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Fluoride-releasing restorative materials and secondary caries

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Dental caries is one of the most common diseases occurring in human beings, and it is prevalent in developed, developing, and underdeveloped countries. [1–11] Within the United States and Western Europe, there has been an overemphasis on national surveys that indicate that more than 50% of children and adolescents are caries-free. In reality, a small percentage of late adolescents and young adults are caries-free. Only about one in six 17-year-olds are caries-free. In fact, 94% of all dentate adults in the United States have experienced dental caries. Caries affects some children, adolescents, and adults to a much greater degree than others (Fig. 1). One fourth of 5- to 17-year-olds accounts for 80% of the caries experience. At age 17, 80% of caries occurs in 40% of these late adolescents. A similar trend is noted with older adults. [7,9] In an ambulatory New England population, 11% of elders more than 70 years of age accounted for 70% of caries. It was noted that these New England elders had a higher caries prevalence rate than New England children. [7] The continuing caries experience throughout adulthood and into the elderly period points out that dental caries is not

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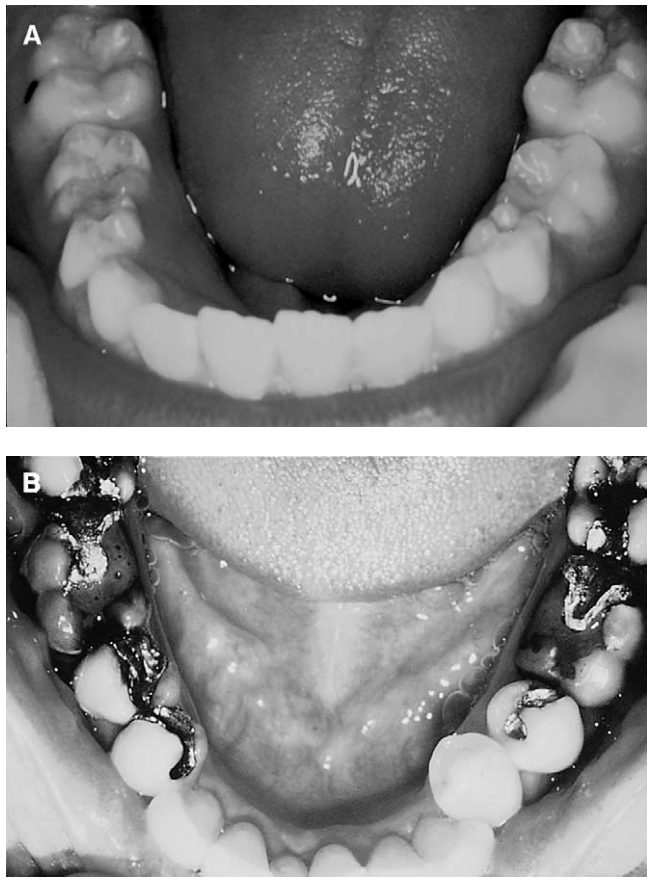

Fig. 1. Variability in caries experience with mixed dentition (A) and in adult (B). Secondary caries and restoration failure are common experiences in most individuals.

a disease limited to children and adolescents. The demand for ongoing preventive and restorative care in adulthood is emphasized in a national survey that found 40% of adults between 18 and 74 years of age in need of immediate dental care. [10,11]

Once a cavity forms, there are several options for restoration of the carious tooth surface. A US Navy Dental Corps study [12] reported on the dental materials placed in 4633 restorations in 17- to 84-year-olds. The following restorations were placed during a 2-week period: amalgams (78%), composite resins (16%), sealants (5%), glass ionomers (1%), and gold restorations (0.2%). It was noted that 67% of amalgams and 50% of composite resins were placed because of primary caries. The remaining restorations were replacements of existing restorations. A comprehensive survey [13] of more than 9000 restorations performed in the United Kingdom found the

following types of restoration placement: amalgams (54%), composite resins (30%), and glass ionomers (16%). Initial restoration placements (49%) and replacements (51%) were quite evenly divided. More recent studies have indicated that approximately 60% of adult restorative care is dedicated to replacing restorations. [1–4,6–12,14–32] With Swedish children and adolescents in 1995, [30] the choice of restorative material was quite different from adult populations. In 3- to 8-year-olds, the restorative materials chosen for primary teeth were compomers (32%), glass ionomer (26%), zinc oxide-eugenol (23%), amalgams (4%), and composite resins (3%). With 6- to 19-year-olds, caries in permanent teeth were restored with composite resins (56%), amalgams (31%), glass ionomers (9%), and compomers (4%). The choice of materials in this Swedish study may reflect the reluctancy toward amalgam usage. Similar studies have not been completed in the United States.

Reasons for restoration placement and replacement

The principal reason for restoration failure is secondary caries in both the permanent and primary dentitions (Table 1). [1,6,8,10–27,30–32] Secondary caries accounts for approximately 60% of all reasons for restoration replacement, regardless of restorative material type. [12,13,19–24] Other reasons include material failure, tooth fracture or defect, endodontic involvement, prosthetic abutment use, technical errors, and deterioration of aesthetic quality with tooth-colored restoratives. [12,13] With pediatric patients, secondary caries is responsible for replacement of restorations in 70% of cases. Fracture of either the restoration or the tooth is a less frequent occurrence in children and adolescents.

