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CLINICAL RESEARCH

Incidence of endodontic therapy after complete or partial coverage glass-ceramic restorations with a follow-up time of over 30 years: A prospective clinical study

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ABSTRACT

Statement of problem. Long-term clinical data are lacking on the comparison of the incidence of endodontic therapy in adhesively luted complete and partial coverage glass-ceramic restorations, as well as on the effect of technique and clinical variables.

Purpose. The purpose of this prospective clinical study was to assess the long-term incidence of teeth requiring endodontic therapy after receiving either complete or partial coverage glass-ceramic restorations.

Material and methods. Participants requiring single anterior complete, posterior complete, or posterior partial (inlay or onlay) coverage restoration, or a combination of these on a vital tooth were recruited from a clinical private practice. Only the participants who chose glass-ceramic partial and complete coverage restorations without the need of endodontic therapy were included in the study. The overall clinical performance of these glass-ceramic restorations was assessed by clinical factors determined at recall. The effect of various clinical parameters (type of restoration, dental arch, tooth position in the dental arch, age and sex of participant, and ceramic thickness) was evaluated by using Kaplan–Meier survival curves to account for attrition bias and other reasons for failure. The statistical significance of differences between parameters was determined by using the log rank test (α=.05).

Results. A total of 1800 participants requiring 4511 glass-ceramic anterior and posterior restorations were evaluated. The mean age of the participants at the time of restoration placement was 62 (range 20 to 99 years, 710 men and 1090 women). Of 4511 restorations, 1476 were anterior complete coverage, 2119 posterior complete coverage, and 916 posterior partial coverage. Endodontic therapy after restoration placement was needed for 76 restorations (10 anterior complete, 50 posterior complete, and 16 posterior partial). The total time at risk was 50 436 years providing an estimated need for endodontic therapy risk of 0.15% per year. The estimated 35-year cumulative survival was 97.36%. The majority of endodontic treatments (67%, 52/76) occurred in the first 5 years.
The estimated cumulative survival of anterior complete coverage, posterior complete coverage, posterior partial inlay, and posterior partial onlay restorations was 98.89% (n=1476, 10 endodontic treatments), 96.38% (n=2119, 50 endodontic treatments), 96.78% (n=553, 11 endodontic treatments), and 98.53% (n=363, 5 endodontic treatments), respectively. Statistically significant differences occurred between anterior complete coverage, posterior complete coverage, and posterior partial coverage inlay restorations, with a higher incidence in posterior complete coverage and posterior partial inlay restorations (P<.05). First molars had the highest rate of endodontic therapy after restoration in both arches. Age and restoration thickness were significant factors, recording statistically higher number of endodontic treatments in participants >52 years and restorations with all surfaces $\geq$1 mm (P<.05). Other clinical variables, dental arch and sex of the participants, were not significantly related to endodontic treatments (P>.05).

Conclusions. The clinical performance of 4511 units over 30 years in service was excellent, with the estimated cumulative survival of 97.36%. Posterior complete coverage and posterior partial inlay restorations had a significantly higher need for endodontic therapy than anterior complete coverage restorations. Their overall clinical performance relative to endodontic treatment was excellent with a cumulative survival of 96.38% and 96.78% over 30 years. There was no difference in the endodontic treatment rate between posterior complete and partial coverage restorations. Thickness of the restoration affected the endodontic treatment rate, with $\geq$1 mm resulting in higher incidence. The age of the participants influenced the endodontic treatment rate, with higher incidence in the >52-year age group. Other confounding clinical variables did not have a significant effect on the endodontic treatment rate. (J Prosthet Dent 2022;■:■-■)

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Clinical Implications

The clinical performance of 4511 units over 30 years was excellent, with the estimated cumulative survival of 97.36%. Posterior complete coverage restorations had significantly higher endodontic treatment rates than anterior complete coverage restorations. Nevertheless, overall clinical performance relative to the endodontic treatment rate of posterior complete coverage restorations was excellent, with a cumulative survival of 96.38%. No statistically significant difference was seen in the endodontic treatment rate after receiving either posterior complete or posterior partial coverage glass-ceramic restorations. Most endodontic treatments (67%, 52/76) occurred within 5 years, with 37% in the first year.

Life expectancy and the number of retained natural teeth at an older age are increasing.[1,2] Although preventive dentistry is widely practiced, dental caries remains a prevalent oral disease.[1] Additionally, tooth structure loss through attrition, abrasion, erosion, or a combination of these also persists in the world population.[3-5] For teeth that have lost moderate amounts of tooth structure, indirect restorations have been considered a treatment option with excellent long-term survival rates.[6-8] Based on the amount of remaining tooth structure, a complete or a partial coverage restoration can be chosen.[9-11]

Adhesively bonded complete and partial glass-ceramic restorations must survive in demanding multifactorial conditions. However, some failures related to technical or biological aspects are anticipated.[12] Recent clinical studies have reported the excellent and statistically similar long-term clinical survival of complete and partial coverage glass-ceramic restorations, with low failure rates or technical complications.[6-8]

Nevertheless, concerns have been raised that biological complications, including pulpal damage and loss of tooth vitality, are linked to the treatment procedures.[12] In particular, complete coverage restorations have been assumed to result in an increased loss of tooth vitality.[13] Therefore, conservative partial coverage restorations have been increasingly advocated, even in the teeth that require lingual, occlusal, and buccal restorations.[14,15] Partial coverage restorations are more conservative because of their limited tooth preparation and their path of insertion.[13]

The incidence of endodontic therapy (IET) after complete coverage restorations has been reported,[16-22] but studies with both long-term follow-up and a high number of units are scarce. Also, most of these studies have been retrospective and on complete coverage metal-ceramic restorations or restorations made using obsolete ceramic systems, with more extensive preparation guidelines. Additionally, the cementation protocol used was that of the conventional technique. The reported maximum of the IET for metal-ceramic and ceramic single crowns varied between 1% and 19% based on the follow-up times of 5 to 25 years.[23-26]

Leucite-reinforced and lithium disilicate glass-ceramics are etchable materials, allowing strong micromechanical bonding to the tooth structure.[27] Strong bonding has been reported to increase the fracture resistance of glass-ceramic restorations and reduce restoration microleakage and micromotion.[28-30] However, the authors are unaware of studies that have compared IET in complete and partial coverage restorations using these leucite-reinforced and lithium disilicate glass-ceramics.

