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Direct posterior restorations: clinical results and new developments

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Enhanced dental care and growing interest in caries-free teeth have changed the prevalence and disease pattern of caries. Patients are living longer and retaining more of their natural teeth [1]. Alterations in dental restorative treatment patterns, combined with the introduction of new and improved restorative materials and techniques, affect the longevity of dental restorations [2]. Marked changes in the use of restorative materials have occurred during the past 10 to 20 years [3–5], and aesthetic considerations are growing in importance for the restoration of posterior teeth [6]. Alleged adverse health effects and environmental concerns about the release of mercury give rise to controversial discussions about the use of amalgam as a contemporary restorative material [3,7–9]. Aesthetic direct alternatives to amalgam restorations include glass ionomers, resin-modified glass ionomers, compomers, and resin-based composite restorations. This article analyzes the dental literature, predominantly of the past decade, for the longevity of direct restorations in class I and II cavities of permanent posterior teeth and identifies new developments in restoring these types of cavities. Only clinical studies with at least 3 years' duration and more than 20 restorations were considered for this survey.

Clinical results of direct posterior restorations in class I and II cavities

Direct resin-based composite restorations

There is widespread use of composite resins for the restoration of posterior teeth, even in stress-bearing areas. The results of selected clinical studies

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are summarized in Table 1. Annual failure rates of posterior composite restorations range from 0% to 9% [10–18].

Mjör [2] reported a median longevity of 6 years for 537 composite restorations placed by general practitioners in Sweden. Secondary caries (38%), bulk fracture (16%), marginal fracture (4%), discoloration (12%), poor anatomic form (9%), and fracture of the tooth (13%) accounted for the failure of these restorations. Discoloration as a reason for replacement of restorations is limited to tooth-colored dental materials. In 1989, Moffa [16] described a survival rate of 80% for class I composite restorations after 5 years and 55% for class II cavities. In another patient population, a survival rate of 41.7% after 12 years of clinical service was reported, with recurrent caries (40.6%), fracture (20.7%), and wear (13.4%) as the main reasons for failure [16]. In the results of a multicenter clinical trial of 711 class I and II Occlusin (ICI Dental; Macclesfield, UK) restorations, Letzel [19] described a 4-year survival rate of 94%. Loss of material due to insufficient wear resistance and recurrent caries accounted for the failure of 35 and 13 restorations of Occlusin, respectively. The results of a cross-sectional survey in Scandinavia indicated a median survival time of 4 years in class I and 4 to 7 years in class II cavities for posterior composite restorations [20]. Secondary caries (>65%) was stated as the main reason for restoration failure, followed by bulk fracture (>20%). Interestingly, Burke et al. [21] recently found a higher mean longevity for class II composite restorations (4.6 years) compared with class I restorations (3.3 years). Manhart et al. [22] reported an 87% survival rate for composite restorations in class I and II cavities after 3 years. In 1990, Qvist et al. [23] reported 3 years as the median longevity for class I and class II composite restorations in Denmark. In 1994, el Mowafy et al. [24] published the results of a comprehensive statistical meta-analysis. They revealed an 89.5% nonfailure rate after 5 years of clinical service for posterior composite restorations. A cross-sectional survey in Sweden exhibited a mean age of 8 years for 2609 failed resin composite restorations, with approximately 33% secondary caries as diagnosis for replacement [25]. Mjör [26] stated a median longevity of 7 years for class I composite restorations and 4 years for mesial-occlusal-distal restorations. Wilson et al. [27–31] reported a success rate of 84% in a 5-year prospective clinical trial with yearly follow-up intervals. Seventy-five percent of the failed restorations were inserted in class II cavities, whereas the remaining 25% were simple occlusal restorations. Wassell et al. [32] reported a survival rate of 96% after 3 years of clinical service for 71 class I and II incrementally placed direct composite restorations. No case of recurrent caries was detected. In a 3-year survey of class I restorations, Smales et al. [18] indicated a perfect survival rate for P-30 (3M Dental; St. Paul, MN) composite restorations and 93.9% for Visio-Molar (ESPE; Seefeld, Germany) restorations. Geurtsen and Schoeler [33] described a clinical survival rate of 87% for 1209 class I and II Herculite XR (Kerr; Orange, CA) restorations. Statistical analysis revealed significantly more alpha ratings in premolars (82%) than in molars (77%). No difference was found for class I and II restorations. The 50% survival time was calculated by extrapolation of the clinical data with a Weibull analysis and was determined to be 9 years. Barnes et al. [10] reported a survival rate of 90% after 5 years for posterior Ful-Fil (Dentsply; Milford, DE) restorations and 77% after 8 years of clinical service. The predominant reasons for replaced restorations were secondary caries and excessive wear. Similar results were indicated by Helbig et al. [12] for bonded P-50 (3M Dental; St. Paul, MN) restorations, with a survival rate of 88.9% after 5 years. The results of Lundin and Koch [34], with a 90% success rate after 5 years and 79% success rate after 10 years, support the above-mentioned findings. Raskin et al. [35] reported an estimated 10-year failure rate between 40% and 50% for class I and II Occlusin restorations. Loss of occlusal anatomic form during the first 5 years and loss of approximal contacts near the end of the study accounted for most of the failures. Recurrent caries and bulk fracture were recorded infrequently. In contrast to other studies, location, class, and size of the restorations were not found to influence the treatment outcome significantly. A 17-year study of ultraviolet-cured posterior composites by Wilder et al. [36] demonstrated an excellent success rate of 76%. Color matching (94% alpha), marginal discoloration (100% alpha), marginal integrity (100% alpha), secondary caries (92% alpha), surface texture (72% alpha), anatomic form (22% alpha), and a mean occlusal wear of 264 μm were recorded after 17 years. Most of the wear (75%) occurred in the first 5 years, confirming the findings of Raskin et al. [35]. Mair [37] indicated a survival rate of 92.9% for three posterior composite resins after 10 years, with mean wear rates between 300 and 400 μm.

Amalgam restorations

Amalgam was the material of choice for the restoration of class I and II cavities for more than 100 years [8]. The results of selected clinical studies are summarized in Table 2. Annual failure rates range between 0% to 7% for non-gamma-2 and gamma-2-containing alloys, with observation periods of up to 20 years [15,18,20,37–56]. Several authors found a higher survival time and a lower annual failure rate for amalgam restorations in class I defects compared with class II cavities [38,41,57]. Robinson [50] found a 10-year median survival time for amalgam restorations in a 20-year survey. Interestingly, he reported a relatively high percentage of mesio-occlusal and disto-occlusal restorations surviving the 20-year period, whereas a high percentage of occlusal restorations did not. This finding seemed to be a result of the development of new approximal caries during the lifetime of occlusally limited restorations. Lavelle [44] described recurrent caries (>50%), fractures (>26%), and dimensional defects (>20%) as being the main problems, whereas pulpal irritations accounted for only 1% of the restoration failures. The findings of a retrospective study of 2344 class I and II amalgam restorations in northeast England demonstrated no statistically significant

Table 1
Longevity of direct composite restorations in posterior teeth[a]

Year of publication	First author	Years	Black class	Restorative materials	Restorations (n)	Patients (n)	SD	Annual failure rate (%)	Remarks
1988	Wilson [31]	5	I and II	Occlusin	67		L	2.8	Large and moderately sized restorations. Higher failure rate in class II than in class I.
1989	Letzel [19]	4	I and II	Occlusin	711		L	1.5	Multicenter clinical trial. Main reason for replacement: wear and recurrent caries.
1989	Lundin [13]	4	I and II	Occlusin and PC4502	137	65	L	4	142-μm average wear after 4 years. Most of the restorations that failed were classified as large.
1989	Moffa [16]	5	I II	Composite resins (not specified)	356		C	4 9	Interproximal gingival area of class II restorations was found to be an area of early failure.
1990	Smales [18]	3	I	Visio-Molar P-30	42 251		L	2 0	Small restorations.
1990	Welbury [55]	5	I	Prisma-Fil and Prisma-Shield	150	103	L	1.1	Minimal composite restorations combined with a fissure sealant.
1991	Barnes [10]	5 8	I and II	Ful-Fil	33	12	L	2 2.9	Main reason for replacement: recurrent caries.
1992	Freilich [11]	3	I and II	Heliomolar, Marathon, P-30, experimental composite	105	46	L	0.3	
1993	Mjör [15]	5	II	P-10	91		L	3	Estimated survival function. Small class II cavities.