The longevity of failed restorations is quite variable and dependent on the restorative material (Table 1). [1,12,13] Amalgams tend to have the greatest median and mean survival times when compared with composite resins and glass ionomers. It must be realized that amalgam restorative materials have been available for well over 100 years, and these materials have been refined for posterior tooth restoration. In contrast, the terms *composite resin* and *glass ionomer* in most clinical studies encompass many different formulations with variable strengths and weaknesses. In such studies of restoration failure and longevity, subtypes of composite resins and glass ionomers were not taken into account.

A sequelae of secondary caries is the effect on the tooth requiring restoration replacement. With removal and replacement, the size of the restoration changes considerably. [6,14,16–18,23,33] When secondary caries is present, the original cavity margin is extended by 0.52 mm. When no caries is present, the margin is extended by 0.25 mm. This implies that the replaced restoration width will be larger by 0.5 to 1.04 mm. After several replacements, there is no doubt that the affected tooth will become weakened and may require full coverage.

Table 1
Reasons for restoration placement and replacement and longevity of failed restorations

US navy dental corp study

	Amalgams (%)	Composite resin (%)
Primary caries	56	47
Primary caries requiring removal of existing restoration	12	5
Secondary caries	15	10
Restoration defect	5	5
Fractures/lost restoration	7	9
Fractured tooth	2	11
Pain/sensitivity	<1	1
Endodontic treatment	2	4
Prosthetic abutment	<1	0
Poor aesthetics	0	7
Longevity of failed restorations		
Mean	7.4 years	6.3 years
Median	6.2 years	5.7 years

UK study

	All (%)	Amalgams (%)	Composite resin (%)	Glass ionomer (%)
Primary caries	41	42	37	45
Secondary caries	22	28	15	13
Tooth fracture	6	7	2	5
Margin fracture	6	7	4	5
Noncarious defect	6	2	NA	14
Bulk fracture	5	7	3	NA
Pain discomfort	4	4	NA	5
Discoloration	3	<1	5	NA
Other	5	3	4	6
Longevity of failed restorations				
Mean	NA	6.8 years	4.5 years	3.8 years
Median	NA	6 years	4 years	3 years

Permanent dentition in children and adolescents (6–19 years old): Swedish study

	All restorations (%)
Primary caries	87
Secondary caries	9
Fracture of restoration or tooth	2
Other	2

Table 1 (*continued*)

	All (%)	Amalgams (%)	Composite resins (%)	Glass ionomers (%)	Compomers (%)
Restoration failure	13	13	12	25	5
Number of times for restoration replacement					
Replaced once	12%				
Replaced twice	1%				
Replaced more than twice	<1%				

NA = not applicable.
Data from references [12], [13], and [30].

Clinical and histopathologic features of secondary caries

Although secondary caries is the cause of failure in 50% to 60% of restorations (Table 1), there is confusion regarding the definition of secondary or recurrent caries. [1,6,8–27,30–32] Oftentimes, marginal gaps and ditching around restorations may be ascribed to secondary caries. Only when marginal gaps are greater than or equal to 250 μm can secondary caries be identified consistently by clinical and microscopic criteria. There are some clinicians that equate a marginal defect of 50 μm or greater with an increased prevalence of secondary caries. With occlusal amalgams, macroscopic caries has been detected in only 20% of ditched margins and 4% of nonditched margins. Microscopic examination of these restorations showed histologic caries in 47% of nonditched margins and 59% of ditched margins. Margin defects and staining are not sufficient to predict the presence or absence of secondary caries and do not allow for treatment decisions.

Secondary (recurrent) caries may be defined most simplistically as caries detected at the margins of an existing restoration. Similar to primary caries, the enamel or root surface adjacent to the restorative material may possess an inactive arrested lesion, an active incipient lesion, or a frankly cavitated lesion (Fig. 2). Clinically, secondary caries has certain features. [6,16–24] A high proportion of secondary caries is located along the cervical and interproximal margins (>90% of failed amalgams, >60% of failed composite resins). With enamel surfaces, recurrent caries may be seen as a white spot (active), or a brown spot (inactive) lesion. The surface may undergo a certain degree of softening before frank cavitation. The enamel lesion color varies depending on the adjacent restorative material. When the cavosurface is involved and undermined by caries, the adjacent enamel surface takes on a brown to gray to blue hue; however, amalgam restorations impart such color changes due to corrosion. Transillumination may be helpful with tooth-colored restorative materials. Radiographs can detect interproximal caries, especially along gingival margins. The interface between the tooth and restoration needs to be evaluated with an explorer; however, care

should be taken to avoid creating an iatrogenic defect along the cavosurface margin or cavitating the lesion's surface.