Therefore, the objective of the investigation was to assess the incidence of teeth requiring endodontic therapy after receiving either a complete or a partial coverage glass-ceramic adhesively bonded restoration in a long-term clinical study with up to 35 years of follow-up. This prospective study was initiated in 1986, and the database parameters, as well as the recall method, were adopted from previously published studies from the same group.[6-8,29,31-34]

The null hypotheses were that no difference would be found in the teeth needing endodontic therapy after receiving either an adhesively bonded complete or a partial coverage etchable glass-ceramic restoration and that none of the confounding variables (dental arch, tooth position in the dental arch, age and sex of participant, and ceramic thickness) would influence the long-term results.

MATERIAL AND METHODS

Participants requiring single unit anterior complete, posterior complete, posterior partial (inlay or onlay) coverage restoration, or a combination of these on a vital tooth were recruited in a clinical private practice. Participants were offered the choice of silver amalgam, composite resin, cast gold, metal-ceramic, or glass-ceramic restorations. They were informed that glass-ceramic restorations were subject to fracture, unlike cast gold restorations. Only participants who chose glass-ceramic restorations, with healthy pulp and no need of endodontic therapy before the restoration, were included in the current study, which was approved by the Tufts Health Science Institutional Review Board #STUDY00000261.

The clinical procedures were standardized and have been reported previously.[6-8] The glass-ceramic materials used were leucite-reinforced (IPS Empress; Ivoclar AG) and lithium disilicate (IPS e. max Press and CAD; Ivoclar AG).

Table 1. Effect of type of restoration on estimated risk for required endodontic treatment after cementation of anterior complete coverage, posterior complete coverage, posterior partial inlay, and posterior partial onlay glass-ceramic restorations

Restoration type	Units	IET	Cumulative Monitoring Years	Estimated Annual Risk of IET (%)	Relative Risk*	Survivor Function
Total	4511	76	50 436	0.15	NA	97.36
Anterior CC	1476	10	19 081	0.05	1.00	98.89
Posterior CC	2119	50	21 446	0.23	4.45	96.38
Posterior PC inlay	553	11	7941	0.14	2.64	96.78
Posterior PC onlay	363	5	1968	0.25	4.85	98.53

Anterior CC	Posterior CC	<.005
–	Posterior PC inlay	.015

Statistically significant difference (P<.05), log rank test. CC, complete coverage; IET, incidence of endodontic therapy; PC, partial coverage. *Relative risk compared with anterior complete coverage restorations.

The participants were recalled every 6 months. The status of the restoration(s) and teeth was evaluated clinically and radiographically and recorded, including the time to the need for endodontic therapy (from pulpal or periapical diagnosis indicating the need for endodontic therapy), or, if endodontic therapy was not needed, the time that the restoration had been retained in the mouth on the vital tooth. The above comprise a portion of the 28 parameters recorded for each participant, and restorations are listed in Table 1.[8] The time in service for a restoration was based upon the date of the last recall.

Definition of incidence of endodontic therapy (IET)

An outcome was recorded as incidence of endodontic therapy (IET) if a restoration required endodontic therapy after its definitive adhesive cementation. The diagnosis for the need for IET was based on the clinical (percussion, palpation, and cold test) and periapical radiographic (2-dimensional) analyses. The treating restorative dentist (K.A.M.) referred the patients to an endodontist for further analysis, diagnosis, and treatment. Any missing data were assigned a missing data value in the database.

Statistical analyses

Data available for the restorations included the variables described above. The survival of restorations or subsets of restorations grouped based on the variables described in Table 1[8] were displayed using Kaplan–Meier survival curves with clustering (frailty model analysis) if there were IETs.[35-38] The significance of differences between survival curves was determined using the log rank test (α=.05). The total time at risk was computed as the sum of the censoring and survival times for each group. Estimated risk was computed as the number of failures in that group divided by the corresponding total time at risk.

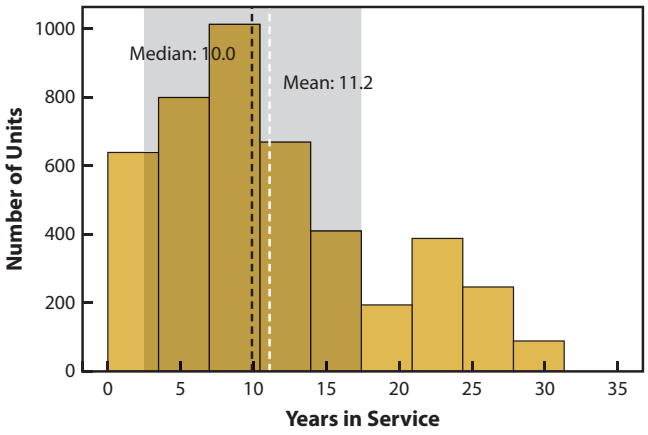

Figure 1. Years in service. *Black dotted line* represents median, and *white dotted line* represents mean time in service. Shaded area represents standard deviation (±7.5).

Various clinical parameters (type of restoration, dental arch, tooth position, age and sex of participant, and ceramic thickness) were evaluated by using Kaplan–Meier survival curves accounting for attrition bias. Statistical significance was determined by using the log rank test (α=.05).

RESULTS

Data collection began in 1986 and was truncated for this analysis after 35 years (420 months) in 2021. The median time in service was 10 years and the mean was 11.2 years (±7.5) (Fig. 1). The study included 1800 participants and 4511 units, of which 1476 were anterior complete coverage, 2119 posterior complete coverage, and 916 posterior partial coverage restorations (Table 1). Of the 1800 participants, 710 were men and 1090 were women. The mean age of the participant at the time of restoration placement was 62 with a range of 20 to 99 years.

There were 76 endodontic treatments recorded, of which 10 occurred in anterior complete, 50 in posterior complete, and 16 in posterior partial coverage restorations, providing a crude estimate of an annual percentage of an endodontic treatment of 0.15%, with the survivor function time at 30 years (Table 1). The incidence of 76 (1.68%) endodontic therapies occurred during a cumulative monitoring period of 50 436 years, with an overall survival rate of 97.36%. The average time to an endodontic treatment was 4.64 (0 to 23) years. A histogram of all times to endodontic treatment (Fig. 2) shows that most (67%, 52/76) occurred within 5 years.