1994	el Mowafy [24]	5	I and II	Composite resins (not specified)	191		C	2.1	
1995	Wassell [32]	3	I and II	Brilliant	71	54	L	1.3	61% class II restorations. No secondary caries.
1997	Geurtsen [33]	4	I II	Herculite XR	109 1100	412	C	3.3	More alpha ratings in premolars than in molars. No difference between class I and II cavities.
1998	Helbig [12]	5	I and II	P-50	27	22	L	2.2	Marginal integrity and surface texture significantly deteriorated after 5 years.
1998	Mair [37]	10	II	P-30, Occlusin, Clearfil Posterior	56		L	0.7	P-30 and Occlusin showed approximately 400-μm wear, Clearfil Posterior 300 μm after 10 years.
1998	Mertz-Fairhurst [14]	10	I	Miradapt plus Delton sealant	85		L	2	Ultraconservative restorations.
1998	Nordbo [17]	7	II	Occlusin Ful-Fil	34 17	37 (all)	L	1.7 5.9	Main reason for replacement: recurrent caries.
1999	Lundin [34]	5 10	I and II	Resin-based composites	137		L	2 2.1	After 10 years an evaluation based on the documentation sent in by the patient's present dentist was made.
1999	Raskin [35]	10	I and II	Occlusin	100	36	L	4–5	Main reason for replacement: loss of anatomic form and approximal contacts.
1999	Wilder [36]	17	I and II	Estilux, Nuva-Fil, Nuva-Fil PA, Uvio-Fil	85	33	L	1.4	264-μm wear after 17 years. Most wear occurred in the first 5 years.
2000	Manhart [22]	3	I and II	Tetric, Blend-a-Lux, Pertac	43		L	4.3	Main reason for failure: marginal opening and secondary caries

[a] Study duration ≥ 3 years; restorations, $n > 20$.
SD = study design; L = longitudinal; C = cross-sectional.

Table 2
Longevity of amalgam restorations in posterior teeth[a]

Year of publication	First author	Years	Black class	Restorative materials	Restorations (n)	Patients (n)	SD	Annual failure rate (%)	Remarks
1969	Allan [38]	10	I	Amalgam (alloys not specified, gamma-2 alloys)	78		C	4.6	Slightly better performance in class I cavities.
			II		92			6.1	
1971	Robinson [50]	20	I and II	Amalgam (alloys not specified, gamma-2 alloys)	145		C	3.9	75% of the amalgam restorations lasted >5 years.
1976	Lavelle [44]	20	I and II	Amalgam (alloys not specified, gamma-2 alloys)	6000		C	4.8	Main reasons for replacement: secondary caries, fracture, dimensional defects.
1976	Lavelle [44]	20	I and II	Amalgam (alloys not specified, gamma-2 alloys)	400		L	7	
1977	Allan [39]	20	I and II	Amalgam (alloys not specified, gamma-2 alloys)	148		C	4.3	
1981	Crabb [41]	10	I	Amalgam (alloys not specified, gamma-2 alloys)	269		C	4.1	Slightly better performance in class I cavities.
			II		530			6.3	
1984	Paterson [47]	15	I	Solila	854		C	6.3	No statistical difference between class I and II amalgams.
			II		1490			7.1	
1989	Letzel [45]	5–7	I and II	Conventional and high-copper alloys	2341		L	0.6	
1989	Moffa [16]	5	I	Amalgam (alloys not specified)	314		C	2	
			II					5	
1990	Welbury [55]	5	I	Amalcap	150	103	L	1.5	All amalgams failed because of recurrent caries.

1991	Jokstad [42]	7–10	II	4 non–gamma-2 alloys 1 conventional alloy	256	141	C	2.7–3.8	Main reasons for replacement: secondary caries and bulk fracture; no significant difference between gamma-2 and non–gamma-2 alloys.
1991	Osborne [46]	14	I and II	5 gamma-2 alloys and 7 non–gamma-2 alloys	367	40	L	0.9	Gamma-2 amalgams had a 84% success rate, non–gamma-2 alloys had 91.6% success rate.
1991	Pieper [48]	9–11	I	Amalgam (alloys not specified)	129		C	1.3–1.6	
			II		413				
1991	Smales [52]	11–18	I and II	New True Dentalloy, Dispersalloy, Indiloy, Shofu Spherical	1680		C	1.0–1.7 and 6.3	Shofu spherical showed an annual failure rate of 6.3%, whereas the other alloys failed 1–1.7% a year.
1991	Smales [53]	18	I and II	New True Dentalloy, Shofu Spherical, Dispersalloy, Tytin, Indiloy	1801		C	1.7	
1991	Smales [160]	15	II		768		C	1.9	No difference in survival time between cuspal coverage class II amalgam restorations and restorations without cusp coverage.
1993	Mjör [15]	5	II	Dispersalloy	88		L	1	Estimated survival function. Small class II cavities.

(*continued on next page*)

Table 2 (*continued*)

Year of publication	First author	Years	Black class	Restorative materials	Restorations (n)	Patients (n)	SD	Annual failure rate (%)	Remarks
1993	Plasmans [82]	4	II		300		L	0.5 2.5	Extensive amalgam restorations in molars; 2% absolute failures (restoration dislodged or removed); 10% relative failures.
1994	Jokstad [20]	>10	I	Amalgam (alloys not specified)	803		C	3.6	Increased number of surfaces in class II restorations resulted in a lower median longevity.
			II		>3000			4.5	
1994	Mahmood [161]	>14	I and II	Amalgam (alloys not specified)	245 (P)		C	6.3	Study conducted in Pakistan (P) and Australia (A).
					455 (A)			5.6	
1996	Gruythuysen [162]	15	II		1544		L	1.2	Factors influencing the replacement rates were gender, type of restoration, and operator.
1996	Smales [59]	15	II	Amalgam (alloys not specified)	160		C	3.5	Cuspal coverage amalgam restorations.
1996	Wilson [56]	5	I and II	High-copper amalgams (Sybralloy, Dispersalloy, Tytin)	172		L	1	Deterioration was greatest in molars and large-sized restorations.
1997	Hawthorne [163]		I and II	Amalgam (alloys not specified)	1371		C	2.2	Life-table method.

1997	Mjör [2]	>25	I and II	Amalgam (alloys not specified)	282		C	5.6	Main reasons for replacement: secondary caries (50%) and fracture (29%).
1997	Roulet [51]	6	I and II	5 high-copper amalgams (Amalcap plus, Contour, Permite C, Dispersalloy, Si-Am-Kap)	163	43	C	2.1	Kaplan-Meier method. Main reason for replacement: fracture.
1997	Smales [54]	5	II	Amalgam (alloys not specified)	160		C	4.5	Extensive amalgam restorations with cusp replacement.
		10						3.3	
		15						3.5	
1998	Kreulen [43]	15	II	New True Dentalloy, Tytin, Cavex	1117	183	L	1.1	Replacement risk for MOD restorations is significantly higher than for MO/OD restorations.
1998	Mair [37]	10	II	New True Dentalloy, Solila Nova	35		L	0.6	
1998	Plasmans [49]	8	II	Cavex (non–gamma-2)	266	130	L	1.5	Large amalgam restorations in molars with cusp replacement.
1999	Cichon [40]	8	1 surface	Amalgam (alloys not specified)	820		C	2.5	Patients with severe mental or physical handicaps.
			2 surfaces					3.4	
			3 surfaces					3.6	
1999	Kamann [57]	6	I	Luxalloy	62		L	2.7	Main reason for replacement: secondary caries.
			II		21			5.6	

[a] Study duration ≥3 years; restorations, n > 20.
SD = study design; L = longitudinal; C = cross-sectional.