Active root-surface secondary caries appears as a yellow discoloration and frequently has undergone surface softening. [11,25,34–40] In contrast, inactive secondary caries in a root surface may become sclerotic and ebonized, with a hardness level similar to that for sound enamel. With both

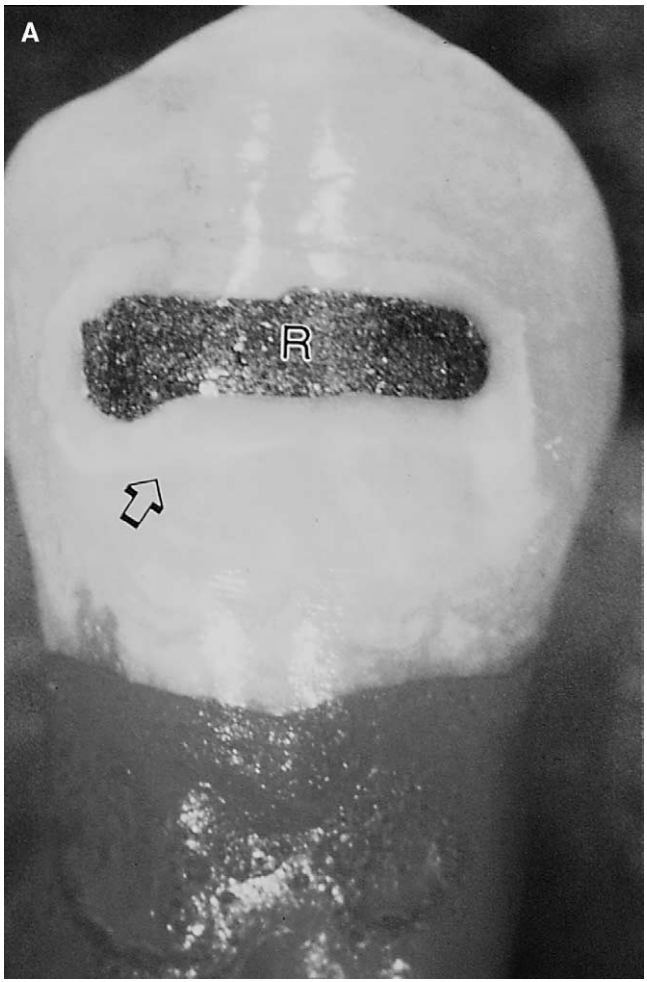

Fig. 2. Secondary *in vitro* caries around an amalgam restoration. (A) An artificial white spot lesion (arrow) surrounds the amalgam restoration. (B,C) Polarized light microscopic examination of this amalgam-restored tooth demonstrates the two components of secondary caries: the primary outer surface lesion (**O, OL**) and the wall lesion (arrow, **WL**). The wall lesion is formed due to percolation of acidic byproducts, lytic enzymes and colonization of plaque along the microspace present between the restorative material (**R**) and the cavosurface tooth structure. Secondary caries formation adjacent to restorations in coronal and root surfaces appear similar.

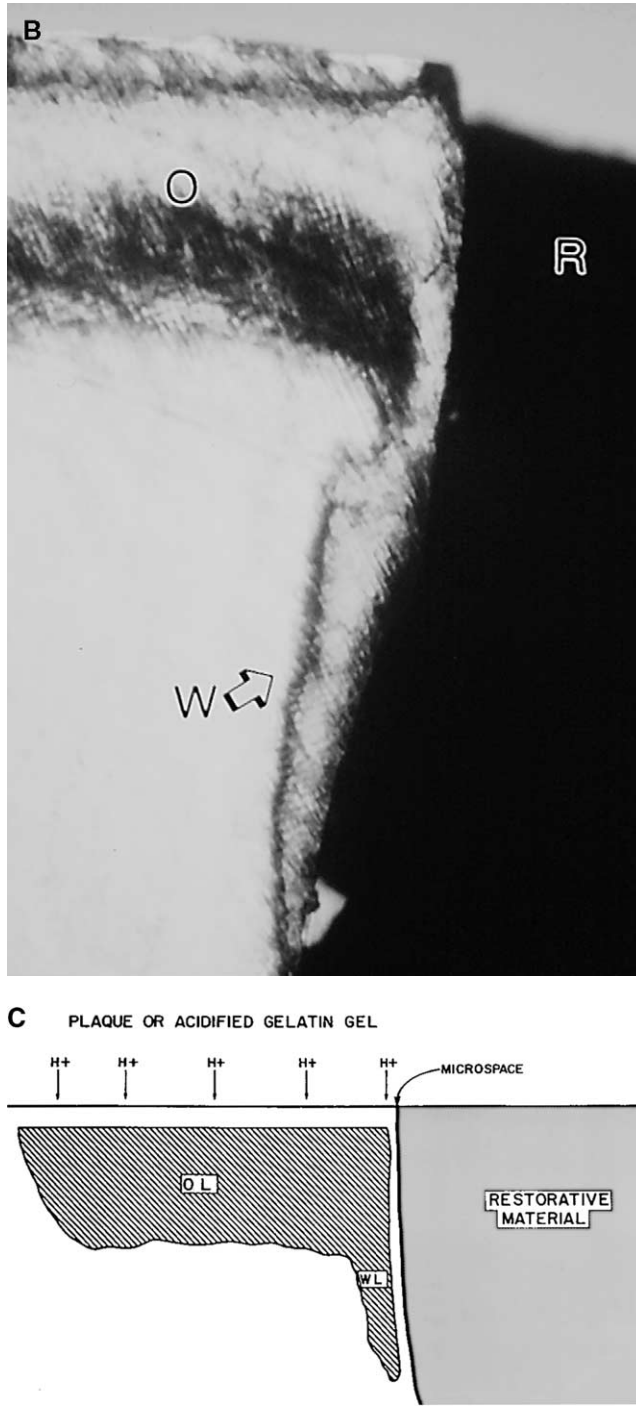

Fig. 2 (*continued*)