IET in anterior complete, posterior complete, and posterior partial coverage restorations

Acid-etched glass-ceramic restorations were subset into 4 type categories (anterior complete coverage, posterior complete coverage, posterior partial inlay, and posterior partial onlay). The survivor functions for these 4 categories are presented in Table 1 and Figures 3–5. The

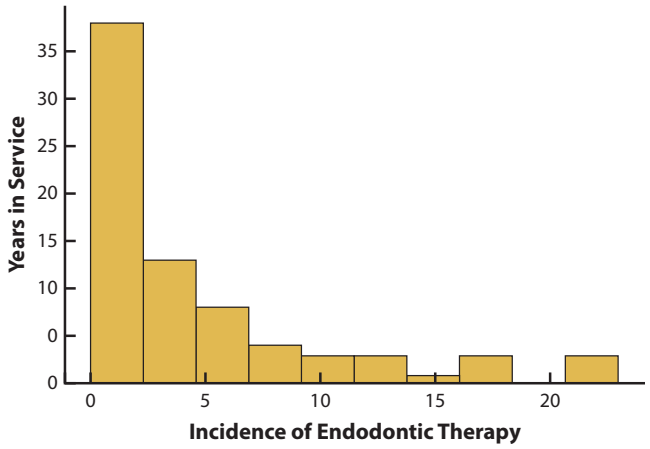

Figure 2. Times to incidence of endodontic therapy.

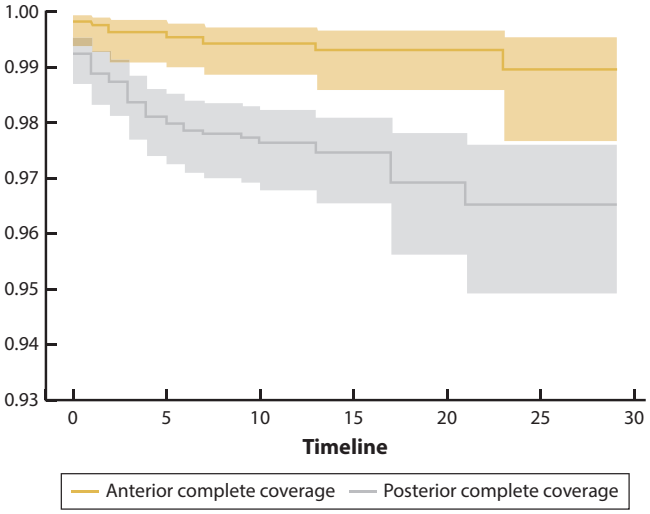

Figure 4. Kaplan–Meier survivor function of anterior complete and posterior partial coverage restorations requiring endodontic treatment after cementation. Significant difference found between these 2 groups (*P*<.005, log rank test). Shaded areas represent 95% confidence intervals.

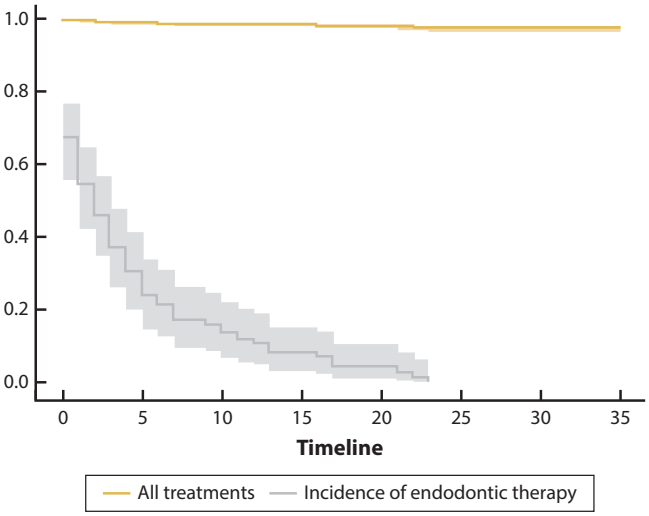

Figure 3. Kaplan–Meier survivor function of all restorations requiring endodontic treatment after cementation. Shaded areas represent 95% confidence intervals.

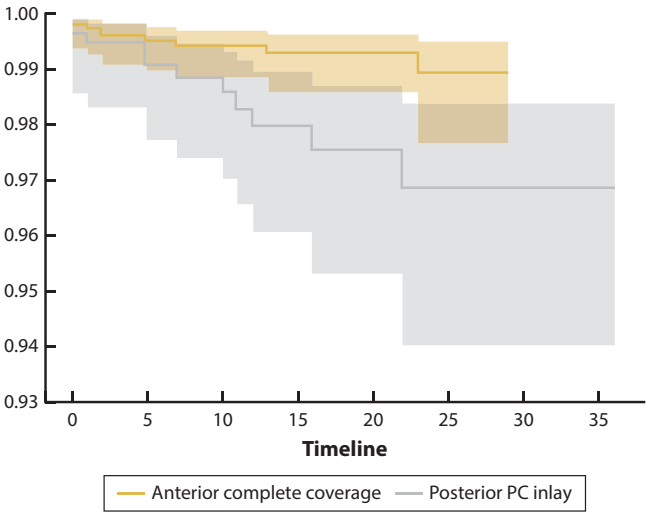

Figure 5. Kaplan–Meier survivor function of anterior complete coverage and posterior partial inlay restorations requiring endodontic treatment after cementation. Significant difference found between these 2 groups (*P*<.005, log rank test). PC, partial coverage. Shaded areas represent 95% confidence intervals.

probability of survival relative to the endodontic treatment of a typical anterior complete coverage restoration was 98.89% (n=1476, 10 IET). The probability of survival relative to the endodontic treatment of a typical posterior complete coverage restoration was 96.38% (n=2119, 50 IET). The probability of survival relative to the endodontic treatment of a typical posterior partial inlay restoration was 96.78% (n=553, 11 IET). The probability of survival relative to the endodontic treatment of a typical posterior partial onlay restoration was 98.53% (n=363, 5 IET).