difference between the median survival time of class I (8 years) and class II (7 years) lesions [47]. Osborne et al. [46] compared the clinical performance of five gamma-2 alloys with seven non-gamma-2 alloys after 14 years of clinical service and found a loss rate of 16% for the gamma-2-containing group, whereas only 8.4% of the non-gamma-2 alloys failed. Furthermore, their findings demonstrated a significantly greater rate of marginal failure for traditional low-copper alloys. As a result of a cross-sectional survey, in 1997 Mjör [2] reported a median longevity of 9 years for 282 amalgam restorations placed by general practitioners in Sweden. The clinical diagnoses of secondary caries (50%) and bulk fracture of the restoration (29%) were the main reasons for replacement. The median survival time of 10 years for small restorations and only 8 years for large restorations showed that cavity size influenced the longevity of amalgam restorations [58]. Moffa [16] demonstrated after 5 years a survival rate of 90% and 75% for class I and class II amalgam restorations, respectively. In another patient population, a survival rate of 65.5% after 12 years of clinical service was reported, with fracture (31.5%), recurrent caries (29%), and defective margins (25.7%) being the main reasons for failure [16]. In a recent survey, Burke et al. [21] reported a mean age of 7.4 years for amalgam restorations in class I defects and 6.6 years in class II defects in the United Kingdom. Smales and Hawthorne [59] found a survival rate of 66.7% after 10 years and 47.8% after 15 years for large, cusp-covered amalgam restorations in Australia. Wilson et al. [56] evaluated 172 class I and II amalgam restorations after 5 years and found a survival rate of 94.8%. The results indicated a tendency for more deterioration in large restorations than in moderate-sized restorations and in molar teeth rather than in premolars. Plasmans et al. [49] observed extensive amalgam restorations; that is, restorations that replaced at least one cusp, in molars and found after 8 years a retention rate of 88% and an age effect. Extensive amalgam restorations performed significantly better for a young age group (≤ 30 years) of patients than for an older patient population (>30 years). Letzel et al. [60] analyzed the survival rate of 3119 amalgam restorations with respect to four different alloy groups. After 13 years, conventional zinc-free alloys exhibited a survival rate of only 25%, whereas conventional zinc-containing alloys and high-copper, zinc-free alloys survived to 70%. High-copper, zinc-containing alloys showed the highest survival rate of 85%. The zinc and copper content of the alloys contributed to the corrosion resistance of the amalgams and influenced the survival rate.

Glass ionomer cements

Annual failure rates of posterior glass ionomer restorations range within 1.9% to 14.4% [18,61–66]. The results of selected clinical studies are summarized in Table 3. Mjör [2] reported a median longevity of 3 years for 155 glass ionomer restorations, comprising all cavity classes, placed by

Table 3
Longevity of glass ionomer restorations in posterior teeth[a]

Year of publication	First author	Years	Black class	Restorative materials	Restorations (n)	Patients (n)	SD	Annual failure rate (%)	Remarks
1988	Hickel [64]	3.5	I	Ketac-Silver (cermet)	87		L	3.3	Small class II restorations (modified) showed better results than regular class II cavities.
			II		104			14.3	
			II (modified)		52			5.5	
1990	Smales [18]	3	I	Ketac-Silver (cermet)	132		L	14.4	Main reasons for replacement: surface cracking and crazing.
1992	Svanberg [66]	3	II	Ketac-Silver	18	18	L	1.9	Caries-active individuals. Tunnel restorations.
1993	Hasselrot [62]	3.5	I and II	Base line and Ketac-Silver	282		L	7.6	Tunnel restorations.
1993	Mjör [15]	5	II	Ketac-Silver (cermet)	95		L	9	Estimated survival function. Small class II cavities.
1994	Krämer [68]	4	I	Ketac-Silver (cermet)	49	50 (all)	L	2.6	Main reason for replacement: bulk fracture.
			II		39			7.1	
1996	Strand [70]	3	I and II	Ketac-Silver (cermet)	161	85	L	10	Tunnel restorations. Main failure reasons: caries (16%), marginal ridge fracture (14%).
1998	Frencken [61]	3	I	Fuji IX	297	142	L	3.9	ART technique in Zimbabwe.
1998	Hasselrot [63]	7	I	Base line Ketac-Silver (cermet)	232	193 (all)	L	7	Tunnel restorations. No difference in failure rates between class I and II.
			II		35			7	
1998	Mallow [65]	3	I	Fuji II	89	53	L	14	ART technique in Cambodia. Placed by dental nurse students.
1999	Pilebro [69]	3	I and II	Ketac-Silver (cermet)	374		L	6.7	Tunnel restorations. Main failure reasons: dentin caries (3%), marginal ridge fracture (14%).
2000	Nicolaisen [71]	3–6	I and II	Glass ionomer	182	94	L	7.6	Tunnel restorations. Both caries activity and operator had significant effects on the survival period.

[a] Study duration ≥3 years.
SD = study design; L = longitudinal; C = cross-sectional.

general practitioners in Sweden. For glass ionomer restorations, fracture of restorations (18%), including bulk fracture (12%) and marginal fracture (6%), together with poor anatomic form as a result of low wear resistance were the main reasons for failure [2]. In a further study including 790 restorations, Mjör [25] revealed a mean age of 5 years of replaced glass ionomer cement restorations. Reasons for replacement were predominantly secondary caries (50%), anatomic form (12%), bulk fracture (11%), and marginal fracture (5%). Smales et al. [53] reported a median survival time of 2.2 years for glass ionomer restorations and 6.2 years and 0.8 years for the 25% and 75% quartile, respectively. In a further study, Smales et al. [18] assessed 132 class I Ketac-Silver (ESPE; Seefeld, Germany) restorations (cermet) and found a 56.8% survival rate after 3 years, which corresponds to an annual failure rate of 14.4%. As a result of surface cracking or crazing, 11.4% of the cermet restorations failed, sometimes within the first 6 months of placement. Mount [67] reported no failures after 10 to 12 years for only eight class I glass ionomer restorations placed in a private practice. As a result of the 5-year clinical observation of metal-modified glass ionomer restorations (Ketac-Silver) in small class II cavities, Mjör and Jokstad [15] described an estimated survival rate of 55%. Failures were mainly attributed to fracture phenomena. Krämer et al. [68] indicated a Kaplan-Meier survival rate of approximately 90% for class I and 72% for class II cermet restorations as the findings of a 4-year clinical investigation. In particular for class II cavities, many fracture-related failures were reported. Hickel et al. [64] reported a survival rate of 88.5%, 50%, and 80.8% after a 2.5- to 3.5-year observation period for cermet restorations (Ketac-Silver) in class I, class II, and small class II cavities, respectively.

Tunnel restorations

Hasselrot [63] placed 232 class I tunnel (partial tunnel) restorations with an unbroken enamel wall and 35 class II tunnel (total tunnel) restorations with perforated approximal enamel and observed after 7 years an annual failure rate of 7% for both restoration types. Of the 7% that failed, the main causes were fractures of the marginal ridge (41%), secondary caries (40%), and progressive enamel cavitation or degradation of the glass ionomer restorations (19%). No performance difference could be found between molars and premolars or between upper and lower teeth. Comparable annual failure rates of 6.7% and 7.6% could be observed in two studies examining the survival of glass ionomer tunnel restorations after 3 and 3.5 years, respectively [62,69]. Svanberg [66] found a distinctly higher survival rate, with a 94.4% success rate and 1.9% annual failure rate after 3 years for 18 cermet (Ketac-Silver) class II tunnel restorations in a population of 18 caries-active Swedish adolescents. Strand et al. [70] reported a success rate of 70% for 161 cermet tunnel restorations after 3 years. Marginal ridge fracture accounted for 14% and caries formation for 16% of the failures. Nicolaisen et al. [71] found a medial survival time of 55 months for 182 glass ionomer tunnel restorations in the Norwegian public dental service. Approximately 90% of the restorations survived 3 years, whereas only 35% survived 5 years. Both caries activity and operator had a significant influence on the treatment outcome.

Atraumatic restorative treatment (ART) restorations

The ART treatment technique is based on removing tooth decay using hand instruments only, after which the cleaned cavity is filled with glass ionomer cement. This technique has been established to provide a minimum of dental health care to rural areas in developing countries where no electricity-driven dental equipment can be used [72]. Phantumvanit et al. [73] indicated 93%, 83%, and 71% success rates for ART restorations in a rural village in Thailand after 1, 2, and 3 years, respectively. The use of the highly viscous glass ionomer cement Fuji IX (GC; Tokyo, Japan) yielded slightly better results, with a survival rate of 98.6%, 93.8%, and 88.3% after 1, 2, and 3 years, respectively [61].

