Dental Materials 42 (2026) 628–635

Contents lists available at ScienceDirect

Dental Materials

journal homepage: www.elsevier.com/locate/dental

Randomized split-mouth clinical trial of CAD-CAM-partial ceramic crowns luted with a self-adhesive resin cement or with a conventional resin cement combined with a universal adhesive after 12 years

Julia L. Pfister [a,*], Fabian Cieplik [b], Karl-Anton Hiller [a], Isabelle M. Schenke [a], Gottfried Schmalz [a,c], Wolfgang Buchalla [a], Marianne Federlin [a], Konstantin J. Scholz [a,b]

[a] Department of Conservative Dentistry and Periodontology, University Hospital Regensburg, Regensburg, Germany
[b] Department of Operative Dentistry and Periodontology, Center for Dental Medicine, Medical Center – University of Freiburg, Faculty of Medicine, University of Freiburg, Freiburg, Germany
[c] Department of Periodontology, School of Dental Medicine, University of Bern, Bern, Switzerland

ARTICLE INFO

Keywords:
Partial ceramic crown
Long-term
CEREC
Universal adhesive
Self-adhesive resin cement

ABSTRACT

Objectives: This study evaluated the long-term clinical performance and survival of CAD-CAM-fabricated partial ceramic crowns (PCCs) luted with either self-adhesive resin cement, or conventional luting composite combined with a universal adhesive, applied without or with selective enamel etching.
Methods: A 12 year follow-up of a randomized split-mouth clinical trial initially including 48 patients was conducted. PCCs were luted with three different randomized luting protocols (all material: Solventum): RXU (RelyX Unicem), SBU-E (RelyX Ultimate/Scotchbond Universal, no selective enamel etching), SBU+E (RelyX Ultimate/Scotchbond Universal, with selective enamel etching). Clinical performance was assessed using FDI criteria at baseline and after 12 years. Survival rates were calculated using Kaplan-Meier analysis, and statistical differences between groups and over time were tested using Chi-square and log-rank tests (α=0.05).
Results: After a median observation period of 12.2 years, 16 patients (38 restorations) were available for clinical evaluation. By including information from files of patients that were not available for clinical evaluation, the Kaplan-Meier survival analysis included 35 patients (87 restorations). The survival rates significantly differed between the groups: RXU (36.4 %), SBU-E (60.7 %), and SBU+E (80.8 %). RXU demonstrated significantly lower survival compared to both SBU-E ($p = 0.034$) and SBU+E ($p = 0.001$), while no significant difference was observed between SBU-E and SBU+E ($p = 0.141$). Clinical performance evaluated according to FDI criteria remained acceptable for all groups and criteria at 12 years, with mostly minor aging-related changes observed, e.g. in terms of a significant increase in marginal staining ($p \leq 0.002$) for all groups and a significant deterioration in marginal adaptation for RXU ($p = 0.009$) and SBU-E ($p = 0.003$) over time. PCCs placed with a universal adhesive and conventional luting composite combination showed a significantly higher survival compared to PCCs placed with self-adhesive resin cement. Selective enamel etching by tendency improved the performance of the conventional luting composite.
Significance: The study highlights the importance of adhesive protocols in achieving long-term survival and clinical success for PCCs, particularly emphasizing the benefits of universal adhesives without or with selective enamel etching combined with luting composites.

1. Introduction

Partial ceramic crowns (PCCs) are a well-established option for restoring severely damaged teeth in the posterior region [1,2]. They offer both functional and esthetic benefits, while their long-term success depends on several factors, including the remaining tooth structure, the material properties of the ceramic and the stability of the entire biomechanical unit of tooth, adhesive material and restoration [1,3,4].

* Correspondence to: Department of Conservative Dentistry and Periodontology, University Hospital Regensburg, Franz-Josef-Strauß-Allee 11, Regensburg 93053, Germany.
E-mail address: julia.pfister@ukr.de (J.L. Pfister).

https://doi.org/10.1016/j.dental.2025.12.001
Received 9 July 2025; Received in revised form 21 October 2025; Accepted 1 December 2025
Available online 15 December 2025

A decisive aspect is the choice of the luting method. Various luting or cementation techniques are discussed, with multi-step adhesive systems combined with conventional luting composites being considered as the gold standard. Nowadays, universal adhesives with fewer steps do not appear to lead to inferior results, as recently summarized in a systematic review on non-carious cervical lesions [5]. Self-adhesive materials without a separately applied adhesive system have been investigated both clinically and *in vitro* both in the form of cements for luting restorations and in the form of filled bulkfill composites. They can also show micromorphological interactions with dental hard tissues [1,6–8]. However, the question of whether glass-ceramic restorations should be cemented with conventional luting composites in combination with universal adhesives or with self-adhesive resin cements has not yet been conclusively answered in long-term clinical studies [9,10].

Studies on direct Class V composite restorations indicate that selective enamel etching prior self-etch adhesive application improves retention and marginal color stability [11]. A notable example is the silane- and MDP-containing universal adhesive Scotchbond Universal (SBU; Solventum, St. Paul, MN, USA), which contributed a survival rate of over 85 % of Class V resin composite restorations after three years [12,13], a survival rate of 100 % of class II resin composite restorations in posterior teeth after one year [14] and over 80 % of such class II restorations in primary molars after 18 months [15]. Another 5-year study on class V restoration in non-carious cervical lesions with Scotchbond Universal achieved retention rates of 93 for total etch, 88.4 % after selective enamel etch, and 81.4 % in self-etch mode, which strengthens the recommendation for additional phosphoric acid application [16]. It should be noted that Class V restorations have different requirements than occlusal load-bearing restorations, and the results are therefore not to be transferred equivalently. CAD-CAM-fabricated ceramic restorations have also shown high clinical success rates. Two meta-analyses showed a 10-year survival rate of at least 89 % for inlays, onlays and overlays made of different glass ceramics [17,18].

A previous study by our group compared different cementation protocols for CAD-CAM-fabricated PCCs: self-adhesive resin cement, conventional luting composite with universal adhesive without selective enamel etching and conventional luting composite with universal adhesive and with selective enamel etching [19]. The mid-term results of this study after 39 months showed that PCCs cemented with self-adhesive resin cement had a significantly lower survival rate than those cemented with conventional luting composite in combination with universal adhesives [19]. Due to the limited availability of long-term clinical data, a follow-up study was conducted to validate these results.