A statistically significant difference occurred between anterior complete coverage and posterior complete coverage restorations, with a higher incidence in posterior complete coverage restorations (Table 1, Fig. 4) (*P*<.001, log rank test). A statistically significant difference was also seen between anterior complete and posterior partial inlay restorations, with a higher incidence in posterior partial inlay restorations (Table 1, Fig. 5) (*P*=.015, log rank test). No statistically significant difference was found in endodontic treatment occurrence between anterior complete coverage and posterior partial onlay restorations (*P*=.06, log rank test) or between posterior complete and posterior partial inlay (*P*=.304) or posterior partial onlay restorations (*P*=.480, log rank test).

Table 2. Effect of arch position on estimated risk for required endodontic treatment after cementation of anterior complete coverage, posterior complete coverage, posterior partial inlay, and posterior partial onlay glass-ceramic restorations

Arch	Procedure	Tooth	N of Units	N of IET	Cumulative Years	Annual Risk	Relative Risk	Survivor Function
Maxilla	Anterior CC	Canine	250	2	3146	0.06%	2.02	99.03%
		Lateral incisor	357	4	4706	0.08%	2.70	98.51%
		Central incisor	459	2	6348	0.03%	1.00	98.82%
	Posterior CC	Third molar	11	0	79	0.00%	0.00	100.00%
		Second molar	174	4	1256	0.32%	10.11	97.49%
		First molar	286	9	2154	0.42%	13.26	96.53%
		Second premolar	329	5	3871	0.13%	4.10	97.63%
		First premolar	365	5	4605	0.11%	3.45	97.72%
	Posterior PC inlay	Third molar	1	0	9	0.00%	0.00	100.00%
		Second molar	40	1	390	0.26%	8.14	97.50%
		First molar	56	2	689	0.29%	9.21	92.08%
		Second premolar	92	2	1217	0.16%	5.22	96.58%
		First premolar	59	3	1048	0.29%	9.09	91.92%
	Posterior PC onlay	Second molar	49	0	230	0.00%	0.00	100.00%
		First molar	68	3	339	0.88%	28.09	95.08%
		Second premolar	26	0	127	0.00%	0.00	100.00%
		First premolar	23	1	166	0.60%	19.12	95.65%
Mandible	Anterior CC	Canine	142	1	1620	0.06%	1.96	99.16%
		Lateral incisor	129	1	1547	0.06%	2.05	99.21%
		Central incisor	139	0	1714	0.00%	0.00	100.00%
	Posterior CC	Third molar	5	0	26	0.00%	0.00	100.00%
		Second molar	181	6	1247	0.48%	15.27	96.37%
		First molar	295	12	2239	0.54%	17.01	89.96%
		Second premolar	288	7	3676	0.19%	6.04	96.49%
		First premolar	185	2	2293	0.09%	2.77	98.82%
	Posterior PC inlay	Third molar	6	1	98	1.02%	32.39	83.33%
		Second molar	94	0	1259	0.00%	0.00	100.00%
		First molar	70	1	1090	0.09%	2.91	98.46%
		Second premolar	96	1	1506	0.07%	2.11	98.96%
		First premolar	39	0	635	0.00%	0.00	100.00%
	Posterior PC onlay	Third molar	2	0	10	0.00%	0.00	100.00%
		Second molar	73	0	423	0.00%	0.00	100.00%
		First molar	67	1	414	0.24%	7.67	98.31%
		Second premolar	39	0	177	0.00%	0.00	100.00%
		First premolar	16	0	82	0.00%	0.00	100.00%

CC, complete coverage; IET, incidence of endodontic therapy; PC, partial coverage.

IET in anterior complete, posterior complete, and posterior partial coverage restorations with dental arch

Acid-etched glass-ceramic restorations were subset into 2 dental arch categories (maxillary and mandibular), and survivor functions are summarized in Table 2. The probability of survival for a typical maxillary restoration was 97.33% at 35 years (n=2645, 43 IET) and in the mandibular was 97.52% at 35 years (n=1866, 33 IET). No statistically significant difference was found between the arches (P=.63, log rank test).

IET in anterior complete, posterior complete, and posterior partial coverage restorations with tooth position

The survivor functions for typical acid-etched glass-ceramic complete and partial coverage restorations with tooth positions are summarized in Tables 2 and 3. First molar restorations had the highest number of endodontic treatments in both arches, and the difference was statistically significant (P<.001, log rank test).

IET therapy in anterior complete, posterior complete, and posterior partial coverage restorations in men and women

Acid-etched glass-ceramic restorations were subset into 2 sex categories (men and women), and survivor functions are summarized in Table 4 and Figure 6. The probability of survival relative to the treatment of a typical anterior complete coverage restoration in men was 97.99% (n=511, 4 IET) at 35 years. The probability of survival relative to the endodontic treatment of a typical posterior complete coverage restoration in men was 95.97% (n=854, 24 IET) at 35 years. The probability

Table 3. Effect of tooth position on estimated risk for required endodontic treatment after cementation of anterior complete coverage, posterior complete coverage, posterior partial inlay, and posterior partial onlay glass-ceramic restorations

Arch	Tooth	N of Units	N of IET	Cumulative Years	Annual Risk	Relative Risk	Survivor Function
Maxilla							
Right	Third molar	6	0	40	0.00%	0.00	100.00%
	Second molar	133	2	955	0.21%	6.71	98.50%
	First molar	206	6	1648	0.36%	11.66	96.71%
	Second premolar	234	4	2783	0.14%	4.60	97.64%
	First premolar	217	4	2783	0.14%	4.60	95.77%
	Canine	120	1	1508	0.07%	2.12	99.11%
	Lateral incisor	183	2	2377	0.08%	2.69	98.16%
	Central incisor	232	1	3202	0.03%	1.00	98.08%
Left	Central incisor	227	1	3146	0.03%	1.02	99.56%
	Lateral incisor	174	2	2329	0.09%	2.75	98.85%
	Canine	130	1	1638	0.06%	1.95	98.96%
	First premolar	230	5	3036	0.16%	5.27	96.53%
	Second premolar	213	3	2432	0.12%	3.95	97.21%
	First molar	204	8	1534	0.52%	16.70	89.51%
	Second molar	130	3	921	0.33%	10.43	97.40%
	Third molar	6	0	48	0.00%	0.00	100.00%
Mandible							
Left	Third molar	4	1	59	1.69%	54.27	66.67%
	Second molar	181	3	1570	0.19%	6.12	98.12%
	First molar	228	5	1931	0.26%	8.29	97.51%
	Second premolar	210	3	2657	0.11%	3.62	97.32%
	First premolar	118	2	1378	0.15%	4.65	98.11%
	Canine	69	1	736	0.14%	4.35	98.25%
	Lateral incisor	64	0	785	0.00%	0.00	100.00%
	Central incisor	64	0	787	0.00%	0.00	100.00%
Right	Central incisor	75	0	927	0.00%	0.00	100.00%
	Lateral incisor	65	1	762	0.13%	4.20	98.41%
	Canine	73	0	884	0.00%	0.00	100.00%
	First premolar	122	0	1632	0.00%	0.00	100.00%
	Second premolar	213	5	2702	0.19%	5.93	97.29%
	First molar	204	9	1812	0.50%	15.90	90.73%
	Second molar	167	3	1359	0.22%	7.07	98.11%
	Third molar	9	0	75	0.00%	0.00	100.00%

