinki.

2.1. Study population

The study samples were consecutively selected from patients who received prosthodontic rehabilitation of a single bounded edentulous space between January 2008 and December 2017 at the Department of Fixed Prosthodontics, at our hospital.

Before treatment initiation, the chief doctor provided the risks and benefits, and necessary information on the cost and duration for each treatment modality, including that of removable partial dentures, and each patient selected a prosthesis for their edentulous space. All prosthodontic treatments were provided by the dentists of our department. Inclusion criteria comprised: 1) patients aged 20−80 years at the time of prosthesis installation; 2) bounded edentulous space replaced with one of the following prostheses: ISP, RBFPD, or CFPD; and 3) vital dental pulp in both TAES. RBFPD were designed as previously described [6]. Exclusion criteria comprised: 1) bounded edentulous space replaced with removable partial dentures; 2) patients who did not visit the hospital after prosthesis installation; and 3) cases in which no preoperative X-ray images of the edentulous space were taken, where the pulp vitality of both TAES could not be determined.

2.2. Baseline data acquisition

Using the patient's medical record, one investigator (SO) obtained the baseline characteristics of each patient at installation of the prosthesis, and another investigator (KM) checked the relevance of the identified data. The following data were abstracted: sex, age at the time of prosthesis installation, location of edentulous space (anterior or posterior), region (maxilla or mandible), number of teeth present, periodontal probing depth of both TAES, and the materials used for the edentulous space. In our hospital, six-point measurements of the periodontal probing depth in the remaining teeth of each patient are routinely performed and recorded by periodontists. In this study, we regarded the maximum value (deepest pocket depth) in both TAES recorded at the most recent exam before prosthesis installation as the representative periodontal pocket depth in each case. The materials used for restoration of the edentulous space, including veneers or core material (hard composite resin or ceramics) of the pontic in the cases of RBFPD/CFPD and the supra-structure in the case of ISP, was recorded. In the case where metal or ceramic was used as the core material without veneers, we recorded it as metal or ceramic, respectively.

2.3. Follow-up and endpoints

One investigator (SO) assessed the conditions of the prostheses and the abutment teeth for the RBFPD/CFPD or the teeth adjacent to the ISP from the patient medical records. As with baseline data, another investigator (KM) rechecked the relevance of the prosthesis and the target teeth. The follow-up period started from the date on which the RBFPD/CFPD was luted or the definitive ISP was installed, and was completed on November 2, 2020. Success was defined as the prostheses and TAES remaining *in situ* and not experiencing the following endpoints (Fig. 1). Three endpoints were established in this study: 1) loss of prosthesis, 2) complications in abutment teeth of RBFPD/CFPD or teeth adjacent to the ISP, and 3) loss of abutment teeth of RBFPD/CFPD or teeth adjacent to the ISP. Loss of FPD was defined as the impossible condition of rebonding after debonding (e.g., due to severe caries of abutment teeth or ill-fitting FPD) or cases that required FPD removal along with abutment tooth extraction due to periodontal lesion or tooth fracture. Loss of ISP was defined as the loss of the implant body. Complications in abutment teeth or teeth adjacent to the ISP included caries (regardless of the presence or absence of pulpitis), tooth fracture, and tooth extraction due to periodontal lesions or other reasons. We regarded a tooth extraction as the loss of abutment teeth or teeth adjacent to the ISP. In addition to the cases that experienced extraction of TAES as a first complication, those that experienced complications other than tooth extraction were followed-up further. We then abstracted the cases if they underwent the extraction of TAES due to recurrent tooth complications. Thus, we abstracted all cases that experienced non-survival of TAES during the follow-up period. In cases with complications and non-survival of TAES, the type of endpoints and date of onset were recorded. Patients who did not return to the hospital within one year prior to the end of the study were regarded as censored cases, in which the complication-free period was established from the date of final treatment completion to the last follow-up visit.

2.4. Statistical analysis

Baseline characteristics in each group were compared using the Kruskal−Wallis test or chi-square test, as appropriate. We calculated the cumulative complication-free rates of the TAES in each group, and the cumulative survival rates of the prosthesis and TAES using the Kaplan−Meier analysis. The log-rank test was utilized to compare the complication-free and survival curves among the three groups. The Mann−Whitney U test was used to compare each predictor between the presence or absence of the aforementioned primary outcomes. To determine the risk factors for complications in TAES, and loss of prosthesis and TAES, we used the Cox proportional hazard model. The following baseline factors were submitted as predictors: type of prosthesis, the patient's sex and age at the time of prosthesis installation, location and region of edentulous space, the material used for the edentulous space, periodontal probing depth, and the number of teeth present. The significance level was set at $p < 0.05$ for each statistic. All the statistical analyses were carried out using IBM SPSS Statistics (Version 25.0, Armonk, NY: IBM Corp.).