enamel and root-surface secondary caries, the responsible microorganisms remain the same as those for primary caries. The diagnosis of secondary caries is dependent on visual inspection, tactile sensation with judicious explorer usage, and radiographic interpretation.

Over the past three decades, naturally occurring and artificially induced secondary caries (Fig. 2) around restorative materials have been characterized microscopically as two separate but interrelated lesions. [6,13,16–18,26,34,35,40–81] The primary (outer) surface lesion develops in the enamel or root surface adjacent to the restoration, whereas the wall lesion forms in the cavosurface tooth structure along the restorative interface. The outer surface lesion may be readily visualized in the enamel or root surface adjacent to the restoration. The wall lesion occurs because of microleakage of oral fluids, percolation of hydrogen ions and lytic enzymes from plaque, and bacterial colonization along the cavosurface wall. Whenever a restorative material is placed, there is a possibility for a microspace (gap) to be formed between the restorative material and the cavosurface enamel, dentin, and cementum. The ability of a material to resist secondary caries development along the cavosurface is dependent on complete removal of carious tissue (leaving no residual caries), formation of an intimate cavosurface-restorative interface with minimal to no microspace, and release of caries-protective agents (fluoride, metal ions, antimicrobials, acidic ions) to the adjacent cavosurface and outer tooth surface.

Risk factors for development of secondary caries are identical to those for primary caries (see box). [3–6,8,16–25,29,34,82,83] The most reliable predictor of caries risk is the prior caries experience of the patient. One factor that may result in a considerable increase in root-surface caries is the larger proportion of dentate elderly persons in the population, with more retained teeth than in the past. [10,11,36–39] The increased number of retained teeth leads to a greater risk for periodontal disease development. With periodontal disease onset, gingival recession occurs and leads to exposure of caries-prone root surfaces. [36–38] It has been shown that 4 years after root-surface exposure owing to periodontal therapy almost two thirds of patients develop root caries. These patients had an average of 6.9 new root caries lesions. Twelve years after periodontal treatment, 80% to 90% have root caries, with an average of 17.2 lesions per person.

Prevention of secondary caries [3,4,6,8,16,17,19,20–24,34] begins at the time of restoration placement, with patient education in proper dental hygiene; fluoride regimen implementation (rinses, gels, fluoridated toothpastes); antimicrobials (chlorhexidine); fluoride-releasing restorative material; salivary cariogenic microorganism assessment; salivary flow rate determination; current medication inventory; dietary review; and medical evaluation, if necessary. More frequent dental examinations, with topical fluoride application, may be indicated for especially caries-prone patients.

Various laboratory methods have been developed to investigate microleakage and caries formation along the restorative-cavosurface interface.

Risk factors for secondary caries development

Saliva factors
- High *Streptococcus mutans* and *Lactobacillus counts*
- Low flow rate
- Low buffering capacity
- Low salivary pH
- Low fluoride levels
- Low IgA levels
- Low lysozyme, lactoferrin, and lactoperoxidase concentrations
- Primary and secondary xerostomia (medications, Sjogren's syndrome, HIV/AIDS infection, radiation therapy, chemotherapy)

Caries experience
- High caries prevalence in primary and permanent dentitions (DMFS/dmfs; DMFT/dmft)
- History of anterior caries
- Extractions for caries
- Multisurface restorations
- Prior secondary caries
- Active coronal or root-surface lesions
- Malocclusion, malposition, and malformed teeth
- Enamel and root-surface defects
- Deep pits and fissures
- Orthodontic appliances
- Exposed root surfaces (gingival recession, periodontal disease, periodontal surgery)
- Partial dentures with plaque-retentive surfaces

Dental plaque factors
- Acidic plaque (Acidogenic bacteria, fermentable carbohydrates)
- Decreased buffering capacity
- Intracellular and extracellular polysaccharides increased
- Elevated plaque and gingival indices
- Low fluoride and calcium levels

Dietary factors
- Frequent ingestion of high-sucrose content and adherent foods
- Low topical fluoride, strontium, molybdenum, aluminum, lithium, and boron intake
- High selenium intake

Restricted or special diets: (cystic fibrosis, phenylketonuria, metabolic disease, chronic diseases)

Access to dental care restricted or low dental knowledge
- Lack of access to topical sources of fluoride (drinking water, toothpastes, rinses, gels, varnishes)
- Lack of preventive and routine dental care
- Lack of fluoride-releasing restorative and preventive materials
- Low socioeconomic status
- Low education status

Medical conditions
- Physically and mentally challenged
- Medically compromised: (autoimmune disease, immune compromise/deficiency, bulemia, frequent regurgitation/reflux, HIV/AIDS, cancer, radiotherapy, chemotherapy, Sjogren's syndrome)

Data from references [3–6], [8], [16–25], [29], [43], [68], [82], [83], [118], and [119].