The primary objective of this follow-up of a prospective, randomized split-mouth study was to evaluate the clinical performance of PCCs over a period of up to 12 years luted with a self-adhesive resin cement or a conventional luting-composite combined with a universal adhesive without or with selective enamel etching. To the best of our knowledge, this is the first study to compare SBU as an adhesive system both in self-etch mode and with selective enamel etching for the luting of indirect CAD-CAM restorations with conventional luting composite. The null hypothesis tested was that there are no significant differences between the cementation methods regarding clinical survival and performance assessed with FDI criteria.

2. Material and methods

2.1. Study design

The present study is a 12-year follow-up examination of a prospective controlled clinical split-mouth study investigating the clinical performance of CAD-CAM-fabricated partial ceramic crowns (PCCs) luted with a self-adhesive resin cement or with a conventional luting composite combined with a universal adhesive either without or with previous selective enamel etching. The 18- and 39-month results of this study have been published earlier [19,20].

The original clinical study as well as the present follow-up investigation were approved by the Internal Review Board of affiliation removed due to anonymization (references 11–101–0065 and 11–65_1–101) and registered with the German Clinical Trials Register (DRKS 00003059). Written informed consent was obtained from all individual patients both before they were included in the study and for this long-term investigation. The study was planned, realized and reported in accordance with the 1964 Helsinki Declaration and its later amendments [21] or comparable ethical standards and the CONSORT statement [22] including its newly published version for this evaluation time point [23].

2.2. Patient selection

48 patients had been originally recruited from the patient pool of affiliation removed due to anonymization. Criteria for inclusion and exclusion have been described earlier in detail [19,20]. Patients had to present three large defects of the dental hard tissues in premolars or molars (occlusal cavity width $> {}^{1}/_{3}$ of the width in bucco-oral direction) suitable for restoration with PCCs and positive sensitivity test to cold of the respective teeth. Furthermore, the teeth to be restored had to be free of any symptoms of pain, show tooth mobility less or equal grade I (mobility discernible, but not visible), and the application of rubber dam isolation had to be possible for insertion of PCCs. The study followed a parallel design with an allocation ratio of 1:1:1 for the three materials applied to the study teeth, resulting in 48 teeth per group at the start [19,20]. Patients and members of the public were not involved in the design, conduct, or reporting of this trial.

2.3. Clinical restorative procedures

The clinical restorative procedures were performed by fifth-year dental students who were trained in the preparation and fabrication of CAD-CAM PCCs and supervised by experienced dentists. The procedures have been previously described in detail [19,20] and are therefore only briefly summarized as follows. Functional cusps were covered while nonfunctional cusps were left uncovered when applicable. It was not feasible when there were hairline cracks or extended composite build-up restorations. Conventional impressions were taken using either a two-step correction impression technique with Silaplast Futur and Silasoft N condensation silicone (Detax, Ettlingen, Germany) or a one-step impression with Impregum Penta Soft polyether (Solventum, St. Paul, MN, USA). Temporary restorations were fabricated chairside using a self-curing bis-acrylic resin (Luxatemp, DMG, Hamburg, Germany) and secured with an eugenol-free temporary cement (RelyX Temp NE, Solventum, St. Paul, MN, USA). Master models were produced using Type 4 dental stone (GC Fujirock, GC Europe, Leuven, Belgium) and served as the basis for the CAD-CAM-fabrication of monolithic fine-particle feldspar K-Na-Al-silicate glass PCCs (VITA Mark II, VITA Zahnfabrik, Bad Säckingen, Germany) with a flexural strength (ISO 6872) of 154 MPa according to the manufacturer documentation using the Sirona CEREC system (SW 4.0, Bluecam, Optispray; Sirona, Bensheim, Germany). The restorations were then characterized and glazed following the manufacturer's instructions (Vita Akzent Plus Glaze Powder, Vita Akzent Plus Glaze Fluid, VITA Zahnfabrik). The random assignment sequence was carried out in such a way that three envelopes were prepared with the three treatment options, which were then blindly assigned to the teeth to be treated in ascending order according to the FDI system of the respective tooth. Patients were also blinded to the respective materials. Clinical follow-up evaluations were performed by blinded clinicians not involved in the clinical procedures which was possible due to the similarity of restorations made from the same ceramic material. The investigated materials were a self-adhesive resin cement (RelyX Unicem 2, Solventum) and a conventional luting composite (RelyX Ultimate, Solventum) either without (SB-E) or with (SB+E) selective enamel etching (15 s, Scotchbond Universal Etchant,

Solventum; 35 % H_3PO_4) before application of a universal adhesive (Scotchbond Universal, Solventum). All restorations were placed under rubber dam isolation. Before insertion, the respective teeth were cleaned with a mixture of pumice and water, thoroughly rinsed by water spray and lightly air-dried. The pretreatment protocols for cavities and restorations during the luting procedure are summarized in Table 1.

Following the pretreatment, all restorations were seated and held in place applying constant finger pressure, and excess cement was removed. Light polymerization was carried out from the buccal, oral, and occlusal surfaces of the restoration for 20 s each (BluePhase C8, Ivoclar Vivadent GmbH, Schaan, Liechtenstein; >1000 mW/cm^2). The occlusal contacts were adjusted if necessary. Excess material was removed, and final polishing was performed.

2.4. Clinical examination

Clinical examination was performed by two blinded examiners out of a pool of trained and calibrated examiners (JLP, KJS, FC and IMS) who had not been involved in the respective treatments and were blinded regarding the luting procedure used for the respective PCC.