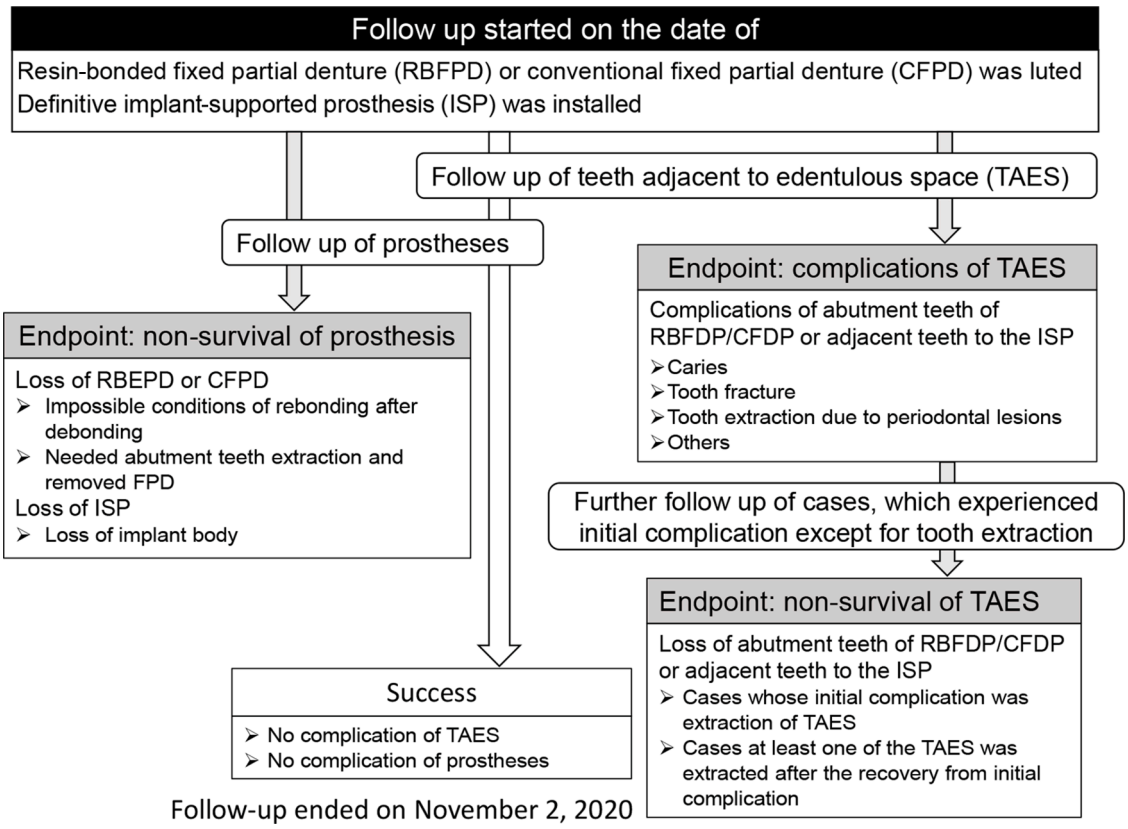


Fig. 1. Follow-up procedures of the study samples and the definitions of complications and non-survival of prostheses and teeth adjacent to edentulous space.

3. Results

3.1. Case flow

In total, 520 target prostheses were installed in 462 patients between 2008 and 2017. However, six cases were excluded for loss to recall just after the installation. Thus, a total of 514 cases (IPS: 103; RBFDP: 216; CFDP: 195) in 456 patients were included for further analysis (Fig. 2).

3.2. Baseline characteristics

Table 1 shows the comparisons of baseline characteristics in each group. There were no significant proportional differences among the three groups in terms of the patient's sex, location of edentulous space, and periodontal probing depth. However, the Kruskal–Wallis test indicated significant differences in the participants' median age among the groups at the time of prosthesis installation ($p < 0.001$). Additionally, there were significant proportional differences in the region of edentulous space ($p = 0.026$), the number of teeth present ($p < 0.001$), and in the materials used for the prosthesis in the edentulous space ($p < 0.001$).

3.3. Survival of prostheses

During the follow-up period, 74 prostheses (one ISP case, 42 RBFPD cases, and 31 CFPD cases) were lost due to the impossibility of rebonding from poor fit after debonding ($n = 26$), removal of FPDs due to secondary caries of abutment teeth ($n = 15$), abutment tooth extraction ($n = 23$), pulpitis ($n = 6$), the complaint of discomfort ($n = 2$), loss of occlusal contact ($n = 1$), and removal of the implant body ($n = 1$) (Table 2). There was a significant statistical proportional difference among the three types of prostheses ($p < 0.001$). Additionally, significant proportional differences were observed in the location of the edentulous space ($p = 0.025$) and the materials used for the prosthesis in the edentulous space ($p < 0.001$).