[6,16–18,41] Techniques used include (1) artificial secondary caries systems evaluated by polarized light microscopy, scanning electron microscopy, and microradiography; and (2) microleakage determination with organic and fluorescent dyes, radioisotopes, bacterial cultures, pigmented chemical tracers, air pressure, neutron activation analysis, and electrical conductivity. Each of these methods has certain advantages and disadvantages. The most often used laboratory techniques are artificial caries systems and microleakage assessment with organic dyes. Studies using these techniques have allowed for rapid evaluation of the effects of restorative materials, bonding agents, remineralizing agents, innovative fluoride-delivery systems, and fluoride-releasing products on microleakage and secondary caries formation.

Fluoride-releasing dental materials

At the current time, there are numerous dental materials from many different manufacturers that have the ability to release fluoride to adjacent tooth structure and into the oral environment. A brief review of the major categories of fluoride-releasing dental materials is in order. [51,58,84–87] Several decades ago, silicate cements composed of a basic glass and phosphoric acid solution were used as tooth-colored restorative materials. Although these materials were not retained well, it was noted that secondary caries was reduced significantly. This reduction was attributable to the substantial fluoride release generated by this restorative material. Glass ionomers were developed from aluminosilicate glass with calcium and a

fluoride flux. The material requires an acidic polymer to induce an acid-base setting reaction. Considerable quantities of fluoride are released initially, with the setting reaction and continuous release of lower levels of fluoride detected for long periods of time. Silver particles have been added to some glass ionomers to increase their physical strength, and these materials are known as glass ionomer *cermets*. Resin-modified glass ionomer (polyalkenoate) represents a hybrid material, with a greater amount of glass ionomer than conventional resin in its makeup. This material uses an acid-base reaction, light- or chemical-activated polymerization, and self-curing for its setting reaction (triple cure). Fluoride is released from this material, but to a lesser extent than conventional glass ionomers. Compomer (polyacid modified composite resin) contains a higher content of composite resin, with a lessened amount of ionomer material and polymerizable acidified monomer. This material is light activated for its setting reaction. Fluoride is released primarily during the setting reaction and to a lesser extent over time. Fluoride-releasing composite resins are also available, and these resins contain some filler particles with releasable fluoride. Long-term fluoride release is quite low. Conventional composite resins lack fluoride-releasing abilities. In summary, there is a continuum of tooth-colored restorative products that range from high fluoride release (glass ionomer) to intermediate fluoride release (resin-modified glass ionomer) to low fluoride release (compomer and fluoride-releasing composite resin) to no fluoride release (conventional composite resin). Physical properties vary with the degree of glass ionomer and composite resin content. In general, decreased physical properties are associated with increased fluoride release.

Continuing research into the development of fluoride-releasing composite resins is ongoing in the hope of maintaining the physical properties of these materials and providing long-term fluoride release. [61] Incorporation of inorganic fluoride has resulted in increased fluoride release, but with creation of voids in the matrix as the inorganic fluoride leaches out of the material. Dispersion of leachable glass or soluble fluoride salts into the polymer matrix allows for a water-soluble diffusion of fluoride from the composite resin into the local environment. Most of the fluoride is released during the setting reaction, with a smaller amount of long-term fluoride release. The addition of organic fluorides to the polymer matrix has been attempted to increase fluoride release. These organic fluorides include methacyrloyl fluoride-methyl methacrylate, acrylic amine-HF salt, t-butylamino ethyl methacrylate hydrogen fluoride, morpholinoethyl methacrylate hydrofluoride, and most recently, tetrabutylammonium tetrafluoroborate. These agents hold promise for increasing fluoride delivery to the adjacent tooth structure while maintaining the physicochemical properties of composite resins.

In addition to the more traditional fluoride-releasing restorative materials, other methods for fluoride release are available. [49,50,53–55,57,59,60, 70,74,88–91] Glass ionomer, resin-modified glass ionomers, and compomers have been formulated as luting agents and cavity liners. Many bonding

agents, total-etch dentin adhesives, and one-step adhesives for various dental materials contain releasable fluoride and protect against secondary caries. Several fluoride-releasing bonding agents for amalgams, as well as fluoridated amalgams, have become available. [76,77,81] Other clinical investigators have proposed exposing the prepared cavity to topical fluoride agents to allow rapid fluoride uptake by dentin, enamel, and cementum before restoration. [57,59,69,90]

Fluoride content in a dental material varies considerably, ranging from 7% to 26% in glass ionomers, resin-modified glass ionomers, and compomers. [28,42,43,46,47,51,58,69,84,85,87,89,90,92–106] The amount of fluoride made available to the oral cavity is not related to the fluoride content of the material, but rather to the ability of the fluoride to leach from the material or to be exchanged for other ions in the oral environment. With all fluoridated dental materials, there is a burst of fluoride release during the setting reaction, and this is followed by a gradual decline in the amount of fluoride leached into the oral environment. The dental material provides a low level of fluoride for a considerable time period (Table 2).