Discussion

Direct posterior resin-based composite restorations

The reasons that the time of clinical service of direct composite restorations is limited have changed significantly [74]. Insufficient wear characteristics resulting in loss of anatomic form and interproximal contacts and degradation were the main problems in the 1970s and early 1980s [75]. Improvements in the filler technology and formulation of composite materials have changed the reasons for replacement, together with the current trend to insert composite restorations even in stress-bearing areas of posterior teeth (Figs. 1–20). Fracture of the restorations, marginal ditching, discoloration, and the formation of secondary caries, in addition to wear, are now the main reasons limiting the longevity of resin-based composites [2,13,15,17,33, 53,76,77]. Microfilled composites showed more fracture-related failures compared with hybrid composites, especially in high-stress class II cavities, because of their inferior mechanical properties. The relatively high incidence of secondary caries associated with the resin composite restorations may be explained on the basis of microbiologic studies that indicated a significantly higher proportion of *Streptococcus mutans* at the cavity margins of composites compared with amalgam and glass ionomer restorations [15,78]. Furthermore, the efficacy of older-generation dentin bonding agents limited the marginal quality of composite restorations, in particular when cavity finish lines were lying within dentin. Despite the dramatic improvements in the formulation of newer-generation bonding agents with enhanced marginal adaptation and bond strengths, a perfect marginal seal is still not achievable. Premolars usually offered significantly better conditions for composite re-

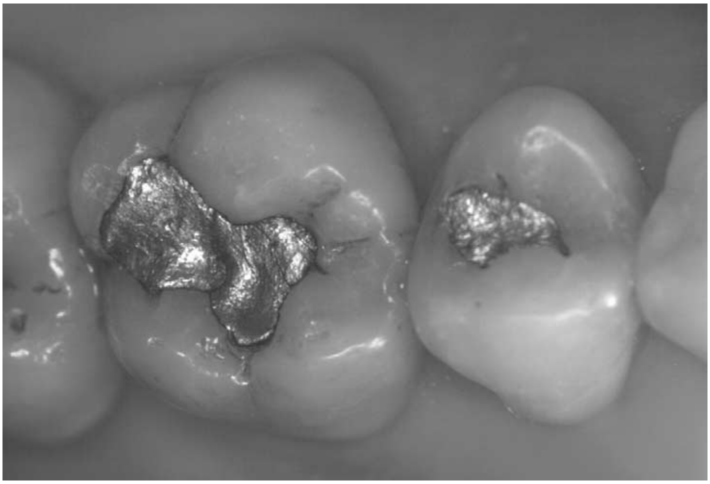

Fig. 1. Preoperative view of an upper second bicuspid and first molar with two amalgam restorations with insufficient margins. A bitewing radiograph reveals carious lesions in the distal proximal area of the premolar and at the mesial proximal surface of the molar.

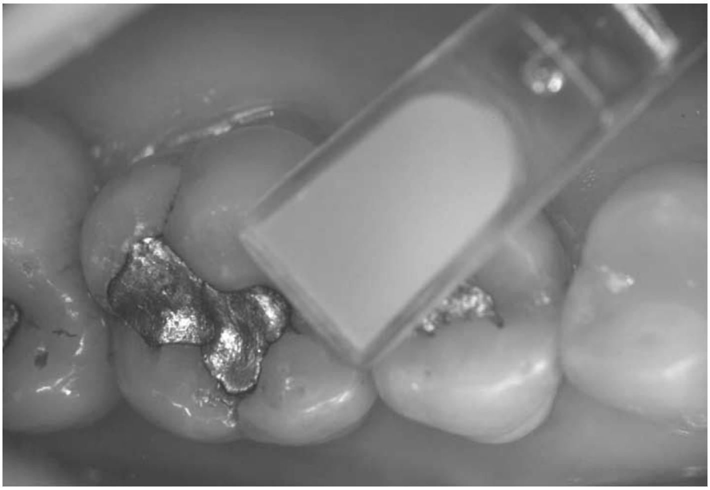

Fig. 2. Shade selection is made, with the manufacturer's shade guide on the wet tooth, after cleaning the tooth with prophylaxis paste.

storations compared with molars [9,22,33]. Cavities are usually smaller, the effect of the chewing forces is less intense, and the access for dental treatment is easier. The latter is important, because the adhesive technique is sensitive to the handling of the materials and the dentist's skill. The possibility of effective tooth care in this area of the mouth is better, too. Daily cleaning procedures by the patient, as well as professional care executed by dentists

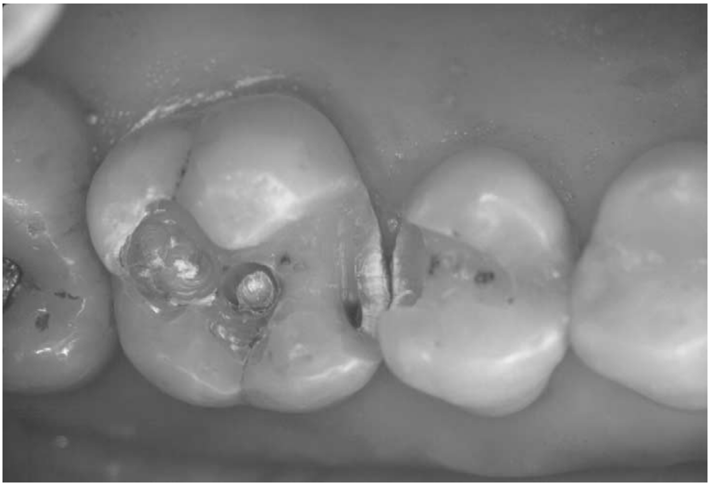

Fig. 3. Situation after removal of the amalgam restorations and primary cavity preparation.

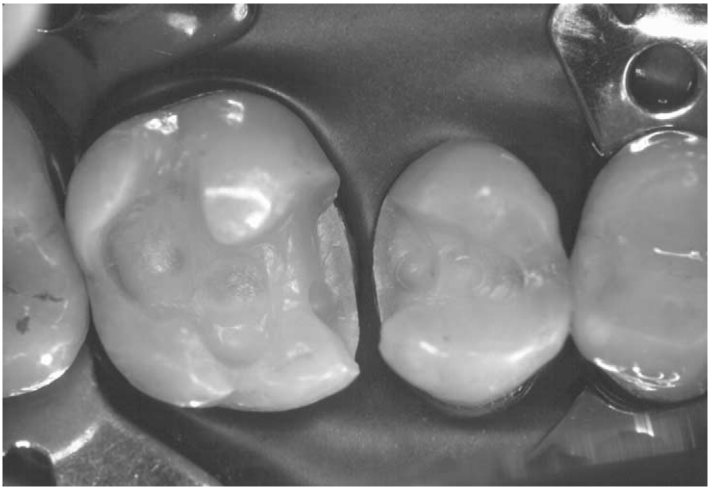

Fig. 4. Caries removal with a low-speed handpiece is accomplished and cavities are finally cut with a finishing diamond bur. Application of rubber dam.

and dental hygienists, can be performed and controlled more easily and more effectively in the premolar region.

Amalgam restorations

Amalgam is considered to be a relatively technique-insensitive dental restorative material that contributes, in conjunction with the mechanical and physical properties, to its good clinical performance over time [79].

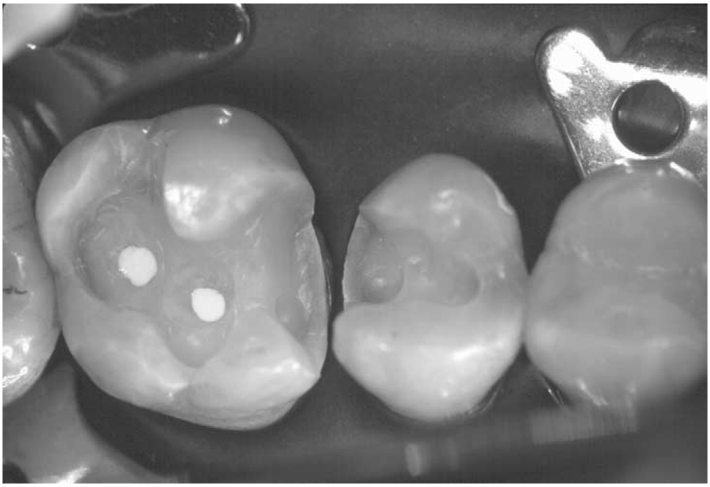

Fig. 5. Placement of a calcium hydroxide liner on deep dentinal areas.

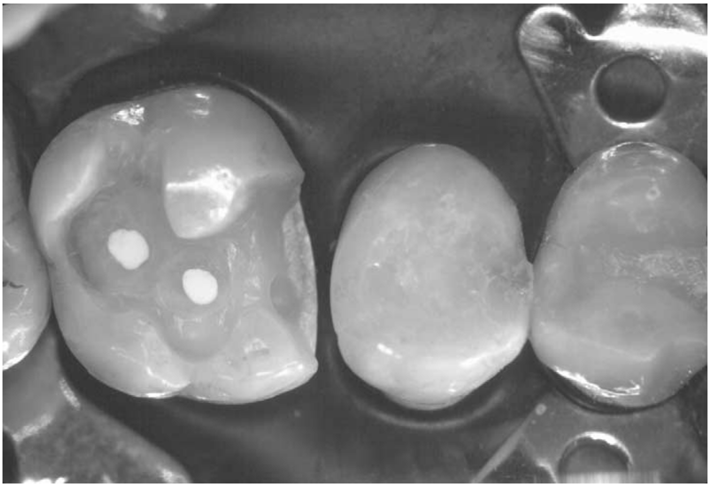

Fig. 6. Situation after restoration of the premolar with an ormocer-based composite restorative (Admira, Voco, Cuxhaven Germany). The distal proximal surface is already finished and polished.