3.4. Complications of TAES

During the follow-up period, 110 cases experienced complications in TAES (Table 3). The complications included caries (87 cases), tooth crown fracture (3 cases), tooth extraction due to a periodontal lesion (19 cases), and one other case that required the removal of FPD and pulpectomy due to severe pulpitis immediately after installation of the prosthesis. There were significant differences in the participants' ages ($p = 0.005$) and the number of teeth present ($p = 0.029$) at the time of prosthesis installation between the groups, relative to the presence or absence of complications in TAES (Table 3). We also observed significant proportional differences in the participants' sex ($p = 0.045$) and location of edentulous space ($p = 0.033$) between the two groups.

3.5. Survival of TAES

Sixteen cases finally underwent extraction due to recurrent tooth complications (e.g., caries) after recovery from initial complications during the follow-up period. After adding the aforementioned 19 cases wherein the initial complications included tooth extraction due to periodontal lesions, a total of 35 cases underwent extraction of TAES (Table 4). There was a significant proportional difference in the participants' sex between the two groups relative to the survival or non-survival of TAES ($p = 0.022$) during the follow-up period (Table 4). In addition, we observed significant differences in the number of teeth present between the two groups ($p = 0.018$).

3.6. Kaplan–Meier estimates of complication-free and survival

Fig. 3 shows the Kaplan–Meier survival curves of the prostheses in

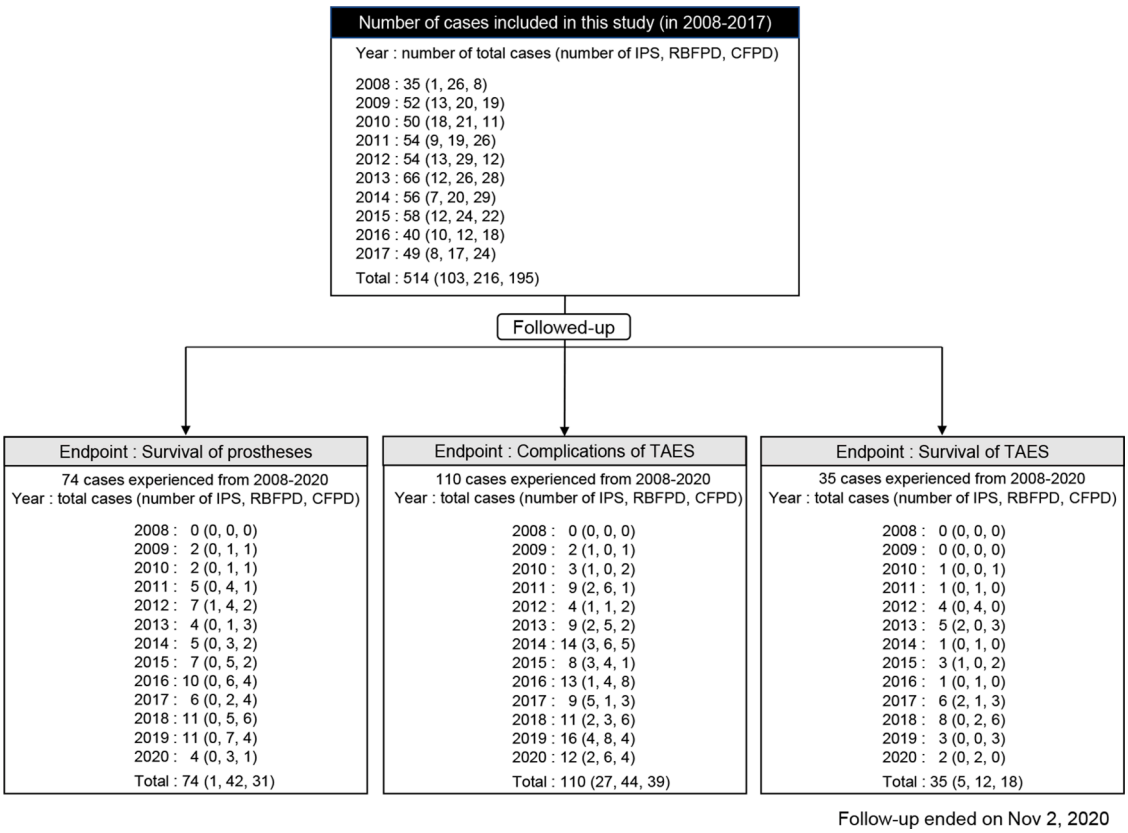


Fig. 2. Case flow of present study.
RBFPD, resin-bonded fixed partial dentures; CFPD, conventional fixed partial dentures; ISP, implant-supported prosthesis; TAES, teeth adjacent to an edentulous space.

Table 1
Baseline comparisons among three groups at the installation of prostheses.