CC, complete coverage; IET, incidence of endodontic therapy; PC, partial coverage.

Table 4. Effect of sex on estimated risk for required endodontic treatment after cementation of anterior complete coverage, posterior complete coverage, posterior partial inlay, and posterior partial onlay glass-ceramic restorations

Procedure	Sex	N of Units	N of IET	Cumulative Years	Annual Risk	Relative Risk	Survivor Function
Anterior CC	M	511	4	6314	0.06%	1.35	97.99%
Posterior CC	M	854	24	7851	0.31%	6.50	95.97%
Posterior PC inlay	M	183	3	2621	0.11%	2.44	97.88%
Posterior PC onlay	M	172	2	798	0.25%	5.33	98.65%
Anterior CC	W	965	6	12 767	0.05%	1.00	99.33%
Posterior CC	W	1265	26	13 595	0.19%	4.07	96.71%
Posterior PC inlay	W	370	8	5320	0.15%	3.20	96.22%
Posterior PC onlay	W	191	3	1170	0.26%	5.46	98.40%

CC, complete coverage; IET, incidence of endodontic therapy; M, men; PC, partial coverage; W, women.

of survival relative to the endodontic treatment of a typical posterior partial inlay restoration in men was 97.88% (n=183, 3 IET) at 35 years. The probability of survival relative to the endodontic treatment of a typical posterior partial onlay restoration in men was 98.65% (n=172, 2 IET) at 35 years.

The probability of survival relative to the endodontic treatment of a typical anterior complete coverage

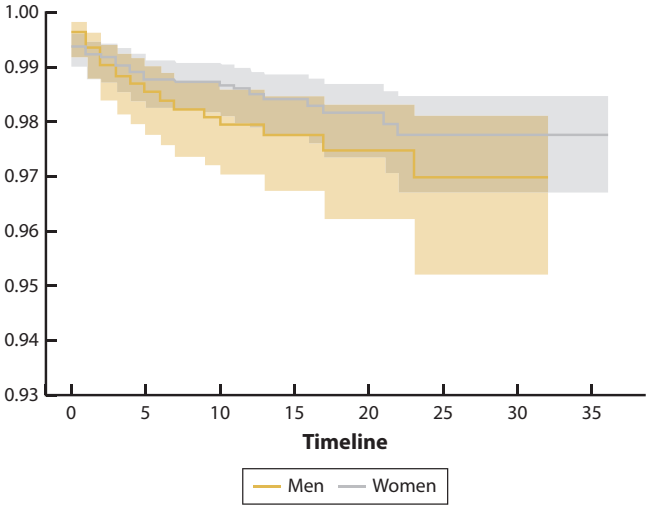

Figure 6. Kaplan–Meier survivor function between all restorations requiring endodontic treatment after cementation in men and women. No significant difference found between these 2 groups (*P*=.22, log rank test). Shaded areas represent 95% confidence intervals.

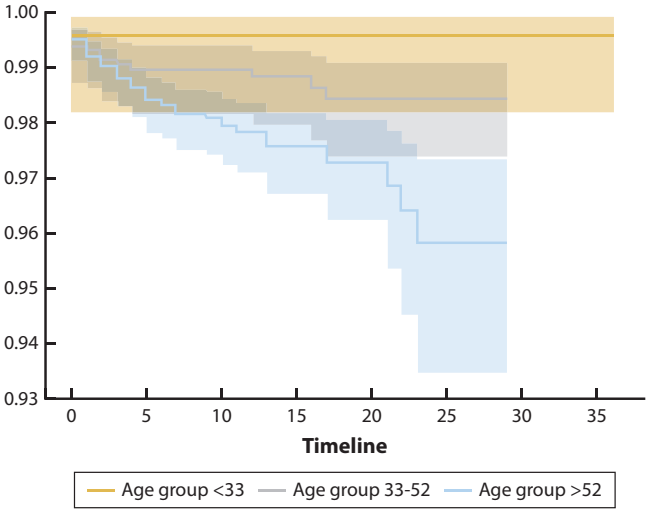

Figure 7. Kaplan–Meier survivor function between all restorations requiring endodontic treatment after cementation in 3 age groups. Significant difference found between these groups (*P*<.05, log rank test). Shaded areas represent 95% confidence intervals.

Table 5. Effect of age on estimated risk for required endodontic treatment after cementation of anterior complete coverage, posterior complete coverage, posterior partial inlay, and posterior partial onlay glass-ceramic restoration

Age Group	N of Units	N of IET	Cumulative Years	Annual Risk	Relative Risk	Survivor Function
<33	441	2	5818	0.03%	1.00	99.55%
33-52	1231	16	18 241	0.09%	2.55	98.40%
>52	2836	58	26 366	0.22%	6.40	95.57%

IET, incidence of endodontic therapy.