The present study reports the results at baseline (BL) and after 12 years (12-y), while previous studies have already reported the results up to 39 months [19,20]. The clinical evaluation of the restorations was conducted using the FDI clinical criteria and scoring system [24]. To assess their clinical performance over a period of 12 years, only the FDI criteria relevant for the study hypotheses were selected for depiction aiming for a better overview:

- Esthetic properties
  - o Surface luster (A1)
  - o Marginal staining (A2b)
  - o Color match and translucency (A3)
- Functional properties
  - o Fracture of material and retention (B5)
  - o Marginal adaptation (B6)
- Biological properties
  - o Periodontal response (C14)

Each restoration was independently examined by both examiners. In the event of a disagreement, a consensus was reached through immediate joint discussion and reexamination. Additionally, the PBI (papilla bleeding index) [25] was assessed to evaluate the patients' oral hygiene, and clinical photographs of each restoration were taken. An exemplary clinical follow-up at 12 years is shown in Fig. 1. Concomitant care or interventions on the study teeth were not performed during the trial. Sample size calculation was not performed for this long-term observation of a clinical cohort, as all patients achievable were included.

Table 1
Pretreatment procedures of cavity and restoration surfaces for RXU, SB-E and SB+E.

	RXU	SB – E	SB + E
Cavity	-	20 s application of Scotchbond Universal in self-etch mode (Solventum)	15 s selective enamel etching (37 % H_3PO_4, Scotchbond Universal, Solventum), 20 s application of Scotchbond Universal (Solventum)
Restoration	60 s etching the basal ceramic surface (5 % hydrofluoric acid, VITA ceramics etch, VITA Zahnfabrik)		
	Silane-containing ceramic primer (RelyX Ceramic Primer, Solventum)	20 s application of Scotchbond Universal (Solventum)	20 s application of Scotchbond Universal (Solventum)

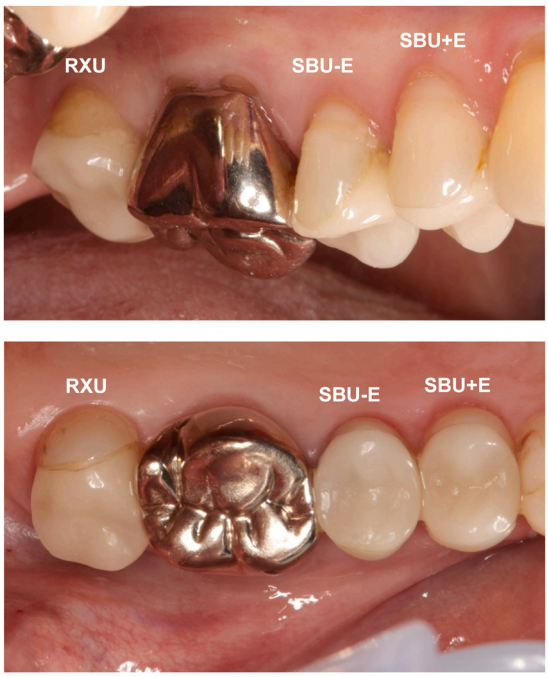

Fig. 1. Clinical follow-up up of teeth 14, 15 and 17 at 12 years.

2.5. Data analysis

Non-parametrical analyses (α = 0.05) were performed using SPSS version 25 (SPSS, Chicago, USA). FDI criteria were analyzed using Chi-square tests for pairwise differences among the three luting procedures and within each luting procedure over time. Based on clinical failures causing complete debonding, trepanation of the restoration in terms of endodontic treatment or need for replacement of the restorations, the Kaplan-Meier survival rates were calculated [26] and log rank (Mantel-Cox) test was used for testing the equality of survival distributions for the different luting procedures. In case of complete debonding, undamaged restorations could be re-cemented; however, since the luting procedure is the focus of the study, such cases were registered as failures and were not further clinically re-examined in the course of the study. All evaluated patients with at least one restoration under risk were included in the statistical analysis, as well as any patient for whom a file analysis was evident whether the PCCs were still in service or when and why they had failed.

3. Results

3.1. Recall rate

Fig. 2 shows the patient flow through the stages of this study. Out of initially 48 patients, 16 patients with 38 restorations could be recruited for a further recall after a median (1st; 3rd quartile) observation period of 147 (143; 148) months which is equivalent to 12.2 years. 9 patients were female (56 %) and 7 were male (44 %). No patients were excluded from any group due to harm or unintended events unrelated to the study as during the course of this long-term evaluation no invasive measures were performed (Fig. 2). The median age of the available patients was 60.3 years (range: 41–73.4 years) at the present evaluation time point. In the 16 patients available for clinical evaluation, 10 PCCs inserted with self-adhesive resin cement were still in service, while 12 PCCs inserted with SB-E and 16 PCCs inserted with SB+E were still in situ. Additionally, by including information from patient files regarding failure documentation without clinically assessing these patients, it was possible to include 35 patients (87 restorations) in total in the Kaplan-Meier survival analysis.