	ISP (n = 103)	RBFPD (n = 216)	CFPD (n = 195)	p-value
Age (years: mean ± SD)	51.94 ± 16.07	55.87 ± 15.10	61.22 ± 11.99	**<0.001**#
Sex (male/female)	47/56	93/123	74/121	0.378*
Location of edentulous space (anterior/posterior)	13/90	39/177	45/150	0.083*
Region of edentulous space (maxilla/mandible)	43/60	124/93	108/87	**0.026***
Number of teeth present (mean ± SD)	25.30 ± 3.06	24.60 ± 3.74	23.39 ± 4.06	**<0.001**#
Deepest probing depth (mm: mean ± SD)	3.24 ± 1.15	3.43 ± 1.21	3.37 ± 1.09	0.445#
Materials used for Prosthesis (metal/composite resin/ceramic)	6/5/92	174/26/16	130/28/37	**<0.001***

ISP: implant-supported prosthesis; RBFPD: resin-bonded fixed partial denture; CFPD: conventional fixed partial denture; n: number of cases; SD: standard deviation.
Statistically significant p-values are indicated with bold letters (#: Kruscal-Wallis test, *: Chi-square test).

Table 2
Results of the univariate statistical analyses comparing each factor between survival and non-survival of the prostheses during the follow-up period.

	Non-survival (n = 74)	Survival (n = 440)	p-value
Type of prosthesis (ISP/RBFPD/CFPD)	1/42/31	102/174/164	**<0.001***
Age (years: mean ± SD)	60.75 ± 10.08	56.49 ± 15.15	0.145#
Sex (male/female)	35/39	179/261	0.286*
Location of edentulous space (anterior/posterior)	7/67	90/350	**0.025***
Region of edentulous space (maxilla/mandible)	39/35	236/204	0.882*
Number of teeth present (mean ± SD)	23.78 ± 3.69	24.36 ± 3.81	0.140#
Deepest probing depth (mm: mean ± SD)	3.60 ± 1.22	3.33 ± 1.14	0.052#
Materials used for prosthesis (metal/composite resin/ceramic)	59/6/9	251/53/136	**<0.001***

ISP: implant-supported prosthesis; RBFPD: resin-bonded fixed partial denture; CFPD: conventional fixed partial denture; n: number of cases; SD: standard deviation.
Statistically significant p-values are indicated with bold letters (#: Mann-Whitney U test, *: Chi-square test).

each group. The 10-year cumulative survival rates of each prosthesis were 99.0% (IPS), 61.5% (RBFPD), and 68.2% (CFPD). The results of the Kaplan−Meier analysis followed by the log-rank test indicated that the cumulative survival rates of ISP were significantly higher than that of the other two groups ($p < 0.001$: ISP vs. RFPD; $p < 0.001$: ISP vs. CFPD). However, we observed no significant difference in the cumulative survival rates between RBFPD and CFPD ($p = 0.069$). The Kaplan−Meier complication-free curves of TAES are shown in Fig. 4. The 10-year cumulative complication-free rates of the TAES in each group were 54.6% (ISP), 56.6% (RBFPD), and 61.3% (CFPD). The estimated complication-free rates among each group showed no significant differences. In contrast, when the complication in TAES was specified to tooth extraction, namely survival rate of target teeth, the 10-year cumulative survival rates of the TAES in each group were 92.6% (ISP), 89.0% (RBFPD), and 75.9% (CFPD) (Fig. 5). The cumulative survival rate of CFPD was significantly lower than that of ISP ($p = 0.037$). In contrast, we observed

Table 3
Results of the univariate statistical analyses to compare each factor between the presence or absence of the complications of teeth adjacent to edentulous space during the follow-up period.

	Presence (n = 110)	Absence (n = 404)	p-value
Type of prosthesis (ISP/RBFPD/CFPD)	27/44/39	76/172/156	0.410*
Age (years: mean ± SD)	61.22 ± 11.51	55.99 ± 15.18	**0.005**#
Sex (male/female)	55/55	159/245	**0.045***
Location of edentulous space (anterior/posterior)	13/97	84/320	**0.033***
Region of edentulous space (maxilla/mandible)	52/58	223/181	0.140*
Number of teeth present (mean ± SD)	23.71 ± 3.75	24.44 ± 3.81	**0.029**#
Deepest probing depth (mm: mean ± SD)	3.52 ± 1.17	3.33 ± 1.15	0.083#
Materials used for prosthesis (metal/composite resin/ceramic)	70/13/27	240/46/118	0.626*

ISP: implant-supported prosthesis; RBFPD: resin-bonded fixed partial denture; CFPD: conventional fixed partial denture; n: number of cases; SD: standard deviation.
Statistically significant p-values are indicated with bold letters (#: Mann-Whitney U test, *: Chi-square test).

Table 4
Results of the univariate statistical analyses to compare each factor between the survival or non-survival of teeth adjacent to edentulous space during the follow-up period.