Table 6. Effect of ceramic thickness on estimated risk for required endodontic treatment after cementation of anterior complete coverage, posterior complete coverage, posterior partial inlay, and posterior partial onlay glass-ceramic restorations

Thickness Category	N of Units	N of IET	Cumulative Years	Annual Risk	Relative Risk	Survivor Function
<1 mm	1067	12	15 997	0.08%	1.00	98.37%
≥1 mm	3444	64	34 439	0.19%	2.48	96.95%

IET, incidence of endodontic therapy.

restoration in women was 99.33% (n=965, 6 IET) at 35 years. The probability of survival relative to the endodontic treatment of a typical posterior complete coverage restoration in women was 96.71% (n=1265, 26 IET) at 35 years. The probability of survival relative to the endodontic treatment of a typical posterior partial inlay restoration in women was 96.22% (n=370, 8 IET) at 35 years. The probability of survival relative to the endodontic treatment of a typical posterior partial onlay restoration in women was 98.40% (n=191, 3 IET) at 35 years.

No statistically significant difference (*P*=.21, log rank test) was found. The relative risk was 1.09 when teeth were restored in men as compared with women.

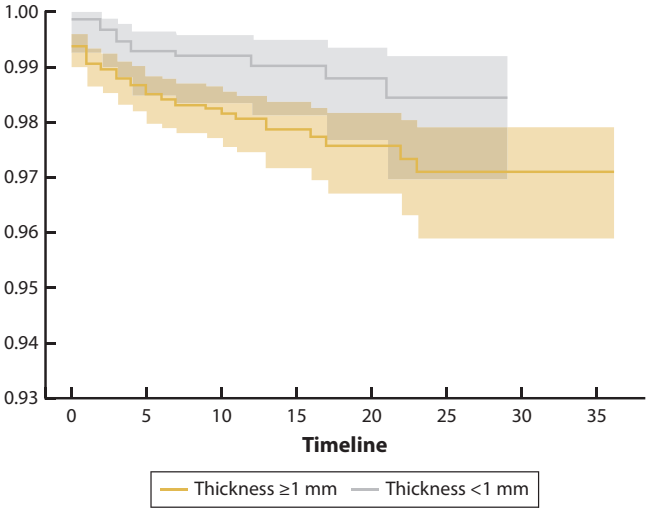

Figure 8. Kaplan–Meier survivor function between all restorations with thickness ≥1 mm and<1 mm requiring endodontic treatment after cementation. Significant difference found between these groups (*P*=.02, log rank test). Shaded areas represent 95% confidence intervals.

IET in anterior complete, posterior complete, and posterior partial coverage restorations in three age groups

Acid-etched glass-ceramic restorations were subset into 3 age categories (<33, 33 to 52, >52). The survivor functions of 3 age groups are summarized in Table 5 and Figure 7. The probability of survival relative to the endodontic treatment of a typical acid-etched glass-ceramic restoration in the <33-year age group was 99.55% (n=441, 2 IET) at 35 years. The probability of survival relative to the endodontic treatment of a typical acid-etched glass-ceramic restoration in the 33- to 52-year age group was

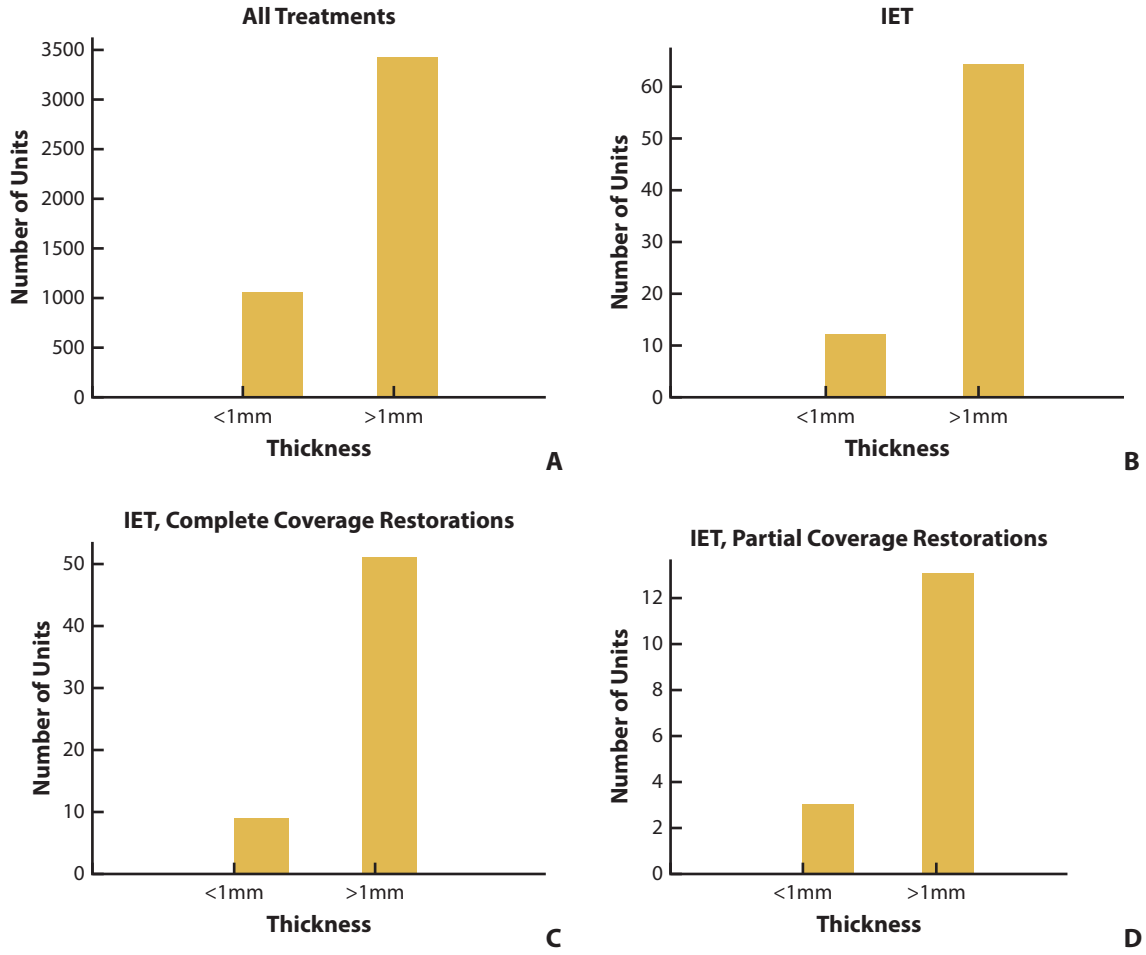

Figure 9. Incidence of endodontic therapy (IET) in ≥1 mm and <1 mm thickness categories. A, All restorations with thickness of ≥1 mm and <1 mm. B, All restorations with IET in thickness categories of ≥1 mm and <1 mm. Significant difference found (*P*=.02, log rank test). C, Complete coverage restorations with IET. D, Partial coverage restorations with IET.