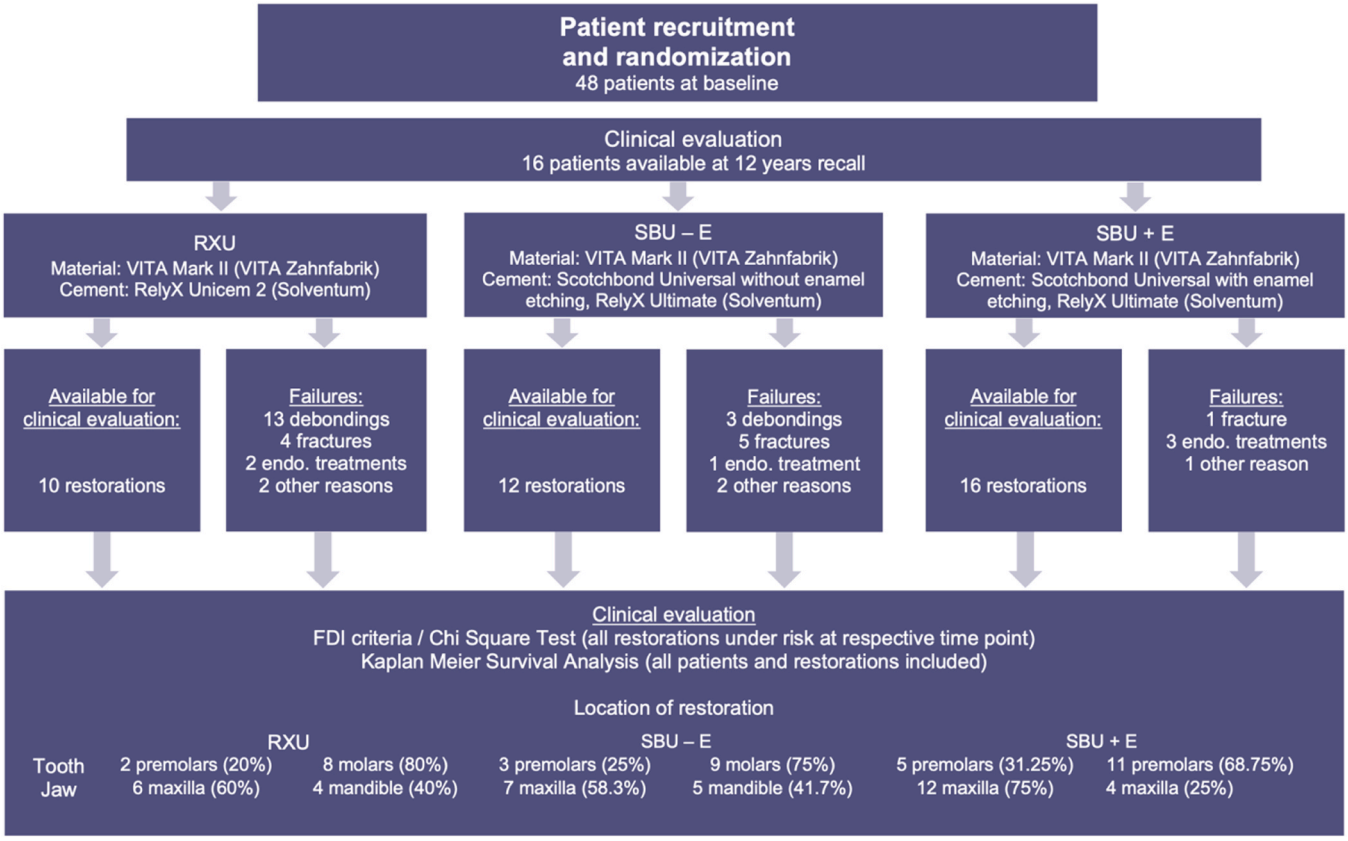

Fig. 2. Flow Chart showing number of examined patients and restoration failures within groups at respective time points. Notably, none of these failures occurred exactly at the 12-year recall, which is why the respective cases are not listed in Table 2 under criterion B5.

3.2. Survival analysis

Table 2 lists the reasons for failure that led to the replacement of the partial crowns. All fractures occurring during the study were irreparable and necessitated replacement of the restoration. The Kaplan- Meier survival analysis included 35 patients and 87 restorations (33 RXU, 28 SBU-E and 26 SBU+E). The survival rates (95 % confidence intervals) of the restorations at 12 years were 36.4 % (± 8.4 %) for RXU, 60.7 % (± 8.2 %) for SBU-E and 80.8 % (± 7.7 %) for SBU+E (Fig. 3). The overall comparison among the three materials using the Log-Rank (Chi-square) test revealed a significant difference ($p = 0.002$). In subsequent pairwise Log-Rank comparisons, significant differences were observed between RXU and SBU-E ($p = 0.034$) and between RXU and SBU+E ($p = 0.001$),

Table 2
Reasons for non-survival and respective year of failure. Notably, none of these failures occurred exactly at the 12-year recall, which is why the respective cases are not listed in Table 2 under criterion B5. Due to the small number of complications and their asymmetric distribution among groups and timepoints, a Kaplan–Meier analysis limited solely to fractures or debondings could not be valuably performed.

Year of failure	Debonding			Fracture			Endod. treatment			Other reasons		
	RXU	SB-E	SB+E	RXU	SB-E	SB+E	RXU	SB-E	SB+E	RXU	SB-E	SB+E
1	6	2		2	1	1	1		2			
2	3	1			1					1		
3	1				1		1					1
4	2			1	1				1	1	1	
6				1							1	
7	1							1				
11					1							
total	13	3		4	5	1	2	1	3	2	2	1

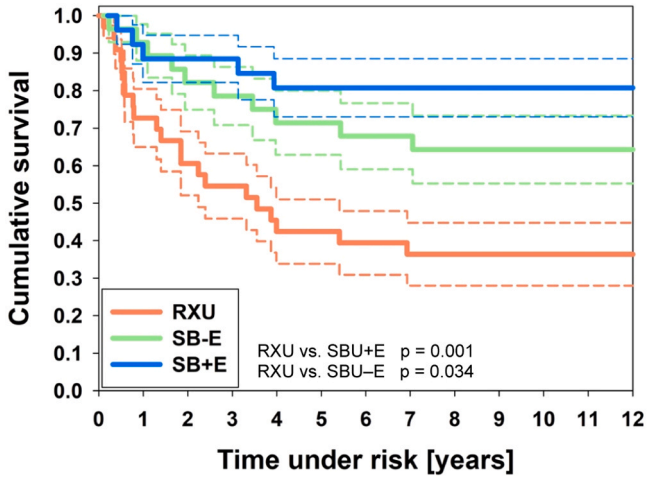

Fig. 3. Kaplan-Meier Survival of the PCCs from the three different luting procedures. Cumulative survival shown with the solid line. The dashed lines indicate upper and lower confidence limits.

whereas the difference between SBU-E and SBU+E was not significant ($p = 0.141$).

3.3. Clinical performance according to FDI criteria

At 12 years, no significant differences were found between the groups (RXU vs. SBU-E, SBU+E vs. SBU-E and SBU+E vs. RXU). Differences near the level of significance were limited in the criterion *fracture of material and retention* ($p = 0.052$), as well as *marginal*

adaptation ($p = 0.064$) when all groups were compared with each other.

Considering individual groups, various changes between baseline and 12 years are noticeable.

Within the **RXU group**, there was significant deterioration in the criteria *marginal staining* ($p < 0.001$), *color match and translucency* ($p = 0.022$), *marginal adaptation* ($p = 0.009$) and *periodontal response* ($p < 0.001$) over time.

The **SBU-E** group demonstrated statistically significant deterioration in the criteria *surface luster* ($p = 0.027$), *marginal staining* ($p < 0.001$), *marginal adaptation* ($p = 0.003$) and *periodontal response* ($p = 0.014$) over time.