Secondary caries, a high incidence of bulk fracture and tooth fracture, cervical overhang, and marginal degradation have been reported in several studies as being the main problems limiting the lifespan of amalgam restorations [2,15,20,21,45,53,77]. The assessment of secondary caries at the margins of a restoration, an important aspect of quality evaluation, is a more complex procedure than generally assumed, however [80]. The rating system is simple in that it has only two classifications: "caries" or "no caries." But

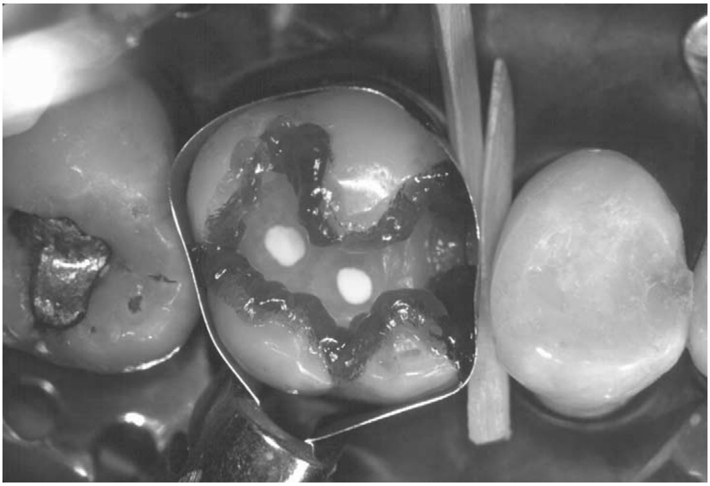

Fig. 7. Placement of a metal matrix band and wooden wedges. 37% phosphoric acid is applied on the enamel margins.

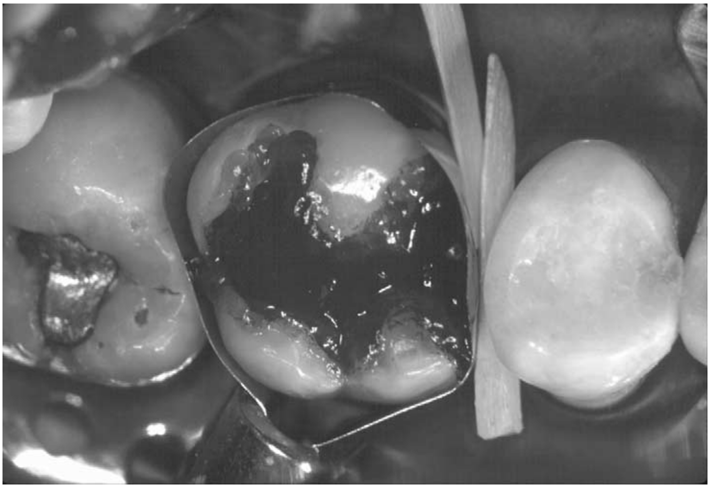

Fig. 8. After 15 seconds, the cavity is filled with phosphoric acid to etch the dentin for a maximum of 15 seconds (total etch).

to obtain consistency in the rating of secondary caries, it is crucial that a thorough calibration of the examiners precedes the clinical study [9]. The necessity of this calibration is obvious by reviewing the findings of a study published by Merrett and Elderton [81] in which nine dentists examined 228 teeth. One dentist scored "caries" in 11 teeth, while another diagnosed "caries" in 54 teeth.

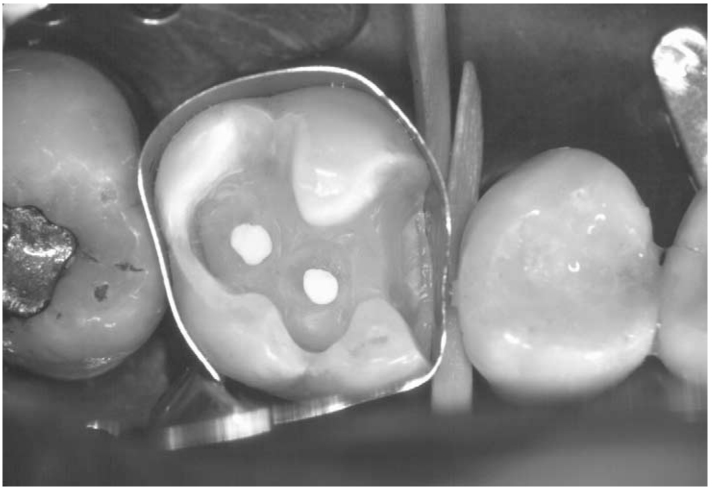

Fig. 9. Thirty seconds after starting the etching procedure, the etchant is thoroughly rinsed with waterspray. Typical frosty white appearance of etched enamel after drying with compressed air. Before application of the bonding agent (Admira Bond, Voco, Cuxhaven Germany), the dentin surfaces are rewetted with a microbrush and distilled water to ensure a proper resin infiltration of the slightly moist collageneous network.

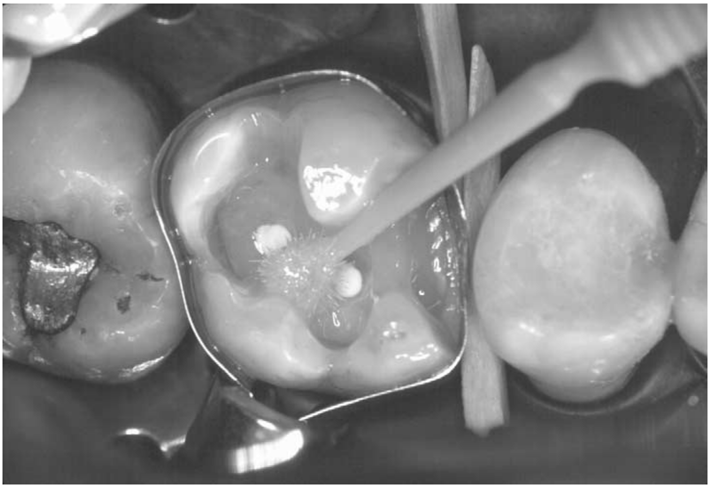

Fig. 10. The cavity is saturated with the adhesive.

The zinc and copper content of the alloy had a strong effect on the survival rates of amalgam restorations, because it influenced the corrosion resistance of the amalgam [60]. High-copper amalgams had generally higher survival rates than did conventional amalgams [45,60]. The lack of adhesive stabilization of hard tooth tissues in combination with large cavity preparations frequently resulted in the fracture of teeth restored with amalgam.

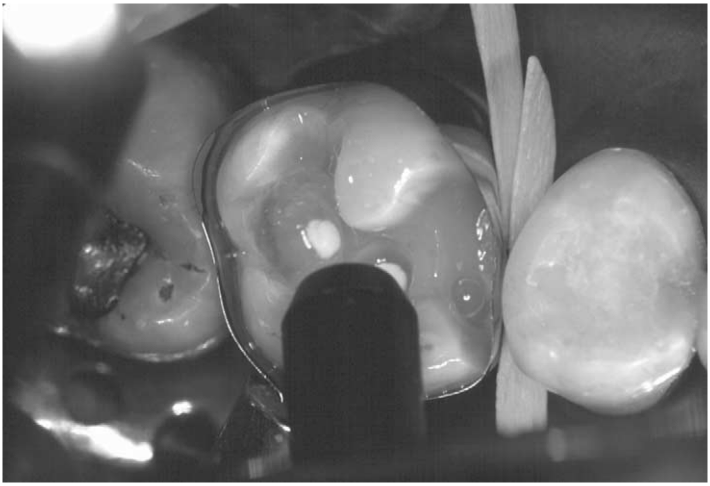

Fig. 11. The adhesive is gently air-dried after 30 seconds to evaporate the solvent.