	Non-survival (n = 35)	Survival (n = 479)	p-value
Type of prosthesis (ISP/RBFPD/CFPD)	5/12/18	98/204/177	0.228*
Age (years: mean ± SD)	62.74 ± 8.61	56.70 ± 14.89	0.072#
Sex (male/female)	21/14	193/286	**0.022***
Location of edentulous space (anterior/posterior)	5/30	92/387	0.473*
Region of edentulous space (maxilla/mandible)	21/14	254/225	0.425*
Number of teeth present (mean ± SD)	22.77 ± 4.31	24.39 ± 3.74	**0.018**#
Deepest probing depth (mm: mean ± SD)	3.80 ± 1.29	3.34 ± 1.14	0.054#
Materials used for prosthesis (metal/composite resin/ceramic)	22/5/8	288/54/137	0.712*

ISP: implant-supported prosthesis; RBFPD: resin-bonded fixed partial denture; CFPD: conventional fixed partial denture; n: number of cases; SD: standard deviation.
Statistically significant p-values are indicated with bold letters (#: Mann-Whitney U test, *: Chi-square test).

no significant difference between IPS and RBFPD ($p = 0.513$), and RBFPD and CFPD ($p = 0.076$).

3.7. Risk factors for complications and non-survival

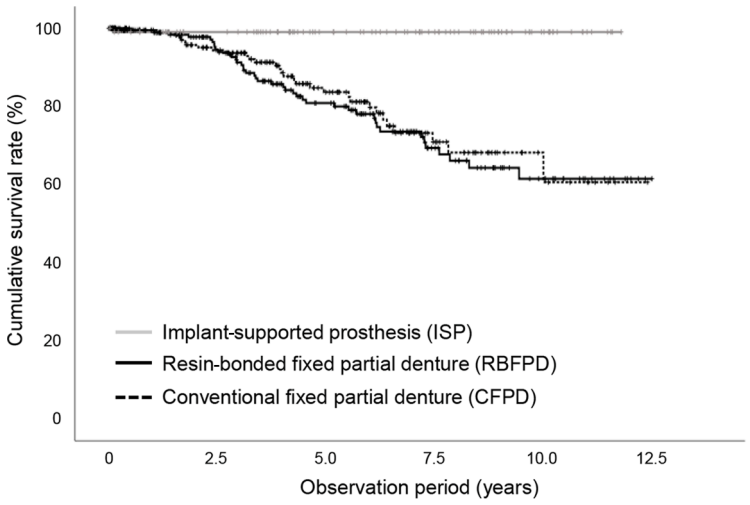
Table 5 indicates the results of the Cox proportional hazard regression analysis, used to determine the significant risk factors for the non-survival of prostheses. Compared with ISP, installation of RBFPD ($p = 0.001$) and CFPD ($p = 0.002$) were observed to be significant independent risk factors. Further, the univariate analysis indicated that there were proportional differences in the location of the edentulous space and the materials used for the edentulous space rehabilitation (Table 2); however, these were confounding factors and not significant risk factors. With regard to the complications in TAES (Table 6), older age at the time of prosthesis installation was the only independent significant risk factor ($p = 0.042$), and several factors that showed significant differences between the presence and absence of teeth complications (Table 3) were not significant risk factors. Table 7 shows the results of the Cox proportion hazard regression analysis, which was used to assess the significant risk factors for loss of TAES. Installation of CFPD ($p = 0.019$) relative to ISP, ceramic prosthesis in the edentulous space ($p = 0.026$), and deeper periodontal probing depth ($p = 0.018$) were observed to be significant risk factors for loss of TAES. Other factors, which indicated significant differences between survival and non-survival of TAES (Table 4), were not significant risk factors in this analysis.

4. Discussion

To the best of our knowledge, this is the first study to directly compare the long-term outcomes of the teeth adjacent to a single bounded edentulism and that of three different types of prostheses—ISP, CFPD and RBFPD—used for rehabilitation of the edentulous spaces, and only those cases in which the adjacent teeth contained vital dental pulp were included in the study. As a previous study indicated that non-vitality of dental pulp was a significant risk factor for complications in TAES [5], the samples in this study were restricted to cases in which both TAES contained vital dental pulp. In this study setting, CFPD cases were added to the study samples and compared with the other prostheses.