98.40% (n=1231, 16 IET) at 35 years. The probability of survival relative to the endodontic treatment of a typical acid-etched glass-ceramic restoration in the >52-year age group was 95.57% (n=2836, 58 IET) at 35 years. A statistically significant difference was found between the age groups, with a higher incidence of IET in the >52-year age group (*P*=.007, log rank test).

IET in anterior complete, posterior complete, and posterior partial coverage restorations with thickness greater than or equal to and less than 1.0 mm

Acid-etched glass-ceramic restorations were subset into 2 thickness categories (≥1 mm and at least 1 surface <1 mm). The survivor functions of 2 thickness categories are summarized in Table 6 and Figures 8 and 9. The probability of survival relative to the endodontic treatment of a typical restoration with all surfaces ≥1 mm was 96.95% (n=3444, 64 IET), with an estimated annual risk of 0.19%. The probability of survival relative to the endodontic treatment of a typical restoration with at least 1 surface <1 mm was 98.37% (n=1067, 12 IET), with an estimated annual risk of 0.08%. A statistically significant difference was found between the thickness categories (*P*=.02, log rank test), with a higher endodontic treatment rate in the restorations with all surfaces ≥1 mm.

DISCUSSION

The long-term clinical performance relative to the endodontic treatment of 4511 glass-ceramic complete and partial coverage restorations was evaluated. The overall survival rate was 97.36% over 30 years. A statistically significant difference was found in the endodontic treatment rate between anterior and posterior complete coverage restorations, between posterior partial coverage inlay and anterior complete coverage restorations, among the tooth categories, age groups, and thickness categories. Therefore, the null hypotheses were rejected. No other statistical confounding variables were recorded.

The long-term performance of indirect restorations can be influenced by multiple oral and systemic patient-

related factors, as well as material and treatment-related procedures.[12] Opinion leaders in dentistry have expressed ongoing concerns that complete coverage restorations result in higher loss of tooth vitality that eventually decreases the long-term prognosis of these teeth.[22] It has been hypothesized that partial coverage restorations would result in a reduced incidence of loss of pulp vitality. The authors are unaware of studies that have compared IET in complete and partial coverage restorations. Therefore, the current study aimed to answer this question and compare the incidence of endodontic treatment after receiving either a complete or a partial coverage glass-ceramic restoration.

Pulp necrosis after receiving complete coverage restorations has been reported to vary between 1% and 19% based on the follow-up times of 5 to 25 years. [16-26] Most of these studies retrospectively evaluated metal-ceramic or obsolete ceramic crown systems that required invasive tooth preparation. Cheung et al[23] reported the survival rate of pulp vitality of single metal-ceramic crowns to be 81.2% after 15 years. This retrospective study was conducted in a dental teaching hospital. Another educational institution-based retrospective study determined the periapical status of crowned teeth after 25 years. Initial survival at 5 years was 98%, decreasing to 83% at 25 years. [25]

The reported loss of tooth vitality in private practice-based studies appears to be lower. A 25-year study conducted in a specialty prosthodontic practice reported 6 teeth with endodontic breakdown and 1 endodontic treatment (7 in total) out of 2340 metal-ceramic crowns.[22] Another single-operator study reported 6 endodontic complications out of 155 metal-ceramic crowns with up to 50 years of observation.[16] The results of the current study are consistent with those of these single-operator specialty practice results, with 76 (1.68%) endodontic therapies in 4511 complete and partial coverage restorations with over 30 years of follow-up.

Predoctoral dental students with little experience and underdeveloped hand skills have been reported to influence the outcomes of various dental procedures.[39,40] In the present study, 1 experienced prosthodontist (K.A.M.) was responsible for all restorations in his practice-based laboratory. Although the results may not be generalized to other clinicians, this experimental design eliminated the major potential confounding factor of hand skills and focused on the true occurrence of endodontic treatment after receiving either a complete or a partial coverage glass-ceramic restoration. Another critical difference between the educational institution and the specialty private practice is the treatment time, with most restorative treatments taking longer in university clinics. In the present private practice, the interim restoration and the timing of impression making and the insertion of the definitive restorations were optimized. Additionally, pulpal evaluation and diagnosis was done before the restorative procedures. Typically, experienced clinicians pursue thorough diagnosis and treatment planning, with less likelihood of leaving pulpal pathology undetected.

Statistically significant difference occurred between anterior complete coverage and posterior complete coverage restorations, with a higher incidence of endodontic therapy in the posterior complete coverage restorations. A statistically significant difference was also seen between anterior complete and posterior partial inlay restorations, with a higher incidence in posterior partial inlay restorations. One of the explanations is the possible lack of the restorative space in the posterior region, instigating more preparations with proximity to the pulp.[41-44] However, existing caries and structural compromise have been shown to result in higher rates of pulpal necrosis and the need for endodontic therapy after preparations.[22,45] Posterior inlay restorations are usually caries-related, whereas onlays could be used for restoring tooth structure loss after erosion or attrition.[9,13,44] The higher rate of endodontic therapy in the first molars can also be explained by the caries-related structural damage, as first molars have a higher prevalence of caries.[46]

No difference was found in the endodontic treatment rate between anterior complete coverage and posterior partial onlay restorations, or between posterior complete and posterior partial coverage restorations (inlay and/or onlay). Therefore, the results of the current study do not support the hypothesis that partial coverage restorations would result in a lower endodontic treatment rate. On the contrary, the authors question the treatment modality of multiple restorations for a single tooth where the amount of tooth structure removal is undoubtably minimized.[14,15] However, multiple single-tooth restorations entail more technique sensitivity and require better hand skills, both from the clinicians and the dental laboratory technician, possibly leading to clinical errors. Additionally, these restorations have several bonding interfaces, and long-term clinical data to demonstrate their behavior in the demanding oral environment are lacking.