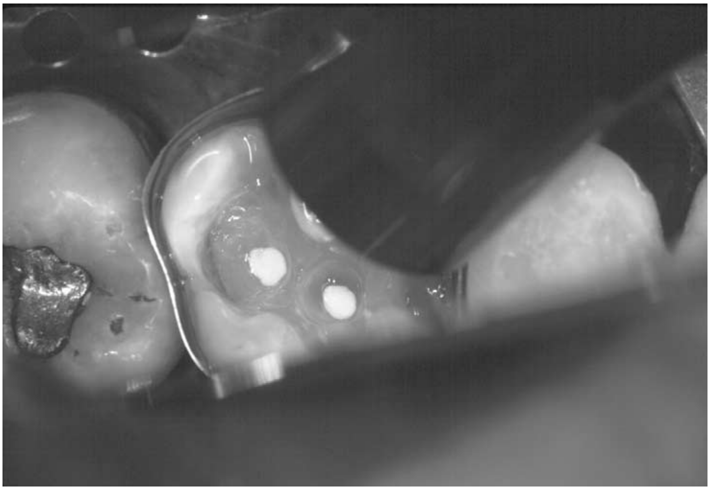

Fig. 12. Light-curing of the bonding agent for 20 seconds.

Large amalgam restorations exhibited a trend toward more deterioration than moderate- and small-sized restorations [56]. Plasmans and van't Hof [82], however, reported a promising success rate of 90% to 98% after 4 years for extensive amalgam restorations in molar teeth.

Glass ionomer cements as posterior restorative materials

Glass ionomer cements have certain advantageous properties, such as sustained fluoride release, chemical bonding to tooth substance, and pulpal

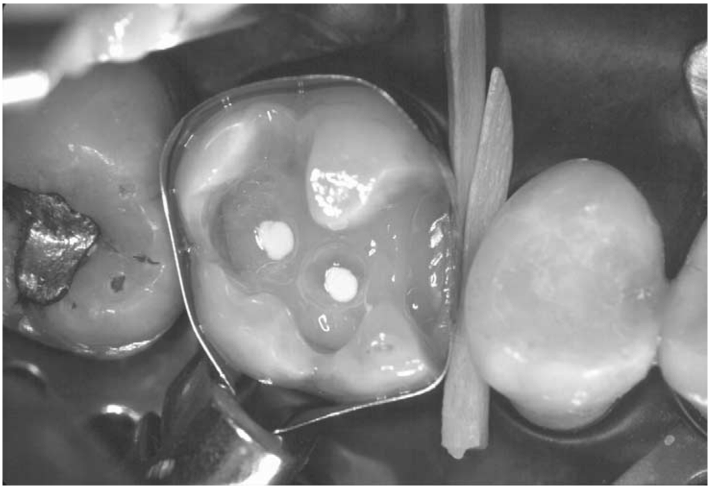

Fig. 13. After the bonding procedure, the cavity depicts a glossy surface.

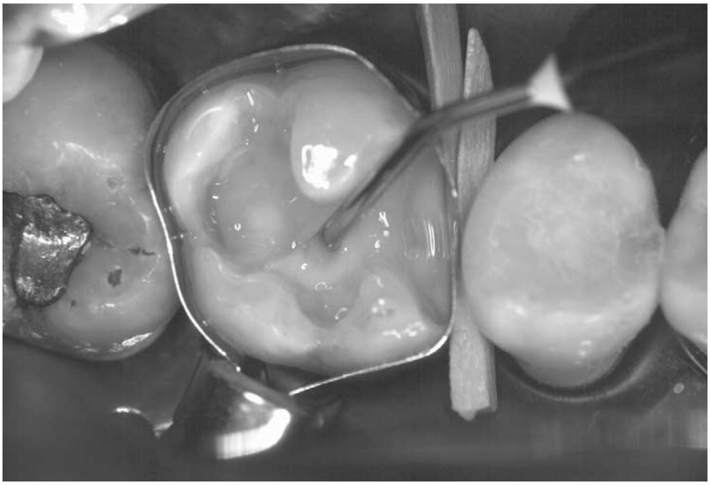

Fig. 14. A thin layer (0.5 mm) of a flowable ormocer-based restorative (Admira Flow, Voco, Cuxhaven Germany) is placed on the gingival seat of the proximal box and the cavity floor with a disposable canula directly out of the syringe. This layer acts as a stress breaker and enhances the adaptation of the higher viscous ormocer (Admira, Voco, Cuxhaven Germany) to the internal point and live angles of the cavity.

biocompatibility, but they are not considered to possess the adequate mechanical properties that qualify them for general use as permanent restoration materials in stress-bearing posterior areas [3,15,26,67,79,83,84]. Many glass ionomer restorations failed because of bulk fractures due to their low mechanical strength [7,15,68,85]. Silver particles sintered to the glass

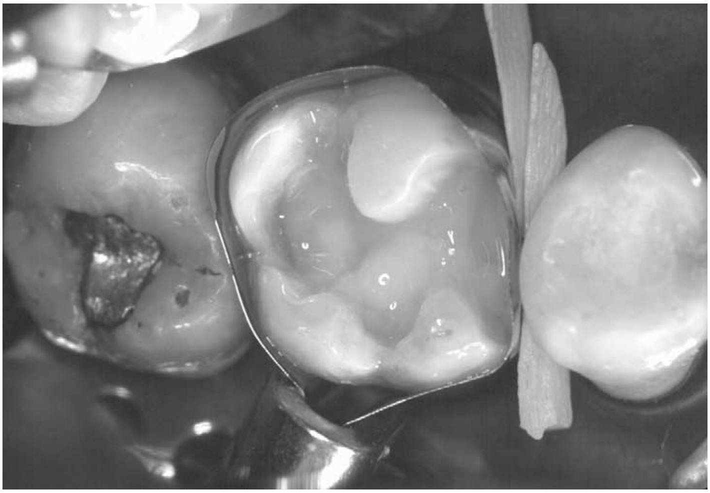

Fig. 15. Situation after placement and light-curing (40 seconds) of Admira Flow. Note the thin layer.

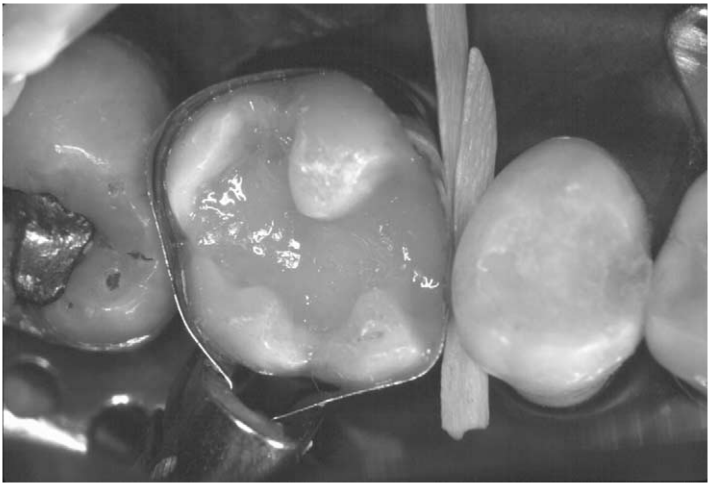

Fig. 16. After re-contouring and burnishing the metal matrix band towards the premolar with a hand instrument to ensure a tight proximal contact, a first horizontal layer of ormocer-based restorative material (Admira) is placed. This increment is of a relatively dark shade (A4) to build-up a dentin core. The material is light-cured for 40 seconds.

ionomer powder particles have been used to increase strength and radiopacity [86], but metal-reinforced glass ionomer cements (cermet) also are not qualified for use as long-term restorative materials in class II cavities [15,64,68].

In contrast to expectations and despite the release of fluoride ions, in some studies secondary caries was surprisingly the main reason for clinical

Fig. 17. Further increments of restorative material are placed to fill the cavity. Excess material is removed and the occlusal anatomy is preshaped while the restorative material is still plastic. Each increment is light-cured separately for 40 seconds. Before removal of the rubber dam, the restorations are visually controlled for underfilled areas.

Fig. 18. Situation after removal of the rubber dam. The restorations show already good contours. Occlusal contact points are marked with articulating paper. Finishing and polishing will be achieved in a short time.

failure of glass ionomer restorations [2,21,25,63,77]. The release of fluoride ions was anticipated to reduce the incidence of secondary caries [84,87], although the fluoride concentration required to establish a long-term anticariogenic effect has not been established. The longevity of glass ionomer

Fig. 19. After adjusting static and dynamic occlusion and finally contouring the anatomy with fine-grit diamond burs, the contact points are again marked with articulating paper.