The third group **SBU+E** showed the least aging. Hereby, there were significant differences in the criteria *marginal staining* ($p = 0.002$) and *periodontal response* ($p = 0.001$) over time.

Table 3 provides an overview of the results. Only one PCC belonging to the RXU group was scored as partially insufficient during the clinical examination (score = 4) because of a localized, displeasing deep marginal staining (Fig. 4). The patient was recommended a polish for repair, which he refused. All other PCCs examined were in the clinically acceptable range (score = 1–3). The changes in all groups can be attributed to signs of ageing. The finding in the periodontal response criterion can be explained by a slight deterioration in individual oral hygiene.

Fig. 4. Tooth 48 at 12 years clinical examination with localized, buccal deep marginal staining.

Table 3
Clinical performance according to FDI criteria.

FDI	Examination time point		FDI Score RXU 1	2	3	4	5	SB - E 1	2	3	4	5	SB + E 1	2	3	4	5	Significant difference 12y RXU vs. SB+E	SB-E vs. RXU	SB+E vs. SB-E	RXU	SB-E	SB+E	over time	All vs. all
A1 surface luster	BL	n	6	4	6			5	5	6			6	4	6										
		%	37.5	25	37.5			31.3	31.3	37.5			37.5	25	37.5										
	12-y	n	3	6	1			3	9				6	9	1			n.s.	n.s.	n.s.	n.s.				
		%	30	60	10			25	75				37.5	56.3	6.3			n.s.	0.027	n.s. (0.064)					
A2b marginal staining	BL	n	16					16					16												
		%	100					100					100												
	12-y	n	2	2	5	1		2	3	7			7	5	4			n.s.	n.s.	n.s.	n.s.				
		%	20	20	50	10		16.7	25	58.3			43.8	31.3	25			0.00	0.00	0.002					
A3 color match and translucency	BL	n	3	12	1			4	10	2			7	6	3										
		%	18.8	75	6.3			25	62.5	12.5			43.8	37.5	18.8										
	12-y	n	5	2	3			7	3	2			10	3	3			n.s.	n.s.	n.s.	n.s.				
		%	50	20	30			58.3	25	16.7			62.5	18.8	18.8			0.022	n.s.	n.s.					
B5 fracture of material and retention	BL	n	16					16					15	1											
		%	100					100					93.8	6.3											
	12-y	n	8	2				12					16					0.06	n.s.	n.s.	n.s. (0.052)				
		%	80	20				100					100					0.063	n.s.	n.s.					
B6 marginal adaptation	BL	n	14	2				13	3				11	5											
		%	87.5	12.5				81.3	18.8				68.8	31.3											
	12-y	n	3	5	2			3	9				9	7				n.s.	n.s.	n.s.	n.s. (0.064)				
		%	30	50	20			25	75				56.3	43.8				0.009	0.003	n.s.					
C14 periodontal response	BL	n	13	3				9	6	1			12	4											
		%	81.3	18.8				56.3	37.5	6.3			75	25											
	12-y	n	1	9				1	11				3	13				n.s.	n.s.	n.s.	n.s.				
		%	10	90				8.3	91.7				18.8	81.3				0.00	0.014	0.001					

Clinically acceptable scores (1–3) are highlighted in light blue, clinically non-acceptable scores (4–5) are highlighted in dark blue. n.s. = not statistically significant ($p > 0.05$). Notably, the failures in the form of debonding and fracture did not occur exactly at the 12 y clinical evaluation, which is why no failures are listed under B5 here. These failures are presented in Table 2 and Fig. 2.

4. Discussion

Long-term investigations of partial ceramic restorations are needed to assess the influence of tooth preparation, choice of material or choice of the luting procedure on restoration longevity [1]. Therefore, the aim of the present study was to follow-up a randomized split-mouth clinical trial to evaluate the clinical performance and survival of PCCs placed with either self-adhesive resin cement or conventional luting composite with or without prior selective enamel etching 12 years after restoration placement [19,20]. Since patients are generally difficult to recruit for a parallel design requiring three crowns, the condition of including a fourth tooth with a total-etch multistep adhesive and conventional luting composite was waived, and the study was planned under the hypothesis that the three experimental groups would not differ significantly.

Despite the inclusion of 48 patients at the beginning of the present study, only 16 patients could be clinically reevaluated after 12 years, which corresponds to a recall rate of 32 % for assessment of clinical performance according to FDI criteria. The main reason for this decline is that the patients could no longer be reached at their contact information after the long period of time. Also, other reasons have already been discussed previously [27], such as the fact that the 12-year observation period was not planned from the beginning of the study and the large catchment area around the affiliation removed due to anonymization with the inconvenience for patients to shoulder long travel distances and associated costs to reach the University Hospital. Nevertheless, clinical survival could still be assessed for 35 patients their patient files, resulting in a recall rate for Kaplan-Meier survival analysis of 73 %.

The clinical course of the present 12.2-year study had already been published twice before, namely after 18 months and after 39 months [19,20]. At 18 months, Kaplan–Meier analysis revealed survival rates of 97.8 % for SB+E, 95.6 % for SB–E, and 75.6 % for RXU, demonstrating statistically significant differences between RXU and both SB–E ($p = 0.007$) and SB+E ($p = 0.002$). At 39 months, RXU showed further deterioration with a survival rate of 69 % compared to 88 % for SB–E ($p = 0.022$) and 96 % for SB+E ($p \leq 0.001$), and this trend was even more pronounced after the present 12.2 years, where survival declined to 36.4 % for RXU versus 60.7 % for SB–E ($p = 0.034$) and 80.8 % for SB+E ($p = 0.001$), highlighting the critical role of observation period, the importance of conducting long-term evaluations in complex clinical evaluations [1,27,28] and the potential long-term benefits of selective enamel etching combined with Scotchbond Universal and a conventional dual-cure luting composite.

Although the difference between the groups SBU-E (60.7 %) and SBU+E (80.8 %) did not reach the level of clinical significance ($p = 0.141$), the numerical difference of 20.1 % might still have clinical relevance and importance, potentially indicating a trend toward improved performance with the addition of selective enamel etching [29,30].