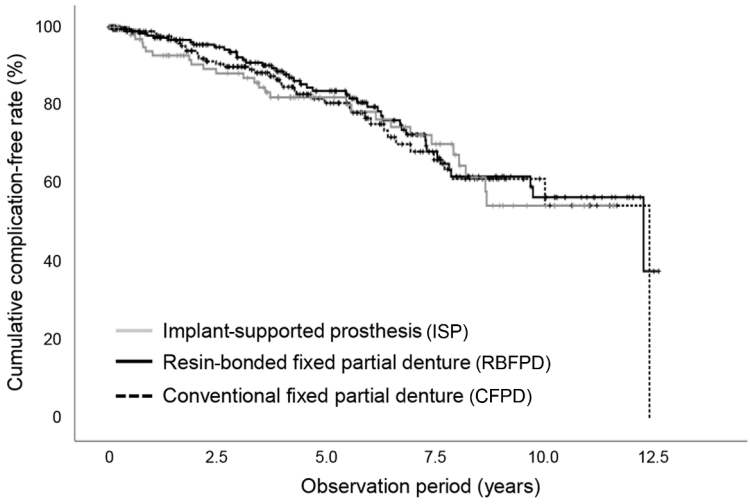
Regarding the survival of prostheses, the 10-year cumulative survival rates were 99.0% (ISP), 61.5% (RBFPD), and 68.2% (CFPD). Kaplan−Meier analysis followed by the log-rank test revealed that the cumulative survival rates of ISP were significantly higher than that of the other two groups. The extremely high survival rate of ISP corresponded with the results of Priest's study [3], which showed a 10-year survival rate of 97.4%. Our findings were also consistent with the results of previous meta-analyses that have shown high survival rates among implant-supported single crowns [7,8]. In addition, previous studies have reported that FPDs had lower survival rates than ISPs [9–11]. Regarding RBFPD and CFPD, there was no significant difference in survival rate in this study. The survival rates of FPDs can be affected by various factors such as restoration design, surface treatment methods, luting agents, and the number of missing and abutment teeth [12,13]. Biological conditions of abutment teeth (e.g., periodontal conditions, pulpal vitality) can also affect their survival [14,15]. Thus, actual survival rates vary somewhat in each study setting [12,13], so it may be futile to compare studies conducted in different settings. In a previous study, Yoshida *et al.* retrospectively analyzed the survival rate of RBFPDs and compared it with that of CFPDs [6]. They reported no significant differences between RBFPDs and CFPDs in terms of both 10-year and 15-year cumulative survival rates. Since their study samples included both vital and non-vital abutment teeth in both groups, we cannot compare our findings directly. However, regarding the lack of significantly different survival rates between RBFPD and CFPD, the results of our study were consistent when compared in terms of the same population and study design. Regarding the risk factors for non-survival of the prosthesis, the Cox proportional hazard regression analysis revealed that the difference in treatment modality was the only significant risk factor. This was due to the fact that only one non-survival case was observed in the ISP group. This factor was too powerful to classify other factors as significant, even if they were significantly different in the univariate analyses between the survival and non-survival groups.

Most of the complications in TAES observed during the follow-up period were caries (79.1%), and most of these cases were managed by restorative treatment. This indicates that the location and severity of most of these caries cases were not advanced or invasive, and were distant from the restoration margins, such as root surface caries. The cumulative complication-free rates were not different among the three groups (Fig. 4). However, the Cox proportional hazard model indicated that older age was the only significant risk factor for complications in TAES. Since several systematic reviews have reported that older age is a significant risk factor for root surface caries [16,17], these findings may



ISP vs. RBFPD: **p<0.001**; ISP vs. CFPD: **p<0.001**; RBFPD vs. CFPD: p=0.069 (log-rank test)

Fig. 3. Kaplan–Meier estimate of survival curves of the prostheses. The log-rank test revealed that the cumulative survival rates of ISP were significantly higher than the other two groups ($p < 0.001$: ISP vs. RFPD, and $p < 0.001$: ISP vs. CFPD). However, no significant difference was observed between RBFPD and CFPD. RBFPD, resin-bonded fixed partial dentures; CFPD, conventional fixed partial dentures; ISP, implant-supported prosthesis.



ISP vs. RBFPD: p=0.761; ISP vs. CFPD: p=0.632; RBFPD vs. CFPD: p=0.654 (log-rank test)

Fig. 4. Kaplan–Meier estimate of complication-free curves of teeth adjacent to edentulous space. The estimated complication-free rates between each group showed no significant difference. RBFPD, resin-bonded fixed partial dentures; CFPD, conventional fixed partial dentures; ISP, implant-supported prosthesis.

support the results of our study. Further, 19 patients (17.3%) underwent tooth extraction due to a periodontal lesion as an initial complication of TAES. The prevalence of severe periodontitis increases gradually with age [18]; therefore, older age was a significant risk factor for complications in TAES.

In this study, 16 cases finally underwent extraction due to recurrent tooth complications (e.g., caries) after recovery from initial complications. Therefore, a total of 35 cases experienced loss of TAES during the follow-up period. The cumulative survival rates of TAES were significantly lower in CFPD than in ISP ($p = 0.037$: log-rank test), whereas we observed no significant difference between ISP vs. RBFPD and RBFPD vs. CFPD. When replacing teeth with a CFPD, the abutment tooth preparation requires a relatively large amount of coronal tooth structure loss. If a large amount of tooth structure has already been lost at the time of restoration, several cases may require extraction when biological complications, such as caries or tooth fracture, develop. However, ISP can provide a tooth replacement option without relying on the surrounding dentition for support. Additionally, they do not require the preparation of TAES. These conditions are advantageous as they decrease the mechanical stress placed on the TAES. Also, complications such as caries could be detected at an early stage and conservatively treated if they develop. This may explain why the cumulative survival rate of TAES was significantly lower in CFPD than in ISP, despite the fact that cumulative complication-free rates of TAES were not significantly different between the two groups. In contrast, an RBFPD can reduce the loss of coronal tooth structure during tooth preparation and employ supragingival margins. For these reasons, the cumulative survival rates of TAES were not significantly different between ISP and RBFPD. The Cox proportional hazard regression analysis revealed that employing CFPD as a tooth replacement option was a significant risk factor when compared to ISP. This finding corresponds to the results of the log-rank test, which compared cumulative survival rates of TAES. As with employing CFPD for tooth replacement, deeper periodontal probing depth was a significant risk factor for loss of TAES. These results indicate that it is difficult