Fig. 20. Completed and highly polished restorations with excellent marginal adaptations and color match. Proximal contacts are contoured physiologically. Before discharging the patient, a fluoride-containing varnish is applied on the tooth to protect the enamel adjacent to the restoration, which is inevitably touched during conditioning/priming and finishing of the restoration. (Dental work and photographs by Dr. J. Manhart.)

restorations is also dependent on the correct technique, because these materials tend to be rather technique sensitive, especially with respect to water adsorption and dehydration [66,85].

For patients with small approximal lesions and intact marginal ridges without cracks or opacities, class I or II tunnel restorations restored with glass ionomer cements were suggested to be a viable alternative, with narrow indications to conventional class II preparations [62,63,66]. The tunnel preparation technique is a more conservative approach for the treatment of approximal lesions than that of Black's classic principles. Carious tissue is removed by way of the occlusal surface through a tunnel preparation [88–90]. Unless the approximal surface is cavitated, the demineralized enamel wall should be preserved because fluoride leaching from the glass ionomer restorative material may contribute to remineralization [84,91]. A significantly higher failure frequency was recorded, however, in the treatment of patients with high caries activity, large initial lesions, and in whom the tunnel restoration did not reach the approximal surface [70]. The tunnel preparation-filled glass ionomer cement is not a generally favorable alternative in primary approximal lesions. In the hands of a well-trained, careful operator, however, it may be chosen as a semipermanent solution for patients with modest caries activity [71].

Clinical trials: design and variables

Clinical trials of dental restorative materials are major investigations in terms of time commitment, the number of investigators involved, and associated research costs [24]. For these reasons, as well as difficulties in obtaining financial support and frequent changes in product formulations, such clinical trials tend to be short, and long-term observations are relatively rare. Although controlled longitudinal, prospective studies would be best when the longevity of restorations is studied, it is unrealistic to expect such investigations to exceed 10 years [79]. Cross-sectional, retrospective studies based on records in dental practices present a suitable approach to determine the survival time of a large number of restorations over a longer time.

A direct comparison of the longevity of different types of restorations and different studies reported by different authors is problematic for several reasons [24,42]. The variables in the study designs are often described poorly or omitted, or differences in clinical procedures, materials used, and variations in study characteristics make direct comparisons among these studies virtually impossible [92]. The annual failure rates among different studies investigating the same type of restorations vary widely (Tables 1–3). Although annual failure rates were calculated for better comparison among the different studies, this calculation is problematic because the progress of restoration failures cannot be assumed to be a linear function for all investigations. Nevertheless, annual failure rates are the only way to compare study results, because only a few studies calculate Kaplan-Meier estimations or provide life-table statistics.

Factors that influence the treatment outcome of clinical studies can be categorized into patient-, dentist-, and material-related factors (Table 4). The influence of factors such as the intra-oral location of the restoration, the dental and hygiene status of the patients (caries-risk status), the consumption of

Table 4
Factors influencing the longevity of dental restorations

Patient	Dentist	Material
Oral hygiene	Correct indication	Strength (fractures)
Preventive measures	Cavity preparation (size, type, finishing)	Fatigue/degradation
Compliance in recall	Handling and application	Wear resistance
Oral environment (quality of tooth structure, saliva, and so forth)	Curing mode	Bond strength
Size, shape, location of the lesion and tooth (number of surfaces, vital versus nonvital tooth, premolar versus molar)	Finishing	Restorative systems (DBA, composite) are chemically compatible
Cooperation during treatment	Correct occlusion	Technique sensitivity
Bruxism/habits	Experience (with material)	Caries-inhibiting effects (release of substances?)

fluoride, the frequency of dental visits, and other clinical factors prevents valid comparisons of the results in the different reports [93]. Furthermore, the quality improvements of the restorative materials over time may have more effect on one group of materials than on another [2]. Keeping these limitations in mind, however, a certain trend can be distilled by comparing the results of different clinical studies on the same subject. Longevity is influenced by parameters at the time of placement and reevaluation (study design, observation period, criteria for failure). Cross-sectional surveys differ from controlled longitudinal studies, in which the clinicians have almost ideal conditions that meet the indications of the investigated materials (Table 5). Results from controlled clinical studies usually do not reflect exactly the situation in general dental practice, however [94,95], and may be of limited significance for general dental practice [2]. Results from longitudinal clinical studies depend highly on the individual skills of the dentists and the care they take in placing the restoration [8,43]. A trend toward better results for longitudinal studies (direct composite restorations, amalgam restorations) can be observed [96].

New developments

Since the introduction of the acid-etch technique by Buonocore [97] in 1955, which can be considered a milestone in the development of adhesive dentistry, numerous improvements in materials and techniques have been achieved. Recent developments and future trends focus mainly on aesthetic adhesive restorations. Especially in some European countries (particularly Germany and Sweden), the use of amalgam restorations has been decreasing significantly, and amalgam is now playing only a minor role [7,85].

Table 5
Typical characteristics of study design

Longitudinal studies	Cross-sectional studies
Selected patients	No patient selection
Trained dentists (without time constraints)	Usually many dentists (private practice)
Standardized treatment procedure	Larger variation of indications
Documentation of baseline status (clinically, photographs, replicas)	Baseline situation and age of the restoration are often unknown
Reasons for failures and differences among materials can be better detected	Reasons and time of failure are often unknown
Study design is time consuming	Time commitment is smaller, with lower study costs
Occasionally, testing of experimental products	Assessment of a large number of patients in relatively short time is possible
The influence of the tested materials on the results can better be distilled	The influence of the operators on the treatment outcome is high
Better results?	Better reality of daily practice?

Resin-based restorative materials

In the past decade, the number of newly developed restorative materials, mainly improvements and derivates of composites (e.g., compomers and ormocers) and glass ionomers (e.g., resin-modified and high-viscosity glass ionomers), accounts for more than all other restorative materials together developed in the history of dentistry. Modifications in the filler technology, filler distribution, and filler loading and alterations in the matrices of the resin-based restorative materials were made.

High-viscosity packable composites have been introduced to the market with high expectations as an alternative to amalgam [4,98]. They are characterized by a high filler load and a filler distribution that gives them different consistency compared with hybrid composites. Packable composites are recommended for stress-bearing posterior cavities and are marketed by emphasizing improved handling properties (with an application technique similar to the manipulation of amalgam) and easier establishing of physiologic interproximal contacts in class II cavities. In contrast to the advertisements of some manufacturers, however, measured values of curing depth suggest that bulk curing of packable composites in deep cavities is still not recommended [98–100].

Low-viscosity flowable composites show different rheologic properties compared with hybrid composites and are indicated for the restoration of minimally invasive cavity preparations, class V cavities, and as a stress-breaking base material under hybrid or packable composites because of their lower elastic modulus.

Interesting perspectives are to be expected from "smart" composite materials (e.g., Ariston pHc; Vivadent, Schaan, Liechtenstein). The intention of this class of materials is a so-called "release on demand" of functional ions (fluoride, calcium, hydroxyl ions) from special filler particles, which should protect the hard tooth substances immediately adjacent to the restoration from demineralization by counteracting the acids produced by microorganisms. The amount of released ions depends on the pH value immediately adjacent to the restorative material. With a decreasing pH value caused by active dental plaque, the release of the protective ions increases, and vice versa. This effect is expected to reduce the formation of secondary caries at the margins of the restorations because of the inhibition of bacterial growth, reduced demineralization, and buffering of acids produced by cariogenic microorganisms [101,102]. Good sealing of dentin is still important, however, and long-term results are pending. Restorative materials that inhibit or at least reduce the ability of plaque to adhere will be of great importance in the immediate future.

Another new approach in restorative dentistry has been the introduction of ormocers (an acronym for *or*ganically *mo*dified *cer*amics) in 1998 [4,103,104]. In addition to dental applications, ormocers are already used widely in modern technology [105–107]. Multifunctional urethane- and thioether(meth)acrylate alkoxysilanes as sol-gel precursors have been developed for the synthesis of inorganic-organic copolymer ormocer composites as dental restorative materials [3,104,108,109]. The alkoxysilyl groups of the silane allow the formation of an inorganic Si-O-Si-network by hydrolysis and polycondensation reactions, and the (meth)acrylate groups are available for photochemically induced organic polymerization [104,109]. Ormocers are characterized by the novel inorganic-organic copolymers in the formulation that allow the modification of mechanical parameters over a wide range [108]. The clinical handling of ormocers is exactly the same as with direct-placement resin composites (Figs. 1–20).