Several studies have shown well-documented fluoride availability for 2.7 to 8 years from glass ionomer-based materials and up to 5 years from composite resins. [42,43,47,58,89,97,98] The ability to continue to release fluoride *in vitro* over extended periods is remarkable, considering the fact that the materials are constantly exposed to an aqueous environment. The quantity of fluoride available for uptake is dependent on the media into which the fluoride-containing restorative is placed. [94,100,103,105] Many laboratory studies report the daily or accumulated fluoride released into water. Artificial saliva tends to decrease the release of fluoride, most likely because of precipitation of calcium, phosphate, and fluoride complexes on the surface of the restorative material. Exposure of the restorative material to demineralizing solutions increases the available fluoride, whereas remineralizing fluids decrease the amount of fluoride released. [94,100,103,105] This tends to hold true for all glass ionomer-based materials. It is well known that during acid challenges glass ionomers mobilize and release increased amounts of fluoride into the environment. [86] This is an important feature for facilitating reprecipitation of mineral into demineralized enamel and root surfaces, thereby enhancing remineralization.

Glass ionomers and other fluoride-releasing restorative materials increase the fluoride composition of adjacent tooth structure (Table 2). [58,75,88–90,93,105–110] The amount of acquired fluoride in sound enamel and root surfaces adjacent to glass ionomer restorations is substantial and may be appreciated for long periods of time. In addition, a dramatic increase in fluoride content in enamel and dentinal cavosurfaces, as well as in the dentinal axial wall, has been shown in a recent electron-probe analysis. [110] Both wavelength and energy-dispersive spectrometry studies also found that fluoride is incorporated into the hybrid layer formed by fluoride-containing dentin adhesives. [107] Fourier transform infrared spectroscopy of the

intermediate layer between glass ionomer and dentin indicates that the primary component of this layer is fluoridated carbonatoapatite. [108] This substance is known to have a low solubility and increased acid resistance. Undoubtedly, readily available fluoride from glass ionomers will enhance the *in vivo* caries resistance of the tooth structure composing the cavosurfaces and tooth surfaces adjacent to such restorations.

In vitro secondary caries and fluoride-releasing dental materials

The ability of a fluoride-releasing material to affect *in vitro* secondary caries formation is illustrated by the reduction in the occurrence of wall lesions along the tooth-restorative material interface (Table 3; Figs. 3 and 4). [26,35,40,42–44,46–53,55,56,59,60,62,64–67,69,70–77,79–81,88,99,111] Many different fluoride-releasing materials reduce wall lesion frequency considerably (from 40% to almost 80%). Typically, restorative materials with a higher fluoride content tend to provide the greatest degree of protection along cavosurfaces. Not only is wall lesion development affected, but also wall lesion depth and length. Reductions in cavity wall depth and length range from 10% to 25% for fluoride-releasing composite resins to 35% to 41% for fluoridated amalgams to 70% to 74% for conventional glass ionomers. In addition, the higher the fluoride release from the dental material, the greater the chance that wall lesion formation will be inhibited and create caries-inhibition zones in the cavosurface tooth structure. Typically, glass ionomers and resin-modified glass ionomers produce inhibition zones in the cavosurface, whereas compomers and fluoride-releasing composite resins rarely develop such inhibition zones. Outer (primary) surface lesions that form in enamel and root surfaces next to the restorations also are affected by fluoride-releasing dental materials. Reductions in outer lesion depths range from less than 10% for fluoridated composite resins to almost 75% for conventional glass ionomers. Cavity liners, desensitizers, and topical fluoride application substantially decrease both outer and wall lesion depths.

The retention of greater amounts of mineral in secondary caries lesions is also apparent from microhardness studies. [68,75,88] These studies have found that the outer lesion adjacent to a glass ionomer had only a 7% reduction in microhardness compared with sound enamel; however, a nonfluoride-releasing composite resin resulted in a 44% reduction in microhardness in the outer lesion compared with sound enamel. The availability of fluoride from the adjacent restoration results in a reduction in mineral loss from the outer lesion.