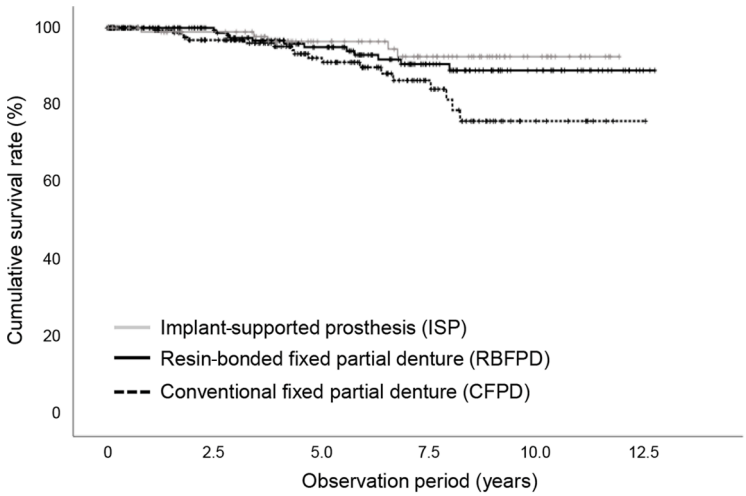


Fig. 5. Kaplan–Meier estimate of survival curves of teeth adjacent to edentulous space. Log-rank test revealed that the cumulative survival rate of CFPD was significantly lower than that of ISP ($p = 0.037$). No significant difference was observed between IPS and RBFPD, and RBFPD and CFPD. RBFPD, resin-bonded fixed partial dentures; CFPD, conventional fixed partial dentures; ISP, implant-supported prosthesis.

Table 5
Results of the Cox-proportional hazard regression analysis to investigate the risk factors for non-survival of the prosthesis.

	p-value	HR	95.0%CI		
Type of prosthesis (RBFPD)	**0.001**	**36.927**	**4.503**	**–**	**302.831**
Type of prosthesis (CFPD)	**0.002**	**27.91**	**3.334**	**–**	**233.610**
Sex (male)	0.211	1.408	0.824	–	2.405
Age (older)	0.214	1.016	0.991	–	1.042
Region of edentulous space (maxilla)	0.807	0.935	0.548	–	1.597
Location of edentulous space (anterior)	0.086	0.188	0.028	–	1.268
Materials used for prosthesis (ceramics)	0.255	0.619	0.271	–	1.414
Materials used for prosthesis (composite resin)	0.369	2.641	0.318	–	21.937
Periodontal probing depth (deeper)	0.126	1.175	0.956	–	1.444
Number of teeth present (smaller number)	0.351	1.038	0.960	–	1.123

HR: hazard ratio; CI: confidence interval; RBFPD: resin-bonded fixed partial denture; CFPD: conventional fixed partial denture.
Statistically significant p-values are indicated with bold letters.

Table 6
Results of the Cox proportional hazard regression analysis to investigate the risk factors for complications of teeth adjacent to the edentulous space.

	p-value	HR	95.0%CI		
Type of prosthesis (RBFPD)	0.276	0.597	0.236	–	1.510
Type of prosthesis (CFPD)	0.343	0.638	0.252	–	1.613
Sex (male)	0.594	1.125	0.729	–	1.735
Age (older)	**0.042**	**1.020**	**1.001**	**–**	**1.041**
Region of edentulous space (maxilla)	0.441	0.841	0.542	–	1.306
Location of edentulous space (anterior)	0.115	0.383	0.116	–	1.264
Materials used for prosthesis (ceramics)	0.481	1.376	0.566	–	3.346
Materials used for prosthesis (composite resin)	0.212	2.222	0.635	–	7.775
Periodontal probing depth (deeper)	0.074	1.158	0.986	–	1.360
Number of teeth present (smaller number)	0.810	1.007	0.949	–	1.070

HR: hazard ratio; CI: confidence interval; RBFPD: resin-bonded fixed partial denture; CFPD: conventional fixed partial denture.
Statistically significant p-values are indicated with bold letters.

to protect the teeth in a state where the periodontal condition has deteriorated, even when ISP is installed in the adjacent area and supports the masticatory force. In this multivariate analysis, ceramic replacement of edentulous space was a significantly higher risk for loss of TAES when compared with metal. The relevant cases (i.e., the cases where TAES were lost, in which ceramic was used for the replacement of the edentulous space) in the group of loss of TAES were minimal (ISP: 4/5 cases; RBFPD: 2/12 cases; CFPD: 2/18 cases). Additionally, the results of the univariate analysis showed no significant differences with regard to the materials used for the prosthesis in the edentulous space. Presently, we are unable to explain the relationship between ceramic tooth replacements and the loss of TAES. Future studies are necessary to determine the mechanisms underlying this relationship.