While prior application of Scotchbond Universal to etched dentin resulted in longer tags but not increased bond strength compared to unetched dentin [31], another in vitro study demonstrated that etching enamel improved the micromorphological interaction in terms of enamel tags, increased bond strength, and enhanced the durability of the bonding for all universal adhesives tested on enamel [32]. One possible reason for this could be that with a universal adhesive featuring an ultramild pH, such as Scotchbond Universal (pH approximately 2.7), a pronounced improvement in microetching patterns can be achieved in enamel when selective etching is performed [33]. Since the mere presence of 10-MDP in Scotchbond Universal does not appear to have a significant effect on surface wetting, topographical changes, or adhesiveness to enamel, selective enamel etching might particularly enhance the performance of this system [34].

The choice of material for the placement of ceramic inlays, onlays and crowns is a decisive factor for clinical performance and clinical survival [35]. In principle, adhesive luting of ceramic restorations has the potential for significantly better survival up to 43 years compared to zinc phosphate cements, as the latter fail more frequently due to secondary caries, the need for endodontic treatment and debonding [35]. Furthermore, adhesively cemented ceramic restorations can naturally be prepared less invasively, as no macro-mechanical retention between the prepared tooth and the restoration is required. This leads to less hard tissue removal, more coronally positioned restoration margins and thus better accessibility for biofilm management, which might help to prevent secondary caries or periodontal complications in the region of the respective teeth [36].

It is also conceivable that the survival rates may be lower in the present study (36.4 % – 80.8 %), because the dental treatments were performed by students, whereas high survival rates of 98.7 % were achieved for non-university settings over up to 15 years [37]. This phenomenon was also previously described by Frankenberger et al. [38]: Two operators with 15 and 5 years of professional experience reached significantly different survival rates after 5 years, ranging from 97.4 % to 75.4 %. This strongly suggests that the survival rates of ceramic restorations placed by students may differ and be lower. However, the survival rate of 80 % after 12 years in this setting suggests that SBU+E is a reliable and long-term stable treatment option. Furthermore, it is important to consider that, on the one hand, the student operators in our setting were supervised during the critical clinical steps, and on the other hand, the glass ceramic used in this study has a flexural strength about three times lower compared to the lithium disilicate ceramics used in the non-university setting study [37]. Therefore, the effect of the ceramic material choice (feldspar vs lithium disilicate) may have been the major factor for the differing results of these two studies, which is also in line with another study investigating lithium disilicate CAD-CAM restorations delivered by 3rd and 4th year students showing a survival probability of more than 84 % after 98 months ran [39]. However, clinical controlled studies comparing the survival of fine particle feldspar ceramic onlays with ceramics with higher flexural strength are lacking.

In the two other long-term studies of our group, the same fine particle feldspar CAD-CAM ceramic was used for most of the study teeth. Fractures, which are the major failure reason influenced by the ceramic material choice could be observed in 7 of the initially 86 study restorations after 15 years [1] and in 3 out of 29 ceramic restorations after 19.9 years, respectively [28]. This aligns with the study results on 65 Vita Mark II CAD-CAM processed restorations without control group by Otto et al., which reported around 95 % survival rate for crowns and 90.5 % for molar endo-crowns or 75 % for premolar endo-crowns after 12 years [40]. Additionally, a systematic review revealed that survival rates of more than 90 % after 10 years for inlays, onlays and overlays made from glass-ceramics and feldspathic porcelain [18] can be achieved highlighting the suitability of these materials despite the introduction of materials with better mechanical properties.

Furthermore, in addition to the lack of clinical experience of the operators, it can be discussed whether the longer treatment times and the additional use of rubber dam in the student course are associated with over-drying of the dentin, which would impair the adhesive bond or particularly the performance of the self-adhesive material [1,41]. A recent systematic review and meta-analysis also indicates that both, selective enamel etching without dentin adhesive and self-etch adhesives had lower debonding incidences and higher survival rates than single-step self-adhesive luting resins for intracoronal restorations [42].

Adhesive placement preceded by selective enamel etching and subsequent rinsing of the tooth with water could contribute to a re-moisturization within the dentin, which in the specific situation of the present study due to longer periods of rubber dam application in a student setup may experience more moisture loss than is subsequently reintroduced by the application of the water-containing adhesive system. This could improve the adhesive bond and thus also influence the improved survival of SBU+E (80.8 %) as compared to SBU-E (60.7 %).

This hypothesis has already been put forward in a long-term split-mouth study on partial ceramic crowns with self-adhesive resin cements but also appears to be potentially applicable to lesser extent when the universal adhesive Scotchbond Universal is applied, which contains water and alcohol as solvents [43]. Since another recent systematic review found no statistically significant differences between the survival rates of different ceramic and ceramic-based partial restorations in the short-term (1–3 years of follow-up) in clinical studies [3], it would also be worth investigating similar long-term cohorts with restorations made from lithium disilicate ceramic like the ones made from glass ceramic here. The results of the present study also highlight a longer observation period, as initially small differences between luting protocols can still increase after longer observation periods, as in the present study between SB-E and SB+E (Fig. 3).

Another retrospective study also examined ceramic restorations in comparison with gold restorations, both fabricated by supervised undergraduate students [2]. The cumulative survival rates of the ceramic restorations were 93.9 after a mean service time of 15.2 years and decreased to 91.7 % after 23.5 years. However, in contrast to the present study, the retrospective study did not describe the luting procedures as exactly as the present study and did not randomize the study teeth according to the luting procedure [2]. Furthermore, it must be mentioned that a retrospective design tends not to include patients with poor compliance in terms of a recall bias [44] and that the other study did not differentiate between inlays and onlays. This could explain why the survival rates of the retrospective study were higher than in the group with the highest survival rate in the present study (SBU+E), which reached just over 80 % after 12 years.

Two further non-controlled, non-randomized studies examined, among other things, partial crowns made of pressed lithium disilicate ceramic over periods of 16.9 years [45] and 12 years [46], resulting in survival rates exceeding 95 %. In these studies, the thickness of the ceramics had no significant impact on outcomes [45]. Moreover, patients with severe wear [46] were successfully treated throughout the entire observation period. This supports the successful integration of partial ceramic crowns into long lasting restorative treatment concepts.