Polymerization shrinkage is often cited as the main problem with resin-based restorative materials [110]. The extent of shrinkage of dental resin-based materials depends on the molecular weight and functionality of the monomers and also on the filler load and technology. Research efforts have been undertaken to synthesize nonshrinking or low-shrinking monomer systems. In the early 1990s, spiro orthocarbonate monomers that demonstrate a ring-opening polymerization, with either no change in volume or an actual expansion, were investigated by several research groups [110–117]. Experimental spiro orthocarbonate:epoxy resin formulations showed expansions between 0.1% to 0.8% [113]. Problems with the biocompatibility and the slow hardening of epoxy resins, however, prevented the development of commercially available dental restorative materials. After replacing the epoxy resins by BisGMA:TEGDMA resins, the shrinkage-reducing or shrinkage-eliminating effect of the spiro orthocarbonates was found to be minimal [110,118]. This disappointing result set back the efforts to counter polymerization shrinkage by means of the spiro orthocarbonates [110]. A new class of bifunctional oxybismethacrylate monomers, exhibiting cyclopolymerization, showed a 30% to 40% reduction in shrinkage compared with dimethacrylates commonly used in dentistry [114,116]. Such low-shrinking resins, which are now available in a form that is compatible to conventional dental dimethacrylates, are currently under research [110,117]. Liquid crystal monomer systems also showed promising laboratory data regarding a substantial reduction of polymerization shrinkage [119].

Siloranes are one of the latest developments of ring-opening monomers for dental purposes [120]. This monomer type can be chemically explained as a merger of siloxanes and oxiranes, combining the properties of both sides. Good biocompatibility and mechanical properties, a high depth of cure (8.5–10 mm), and low shrinkage values (0.5–0.8 vol%) of experimental silorane-based composites present interesting perspectives for this material class [120]. As for all other materials in an experimental stage of development, however, extensive in-vitro tests are required before the first in-vivo studies.

Improvements in the filler technology on the basis of nanoparticle fillers also may have the potential to lead to the development of new resin-based dental restoratives with enhanced mechanical properties [121,122]. Considerable research efforts focus on the successful integration of nanoparticles into the filler technology [123–125].

Dentin adhesive systems and bonding philosophies

Improvements and further developments of dentin adhesive systems are ongoing at a rapid rate [126,127]. Manufacturers are trying to develop bonding agents and bonding techniques that are easy to manipulate, time-saving, and economic; that demonstrate a wider "window of opportunity" by reducing technique sensitivity; and that increase application safety [7].

In contrast to the first generation of self-etching primers, which aimed to replace conditioning of enamel and dentin with phosphoric acid but showed only insufficient bond strength values to enamel while dentin bond strengths could be considered satisfactory, recent newly developed self-etching adhesives such as Prompt L-Pop (ESPE; Seefeld, Germany), Clearfil Liner Bond 2, and SE Bond (Kuraray; Osaka, Japan) have been developed. These materials yield excellent bond strength values to enamel (up to 41.2 MPa) and dentin (22.5 MPa) [128–131]. First clinical results after 6 and 12 months of service showed excellent results for these materials [132–134]. The total-etch procedure is still a gold standard in bonding technology, but these newly formulated self-etching primers seem to have the potential to rival the established procedures. The encouraging short-term clinical data need to be supported by ongoing long-term clinical evaluations, however.

Discussions are ongoing as to whether the total-etch and total-bond philosophy or the placement of a base and establishing adhesion to the cavity walls and margins only (selective bonding) yields better long-term results and marginal seals of adhesive restorations in class I and II cavities. Selective bonding is promoted for resulting in resin-based restorations with better long-term marginal integrity and less internal stresses in the body of the restoration, because at the beginning of the polymerization, before the gel point is reached, the shrinkage of the system can be partially compensated by a flow of molecules from free, unbonded restoration surfaces. Although total-bonded restorations allow this flow of molecules only from the surface of the restoration, selective-bonded restorations are said to allow an additional stress-relieving molecule flow at the bottom of the restoration (better C-factor).

Simplifications of the application procedure and time saving, together with an increase in application safety and quality of adhesion, are the main goals in the further development of future adhesive systems and protocols.

Light polymerization units and concepts

Within the past few years, several new polymerization concepts and curing units have been introduced to the dental profession. Conventional quartz tungsten halogen curing lights with higher light intensities, plasma arc curing lights, blue light emitting diode curing lights, and argon lasers are used for polymerization of direct resin-based restorative materials [135, 136]. The so-called "softstart polymerization," which is characterized by an initial low-power density followed by higher-power density, ideally after passing the gel point (two-step mode, Elipar Highlight, ESPE, and ramped/exponential mode, Elipar Trilight, ESPE) is advocated to minimize internal stresses in the composite and to reduce marginal gap formation while maintaining adequate mechanical properties and biocompatibility [137–145]. Pulse activation of photopolymerizable composites reduces contraction stresses at the cavosurface margins [146].

Argon lasers are used as the light source to polymerize composite resins because the wavelength of light emitted by this laser is optimal for the initiation of the light initiator system. Few discrete lines of the desired wavelength are emitted, and the demand of wavelength adjustment is fulfilled almost ideally [137]. There is strong controversy about many aspects of the effectiveness of laser curing compared with conventional light curing. Research indicates that the argon laser offers a greater depth and degree of polymerization, with less time required and an enhancement of the physical properties of polymerized composite resins [147–149]. These advantages are counterweighed by reports that the increased polymerization caused by the laser results in increased shrinkage, brittleness, and marginal leakage [147,150,151]. When new monomers or composites with less shrinkage (less than 1%) are on the market, probably in a few years, fast curing devices such as lasers will increase in importance.

Plasma arc curing units with high intensities and short exposure times (1 to 3 seconds) are marketed by manufacturers for reduced polymerization shrinkage but are currently not qualified to cure current resins sufficiently.

Physical properties and degree of polymerization, measured indirectly by determining microhardness, are significantly worse with only 3 seconds of exposure [152]. Several polymerization cycles are necessary to cure resins properly. The narrow spectrum of emitted wavelengths is another shortcoming of plasma lights, because not all commercially available resins can be cured properly owing to incompatibilities of emitted wavelength and photoinitiator systems of the restorative materials.

Blue light-emitting diode technology is the latest development for polymerizing resin-based materials [136,153,154]. In contrast to tungsten filament halogen curing units, the blue light-emitting diodes do not require filters to produce light in the 400- to 500-nm region to excite camphoroquinone photoinitiators and do not generate the large quantity of heat associated with halogen lamps [136]. The heat adversely affects filters and reflectors with time, leading to a reduction in curing effectiveness. Light-emitting diodes with an emission spectrum matching the needs of resin-based dental composites have been available only recently [137].

Cavity preparation

Oscillating sonoabrasive preparation methods with geometrically defined working tips create standardized cavities for restoration with prefabricated shape-congruent ceramic inserts (Sonicsys Approx System; Kavo, Biberach, Germany, and Vivadent; Schaan, Liechtenstein) [155–159]. The working tips of the Sonicsys Approx and Sonicsys Micro System are only diamond coated on one side, which allows preparation even in narrow interproximal areas without endangering the adjacent tooth. Special Sonicsys working tips for ceramic and cast-gold cavity preparations ensure precise cavity geometries for these restoration types [156]. Another oscillating system is based on the EVA-System (Kavo; Biberach, Germany). It uses files for the preparation of interproximal bevels and for finishing the margins of interproximal box, crown, and veneer preparations. These oscillating instruments overcome the major limitations of rotary burs for tooth preparation and facilitate conventional cavity preparation. In addition, they allow the use of cavity designs that could not be achieved with conventional instruments [157].

Summary

The longevity of dental restorations is dependent on many different factors, including those related to materials, the dentist, and the patient. The main reasons for restoration failure are secondary caries, fracture of the bulk of the restoration or of the tooth, and marginal deficiencies and wear. The importance of direct-placement, aesthetic, tooth-colored restorative materials is still increasing. Amalgam restorations are being replaced because of alleged adverse health effects and inferior aesthetic appearance. All alternative restorative materials and procedures, however, have certain limitations. Direct composite restorations require a time-consuming and more costly treatment procedure and are actually only indicated for patients with excellent oral hygiene. Glass ionomers can be considered only as long-term provisional restorations in stress-bearing posterior cavities. Future treatment regimens that are made possible by the development of sophisticated preparation techniques, improved dentin bonding agents, and resin-based restorative materials will result in the therapy of more small-sized lesions rather than large restorations. The importance of indirect inlay techniques will shift more and more toward the direct restoratives. As the cavities become smaller, it is to be expected that the use of improved direct restorative materials will provide excellent longevity even in stress-bearing situations.

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