Both lesion depth and mineral loss are related in a linear fashion to the amount of fluoride released over time. [40,75] In fact, under plaque conditions, complete inhibition of secondary caries may be realized if 200 to 300 μg of fluoride are released per cm^2 of the dental material over a 1-month period. [42,43,47]

Table 2
Fluoride release from restorative materials

Fluoride release (μg Fl/cm^2/d)					
	3 Days	7 Days	14 Days	50 Days	100 Days
Glass ionomer	15.5	7.5	4.9	2.2	1.8
Resin-modified glass ionomer	4.0	2.6	2.0	1.1	0.9
Compomer	5.0	3.2	2.1	1.0	0.8
Composite resin with 30% TBATFB	3.3	1.9	1.9	1.9	1.9

Fluoride release (ppm Fl/d)			
	1 Day	84 Days	253 Days
Resin-modified glass ionomer	14	3	2
Compomer	1	1	1

Varying fluoride loading dose (ppm Fl/d)				
	2 Days	10 Days	20 Days	30 Days
Control resin-modified glass ionomer	4.2	1.0	0.9	0.5
1% Fl resin-modified glass ionomer	8.0	1.9	1.1	0.7
2% Fl resin-modified glass ionomer	20.3	4.1	2.4	1.5
3% Fl resin-modified glass ionomer	27.0	5.8	3.6	2.4

Cumulative fluoride release (ppm Fl)					
	1 Day	7 Days	14 Days	28 Days	70 Days
Glass ionomer	16	37	52	59	156
Resin-modified glass ionomer	15	20	32	41	92
Nonfluoride resin	<0.1	<0.1	<0.1	<0.1	<0.1

Fluoride release into various media (μg Fl/cm^2)

	Water	Artificial saliva	Demineralizing-remineralizing fluid
Glass ionomer	7.6	1.3	8.3
Resin-modified glass ionomer	5.9	3.1	12.3
Compomer	2.1	1.0	7.0
Nonfluoride composite resin	0.1	0.1	0.3

Fluoride release with caries challenge (μg Fl/cm^2)

	Demineralizing fluid	Remineralizing fluid
Glass ionomer	11.4	2.6
Resin-modified glass ionomer	12.1	3.7
Compomer	6.6	1.7
Nonfluoride composite resin	0.8	0.3

Fluoride uptake by tooth structure (ppm Fl)

	30 Days	60 Days	90 Days
Glass ionomer			
Enamel surface	2755	2720	2745
Root surface	16,692	7454	6465

	Enamel cavosurface	Dentin cavosurface	Axial wall
Glass ionomer	3900	6700	5700
Resin-modified glass ionomer	3800	6300	5600

Data from references [55], [61], [94], [100], [101], [103], [106], and [109].

Table 3
Secondary caries and fluoride-releasing dental materials

Secondary caries reduction (% reduction)				
	Outer lesion depth (%)	Wall lesion length (%)	Wall lesion depth (%)	Wall lesion frequency (%)
Glass ionomer	74	70	74	79
Glass ionomer-silver (cermet)	53	56	50	NA
Resin-modified glass ionomer	46	NA	NA	44
Compomer	40	NA	NA	31
Fluoridated amalgam	48	35	41	53
Fluoridated composite resin	8	10	25	NA
Glass ionomer liner				
Amalgam	18	30	52	NA
Composite resin	20	27	28	NA
Fluoridated desensitizer with amalgam	13	NA	NA	42
Fluoridated sealant	35	NA	NA	50
Glass ionomer sealant	46	NA	NA	50
APF application and amalgam	94	NA	NA	NA

	Resin-Modified Glass Ionomer	Compomer	Glass ionomer liner
Demineralization inhibition at dentinal margins (% reduction)	38	39	54

	Glass ionomer	Nonfluoridated composite resin
Microhardness after demineralization (% reduction)	7	44

NA = not applicable.

Data from references [26], [35], [40], [42–44], [46–49], [50–53], [55], [56], [59], [60], [62], [64–69], [70–77], [79], [80], [81], [88], [99] and [111].

Remote effect of fluoride-releasing dental materials

The local environment for fluoride release is relatively extensive and is not limited to the immediately adjacent cavosurface or surface enamel (Table 4). [47,62,63,78,109] Fluoride uptake *in vitro* by enamel and root surfaces from conventional glass ionomers is substantial and maintained for at least 6 months. [109] Enamel located 1.5 to 7.5 mm from glass ionomers increases its fluoride content by more than 2000 ppm. Root surfaces up to 7.5 mm from glass ionomers have a greater ability to absorb fluoride than enamel (more than 5000 ppm). Perhaps even more remarkable is that the glass ionomer-restored teeth were stored in artificial saliva, which is known to reduce the amount of fluoride available for uptake.

The amount of mineral loss from *in vitro* lesions adjacent to and up to 7 mm from glass ionomer restorations is reduced significantly (Table 4). [78] When compared with nonfluoride-releasing restorations, the placement of

a glass ionomer results in reductions in mineral loss that range from almost 80% at 0.2 mm from the restoration to 37% at 7 mm from the restoration margin. Similarly in polarized light microscopic studies, mean lesion depth for primary tooth enamel and permanent tooth root surfaces increased gradually the farther the lesion was located from the glass ionomer restoration. [62,63] In contrast, *in vitro* microradiographic studies found a lessened effect for fluoride-releasing composite resins. [47] The lesion depth and mineral loss were reduced in close proximity to the fluoridated resin, whereas tooth surfaces positioned 3 to 4 mm from the fluoridated restoration did not receive the benefits of fluoride release.