5. Conclusions

This study demonstrates that conventional luting composite combined with a universal adhesive significantly enhances the survival rates of CAD-CAM-fabricated partial ceramic crowns over a 12-year period compared to self-adhesive resin cement. Selective enamel etching may further improve longevity and clinical performance of a universal adhesive combined with conventional dual-cure luting composite.

CRediT authorship contribution statement

Julia L. Pfister: Contributed to conception and design, Contributed to acquisition, analysis and interpretation, Drafted the manuscript

Fabian Cieplik: Contributed to conception and design, Contributed to acquisition and interpretation, Critically revised the manuscript

Karl-Anton Hiller: Contributed to conception and design, Contributed to analysis, Critically revised the manuscript

Isabelle M. Schenke: Contributed to conception and design, Critically revised the manuscript

Gottfried Schmalz: Contributed to conception and design, Critically revised the manuscript

Wolfgang Buchalla: Contributed to conception and design, Critically revised the manuscript

Marianne Federlin: Contributed to conception and design, Critically revised the manuscript

Konstantin J. Scholz: Contributed to conception and design, Contributed to acquisition, analysis and interpretation, Drafted the manuscript

All authors gave their final approval and agree to be accountable for all aspects of the work

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported in the initial phase by 3M Espe, Seefeld, Germany.

Data availability

All data supporting the findings of this study are included in this published article.

References

[1] Pfister JL, Federlin M, Hiller KA, Schmalz G, Buchalla W, Cieplik F, et al. Randomized clinical split-mouth study on partial ceramic crowns luted with a self-adhesive resin cement with or without selective enamel etching: long-term results after 15 years. J Adhes Dent 2023;25(1):177–86.
[2] Krug R, Droste L, Schreiber C, Reichardt E, Krastl G, Hahn B, et al. Long-term performance of ceramic in/-onlays vs. cast gold partial crowns – a retrospective clinical study. Clin Oral Invest 2024;28(5):298.
[3] Prott LS, Pieralli S, Klein P, Spitznagel FA, Ibrahim F, Metzendorf M, et al. Survival and complications of partial coverage restorations on posterior teeth—a systematic review and meta-analysis. J Esthet Restor Dent 2024.
[4] Breemer C van den, Gresnigt M, Özcan M, Kerdijk W, Cune M. Prospective randomized clinical trial on the survival of lithium disilicate posterior partial crowns bonded using immediate or delayed dentin sealing: short-term results on tooth sensitivity and patient satisfaction. Oper Dent 2019;44(5):E212–22.
[5] Dreweck F, Burey A, Dreweck M de O, Fernandez E, Loguercio AD, Reis A. Challenging the concept that OptiBond FL and clearfil SE bond in NCCLs are gold standard adhesives: a systematic review and meta-analysis. Oper Dent 2021;46(6):E276–95.
[6] Scholz KJ, Bittner A, Cieplik F, Hiller KA, Schmalz G, Buchalla W, et al. Micromorphology of the adhesive interface of self-adhesive resin cements to enamel and dentin. Materials 2021;14(3):492.
[7] Schenke IM, Pfister JL, Hiller KA, Buchalla W, Cieplik F, Ettenberger S, et al. Randomized clinical split-mouth study on a self-adhesive vs. a conventional bulk-fill composite in class II cavities: results after five years. J Dent 2025:105663.
[8] Ellithy MS, Abdelrahman MH, Afifi RR. Comparative clinical evaluation between self-adhesive and conventional bulk-fill composites in class II cavities: a 1-year randomized controlled clinical study. J Esthet Restor Dent 2024;36(9):1311–25.
[9] Politano G, Meerbeek BV, Peumans M. Nonretentive bonded ceramic partial crowns: concept and simplified protocol for long-lasting dental restorations. J Adhes Dent 2018;20(6):495–510.
[10] Breemer CRG van den, Gresnigt MMM, Cune MS. Cementation of glass-ceramic posterior restorations: a systematic review. Biomed Res Int 2015;2015:148954.
[11] Szesz A, Parreiras S, Reis A, Loguercio A. Selective enamel etching in cervical lesions for self-etch adhesives: a systematic review and meta-analysis. J Dent 2016;53:1–11.
[12] Perdigão J, Ceballos L, Giráldez I, Baracco B, Fuentes MV. Effect of a hydrophobic bonding resin on the 36-month performance of a universal adhesive—a randomized clinical trial. Clin Oral Invest 2020;24(2):765–76.
[13] Haak R, Werner MS, Schneider H, Häfer M, Schulz-Kornas E. Clinical outcomes and quantitative margin analysis of a universal adhesive using a randomized clinical trial over three years. J Clin Med 2022;11(23):6910.
[14] Perdigão J, Chew HP, Lee IK, Woodis K, Hatch B. Prospective, randomized clinical trial evaluating the clinical performance of a new universal adhesive in Class I and Class II restorations at 1 year. Clin Oral Invest 2024;29(1):38.
[15] Lenzi TL, Pires CW, Soares FZM, Raggio DP, Ardenghi TM, Rocha R de O. Performance of universal adhesive in primary molars after selective removal of carious tissue: an 18-month randomized clinical trial. Pedia Dent 2017;39(5):371–6.
[16] Matos T de P, Perdigão J, Paula E de, Coppla F, Hass V, Scheffer RF, et al. Five-year clinical evaluation of a universal adhesive: a randomized double-blind trial. Dent Mater 2020;36(11):1474–85.
[17] Naik VB, Jain AK, Rao RD, Naik BD. Comparative evaluation of clinical performance of ceramic and resin inlays, onlays, and overlays: a systematic review and meta analysis. J Conserv Dent JCD 2022;25(4):347–55.
[18] Morimoto S, Rebello de Sampaio FB, Braga MM, Sesma N, Özcan M. Survival rate of resin and ceramic inlays, onlays, and overlays. J Dent Res 2016;95(9):985–94.
[19] Scholz KJ, Tabenski IM, Vogl V, Cieplik F, Schmalz G, Buchalla W, et al. Randomized clinical split-mouth study on the performance of CAD/CAM-partial ceramic crowns luted with a self-adhesive resin cement or a universal adhesive and a conventional resin cement after 39 months. J Dent 2021;115:103837.