All the restorations in the present study were adhesively luted. Leucite-reinforced Empress and lithium disilicate e. max are both etchable materials, allowing strong micromechanical bonding to the dental substrates.[27] The dental substrates were also treated according to standardized bonding protocols.[6-8]

Etching the prepared tooth with phosphoric acid removes the smear layer and associated bacteria, providing a more predictable bonding substrate.[47-49] After the dentin had been acid etched, a desensitizer (GLUMA; Kulzer GmbH) consisting of 5% glutaraldehyde and 35% water-soluble monomer 2-hydroxyethyl methacrylate (HEMA) was applied before the dentin

bonding agent.[6-8] Application of this desensitizer to etched dentin has been shown to increase the stability of the resin-dentin bond through the inhibition of matrix metalloproteinases (MMPs).[50] Additionally, the HEMA enhances wetting properties and promotes adaptation of hydrophobic resin to hydrophilic dentin.[51,52] Resin cements have been reported to result in low solubility[29,32,53] and the combination of the desensitizer with standardized bonding protocols and resin cements may have minimized micromotion and microleakage, resulting in reduced pulpal inflammation. The findings of the current study encourage the use of adhesive cementation protocols for complete and/or partial coverage glass-ceramic restorations for predictable long-term outcomes.

A statistically significant difference was found among the age groups, with a higher incidence of endodontic therapy in the >52-year age group. Walton et al,[22] reporting on the outcomes of metal-ceramic restorations, explained that structurally damaged teeth had reduced survival rates. Although the current study did not categorize the status of the teeth before receiving the restoration, it is likely that the older age group would have more preexisting dental conditions. Although younger patients are characterized as having larger pulp chambers than older patients with reduced pulp space because of the deposition of secondary dentin with age,[54,55] if the preparation is completed according to the protocols, this does not seem to result in a higher incidence of loss of tooth vitality after a complete or a partial coverage restoration.

A statistically significant difference was found between the glass-ceramic thickness categories, with a higher incidence of endodontic therapy in the restorations with all surfaces ≥1 mm (Figs. 8 and 9). Previous studies from the same group of authors did not find statistically significant differences in the clinical survival of these 2 thickness categories.[6-8] If survival is not compromised, but pulpal vitality results are improved these findings should encourage the updating of preparation protocols for glass-ceramic restorations and the introduction of more conservative (<1 mm) preparations.

What is considered minimally invasive dental treatment is unclear, particularly when there is a significant carious lesion. Treatment with indirect complete and partial coverage ceramic restorations may in fact entail the removal of more tooth structure than a direct restoration to eliminate undercuts and create the required taper and the path of insertion.[13] However, large direct composite resin restorations in posterior teeth have been reported to have an annual failure rate of 1% to 3%,[56] with a trend for increased failure rate with larger restorations.[57] According to national insurance databases, 4-year annual failure rates range from 4% to 9%, with the highest rates for restorations of 3 or more surfaces.[57,58] Whether recurrent caries and retreatment of a failed direct restoration or a preparation for an indirect restoration would result in more conservative tooth structure outcomes has yet to be quantified and determined. Perhaps time in service should be part of the definition of minimally invasive dentistry. Would there be more biological and financial benefits from a restoration that needs to be replaced with a certain frequency or from one that can last for 30+ years?

Preexisting dental conditions such as structural damage or caries are risk factors that may compromise the long-term prognosis of a tooth. Any treatment procedure has a biological effect on the pulp. In fact, a recent study reported statistically significant differences in pulp necrosis in teeth with preoperative caries or preexisting restorations.[45] Another unanswered question is how long the restorations are expected to last. Can a failure after 30 years be still considered a failure?[12]

The average time to endodontic therapy was 4.64 (0 to 23) years, with most (67%, 52/76) occurring within 5 years. This shows that should a tooth necessitate endodontic therapy after receiving either a complete or a partial coverage glass-ceramic restoration this will be expected to happen within the first 5 years after the treatment procedure.

It is difficult to provide clinical evidence in prosthodontics. To detect clinically relevant information, a high number of units and long-term follow-up are needed.[59] Therefore, the current study, evaluating 4511 units over 30 years, holds value. More importantly, the authors are unaware of a previous study that compared the number of required endodontic therapy after receiving either a complete or a partial coverage glass-ceramic restoration. Based on the findings of the current study, the authors recommend choosing between a complete or a partial coverage restoration, not based on an expected improved biological outcome but rather on the extent of caries, periodontal condition, size of the failing preexisting restoration, and amount of remaining healthy tooth structure that would allow for adequate support and resistance and retention form. The clinical performance of 4511 vital teeth with restorations was excellent, with an estimated cumulative survival of 97.36% relative to the endodontic therapy. The results emphasize that providing endodontic therapy before a fixed prosthesis in teeth with a healthy pulp can be considered unnecessary for long-term success.

CONCLUSIONS

Based on the findings of this clinical study, the following conclusions were drawn:

1. The clinical performance of 4511 units up to 35 years was excellent, with an estimated cumulative survival of 97.36% and two-thirds of endodontic treatments occurring within the first 5 years.

2. Posterior complete coverage restorations had a significantly higher rate of endodontic treatment than anterior ones. Their overall clinical performance relative to the IET was still high, with a cumulative survival of 96.38% over 30 years.
3. Posterior inlay restorations had a significantly higher endodontic treatment rate than anterior complete coverage restorations. Their overall clinical performance relative to the endodontic treatment was still high, with a cumulative survival of 96.78% over 30 years.
4. A statistically significant difference was found between the first molars and other teeth, with a higher rate of endodontic treatment for the first molar group.
5. A statistically significant difference was found between the age groups, with a higher rate of endodontic treatment for the >52-year age group.
6. A statistically significant difference was found between the thickness categories, with a higher incidence in the restorations with all surfaces $\geq$1.
7. No significant difference in the endodontic treatment rate was found between posterior complete and partial coverage onlay restorations or between men and women.
8. The type of restoration (complete or partial) should be chosen considering the extent of caries, periodontal condition, size of the failing preexisting restoration, and the amount of remaining healthy tooth structure that would allow for proper support and resistance and retention form.
9. Endodontic therapy before a fixed prosthesis in teeth with a healthy pulp can be considered unnecessary for long-term clinical success.

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