The major strength of this study is that the target cases were restricted to ones in which both TAES contained vital dental pulp. Several previous studies have demonstrated that pulp non-vitality is a significant risk factor for long-term outcomes of the prosthesis and TAES [5,6,14,19,20]. Therefore, the study design we employed properly evaluated the long-term consequences of different prostheses in single bounded edentulous spaces. As with the current study, retrospective research designs are often adopted to assess long-term consequences; however, there are often a limited number of predictors that can be evaluated. Thus, several important factors that can affect the prognosis of prostheses and TAES were not included in this study design. Several mechanical issues have been recognized as significant risk factors. Balasubramaniam reported that no occlusal contact on the pontic in lateral excursion yields better survival rates of RBFPD [21]. In addition, parafunctional habits (e.g., bruxism) have harmful effects on the survival of prostheses [22,23]. Although occlusal conditions may change over the course of the follow-up period, future studies identifying the initial occlusal factors at the onset of the study would help to clarify this point. Furthermore, as with occlusal factors, the experience of the operator could affect the outcome of this study. Since this study was retrospectively conducted in the usual clinical setting, this factor could not be controlled in each group. In particular, the operators' mean experience might have been longer in the ISP group than in the other groups. Nevertheless, the 10-year cumulative survival rates of the TAES were not significantly different between the ISP and RBFPD groups. This

Table 7
Results of the Cox-proportional hazard regression analysis to investigate the risk factors for tooth loss adjacent to the edentulous space.

	p-value	HR	95.0%CI		
Type of prosthesis (RBFPD)	0.095	3.764	0.793	–	17.856
Type of prosthesis (CFPD)	**0.019**	**6.220**	**1.342**	**–**	**28.819**
Sex (male)	0.081	2.133	0.912	–	4.986
Age (older)	0.354	1.018	0.980	–	1.057
Region of edentulous space (maxilla)	0.319	1.532	0.662	–	3.546
Location of edentulous space (anterior)	0.221	0.280	0.036	–	2.150
Materials used for prosthesis (ceramics)	**0.026**	**3.927**	**1.179**	**–**	**13.085**
Materials used for prosthesis (composite resin)	0.505	2.299	0.199	–	26.542
Periodontal probing depth (deeper)	**0.018**	**1.375**	**1.057**	**–**	**1.789**
Number of teeth present (smaller number)	0.489	0.963	0.867	–	1.071

HR: hazard ratio; CI: confidence interval; RBFPD: resin-bonded fixed partial denture; CFPD: conventional fixed partial denture.
Statistically significant p-values are indicated with bold letters.

was one of the major findings of this study that might be more emphasized under controlled conditions. However, future studies taking this issue into account are needed.

Another drawback of this retrospective study was the possibility of baseline differences and sampling bias. The ages of the patients among the three groups at the time of prosthesis installation were significantly different (Table 1). As observed in the Cox proportional hazard model, older age was a significant risk factor for complications in TAES. Even though the relationship between older age and complications in TAES is discussed above, we cannot deny the potential influence of sampling bias. However, due to differences in individual preferences and economic situations, it is ethically difficult to randomly allocate treatments to each patient. Therefore, a future analysis using propensity score matching would be helpful in addressing this issue.

5. Conclusions

Within the limitations of this study, when (i) both TAES were vital, and (ii) the single bounded edentulous spaces were rehabilitated with ISP, RBFPD, or ISP, we found no significant differences in the long-term complications of TAES among the aforementioned three types of prostheses; therefore, the type of prosthesis used was not a significant risk factor for the development of complications in TAES. The cumulative survival rate of TAES was significantly lower in CFPD than that in ISP. Furthermore, compared to ISP, installation of CFPD was a significant risk factor for loss of TAES. However, no significant difference was observed between ISP and RBFPD. These results suggest that RBFPD, which can minimize the invasion of abutment teeth, may provide a prognosis equivalent to that of a single standing ISP in terms of TAES.

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CRediT authorship contribution statement

Shun Okuni: Investigation, Formal analysis, Validation, Software. **Kenji Maekawa:** Conceptualization, Methodology, Investigation, Data curation, Project administration, Validation, Writing – original draft, Visualization. **Takuya Mino:** Formal analysis, Validation. **Yoko Kurosaki:** Methodology, Validation, Project administration. **Takuo Kuboki:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare no competing financial interests or personal relationships that influenced the work reported in this study.

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