[20] Vogl V, Hiller KA, Buchalla W, Federlin M, Schmalz G. Controlled, prospective, randomized, clinical split-mouth evaluation of partial ceramic crowns luted with a new, universal adhesive system/resin cement: results after 18 months. Clin Oral Invest 2016;20(9):2481–92.
[21] Association WM. World medical association declaration of helsinki: ethical principles for medical research involving human subjects. JAMA 2013;310(20): 2191–4.
[22] Moher D, Hopewell S, Schulz KF, Montori V, Gøtzsche PC, Devereaux PJ, et al. CONSORT. CONSORT 2010 explanation and elaboration: updated guidelines for reporting parallel group randomised trials. Int J Surg 2012;10(1):28–55.
[23] Hopewell S, Chan AW, Collins GS, Hróbjartsson A, Moher D, Schulz KF, et al. CONSORT 2025 statement: updated guideline for reporting randomised trials. PLOS Med 2025;22(4):e1004587.
[24] Hickel R, Mesinger S, Opdam N, Loomans B, Frankenberger R, Cadenaro M, et al. Revised FDI criteria for evaluating direct and indirect dental restorations—recommendations for its clinical use, interpretation, and reporting. Clin Oral Invest 2022:1–20.
[25] Saxer U.P., Mühlemann H.R. [Motivation and education]. Schweizerische Monatsschrift Für Zahnheilkunde Revue Mensuelle Suisse D'odonto-stomatologie Sso. 1975;85(9):905–919.
[26] Kaplan EL, Meier P. Nonparametric estimation from incomplete observations. J Am Stat Assoc 1958;53(282):457.
[27] Cieplik F, Ihlenfeld I, Hiller K, Pummer A, Schmalz G, Buchalla W, et al. Tooth survival and clinical outcomes up to 26 years after guided tissue regeneration therapy in deep intra-bony defects: follow-up investigation of three randomized clinical trials. J Clin Periodo 2020;47(7):863–74.
[28] Cieplik F, Pfister JL, Hiller KA, Schenke IM, Schmalz G, Buchalla W, et al. Gold vs. CAD/CAM ceramic partial-crowns: 20-year randomized clinical study. Dent Mater 2025;41(8):986–93.
[29] Calder RA, Patel JJ. Statistical thinking: clinical versus statistical significance. WMJ Publ State MéD Soc Wis 2024;123(3):238–40.
[30] Greenstein G, Lamster I. Efficacy of periodontal therapy: statistical versus clinical significance. J Periodo 2000;71(4):657–62.
[31] Wagner A, Wendler M, Petschelt A, Belli R, Lohbauer U. Bonding performance of universal adhesives in different etching modes. J Dent 2014;42(7):800–7.
[32] Suzuki T, Takamizawa T, Barkmeier WW, Tsujimoto A, Endo H, Erickson RL, et al. Influence of etching mode on enamel bond durability of universal adhesive systems. Oper Dent 2016;41(5):520–30.
[33] Wang L, Bai X, Liu Y, Islam R, Hoshika S, Sano H, et al. The effect of an extra hydrophobic resin layer on the bond strength and durability of one-step universal adhesives used as a primer. J Dent 2023;135:104568.
[34] Foly JCS do N, Weissheimer M, Gaspar CF, Fehrenbach J, Miotti LL, Piva E, et al. Bonding performance of universal adhesive systems to enamel – effects of the acidic composition. Dent Mater 2025;41(3):272–82.
[35] Masaka N, Yoneda S, Masaka K. An up to 43-year longitudinal study of fixed prosthetic restorations retained with 4-META/MMA-TBB resin cement or zinc phosphate cement. J Prosthet Dent 2023;129(1):83–8.
[36] Srimaneepong V, Heboyan A, Zafar MS, Khurshid Z, Marya A, Fernandes GVO, et al. Fixed prosthetic restorations and periodontal health: a narrative review. J Funct Biomater 2022;13(1):15.
[37] Offer K, Kohorst P, Linsen S. A total of 1,132 all-ceramic single-tooth restorations show acceptable survival rates up to 15 years in a non-university setting. Int J Prosthodont 2022;35(6):815–23.
[38] Frankenberger R, Reinelt C, Petschelt A, Krämer N. Operator vs. material influence on clinical outcome of bonded ceramic inlays. Dent Mater 2009;25(8):960–8.
[39] Tran C, Lee S, Gao F, Philip S, Pan A, Bolch C, et al. Survivability of lithium disilicate CAD/CAM restorations delivered by predoctoral students. J Dent Educ 2025;89(10):1495–505.
[40] Otto T, Mörmann WH. Clinical performance of chairside CAD/CAM feldspathic ceramic posterior shoulder crowns and endocrowns up to 12 years. Int J Comput Dent 2015;18(2):147–61.
[41] Ferracane JL, Stansbury JW, Burke FJT. Self-adhesive resin cements – chemistry, properties and clinical considerations. J Oral Rehabil 2011;38(4):295–314.
[42] Alghauli MA, Alqutaibi AY, Wille S, Kern M. Clinical reliability of self-adhesive luting resins compared to other adhesive procedures: a systematic review and meta-analysis. J Dent 2023;129:104394.
[43] Pongprueksa P, Miletic V, Munck JD, Brooks N, Meersman F, Nies E, et al. Effect of evaporation on the shelf life of a universal adhesive. Oper Dent 2014;39(5):500–7.
[44] Talari K, Goyal M. Retrospective studies – utility and caveats. J R Coll Physicians Edinb 2020;50(4):398–402.
[45] Malament KA, Margvelashvili-Malament M, Natto ZS, Thompson V, Rekow D, Att W. Comparison of 16.9-year survival of pressed acid etched e.max lithium disilicate glass-ceramic complete and partial coverage restorations in posterior teeth: performance and outcomes as a function of tooth position, age, sex, and thickness of ceramic material. J Prosthet Dent 2021;126(4):533–45.
[46] Margvelashvili-Malament M, Thompson V, Polyakov V, Malament KA. Over 14-year survival of pressed e.max lithium disilicate glass-ceramic complete and partial coverage restorations in patients with severe wear: a prospective clinical study. J Prosthet Dent 2025;133(3):737–46.