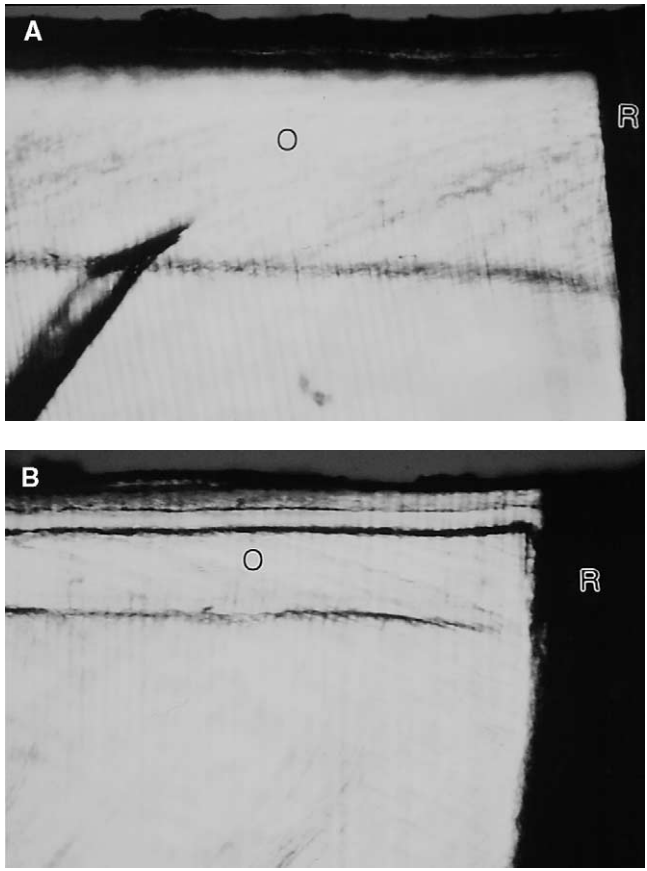

Fig. 3. *In vitro* secondary caries formation in root surfaces adjacent to restorations (**R**) filled with nonfluoride releasing (A) and fluoride-releasing dental materials (B–D). Dramatic reductions in the primary outer root surface lesion (**O**) depth occur when nonfluoride releasing composite resin (A) restorations are compared with fluoride-releasing composite resin (B) restorations, and compomer restorations (C), and resin-modified glass ionomer restorations (D). (arrow = wall lesion).

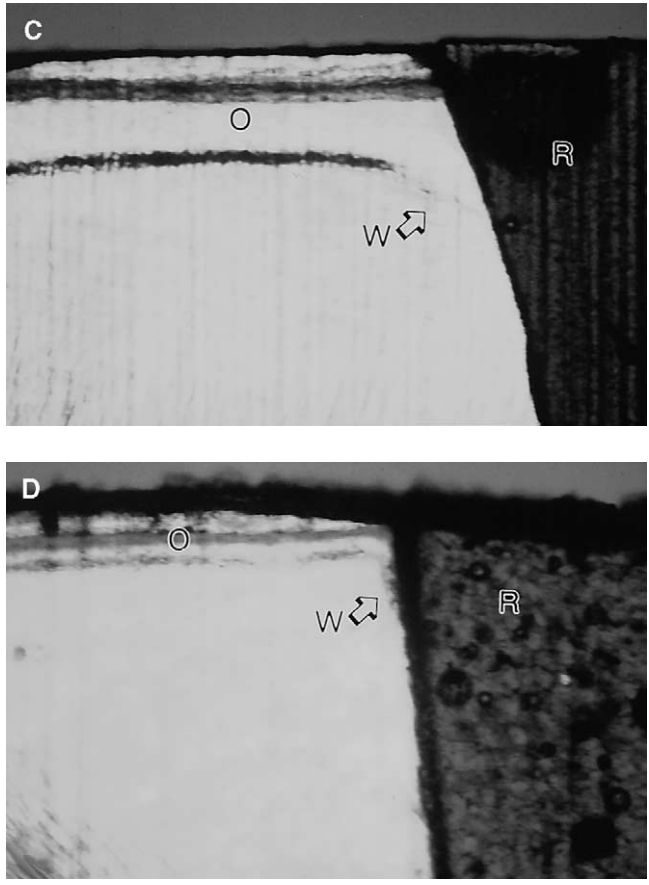

Fig. 3 (*continued*)

Tooth surfaces opposing adjacent teeth restored with glass ionomers receive a certain degree of protection against caries formation *in vivo* (Fig. 5). [28,44,88,111–116] In a 3-year longitudinal study, [114,115] approximately 25% of interproximal tooth surfaces adjacent to teeth restored with glass ionomer tunnel restorations had developed caries. In marked contrast, slightly more than 80% of interproximal surfaces in teeth adjacent to amalgam-restored teeth succumbed to caries. A similar 3-year clinical study [28] with primary teeth found an almost two-fold increase in interproximal caries in teeth adjacent to amalgams when compared with those next to glass ionomers. Another study found that the use of a resin-modified glass ionomer base under a resin decreased the risk of caries development in the opposing interproximal surface to a similar degree. [116]

Remineralization of existing lesions also may occur when these lesions are in close proximity to a fluoride-releasing dental material. [111,117]

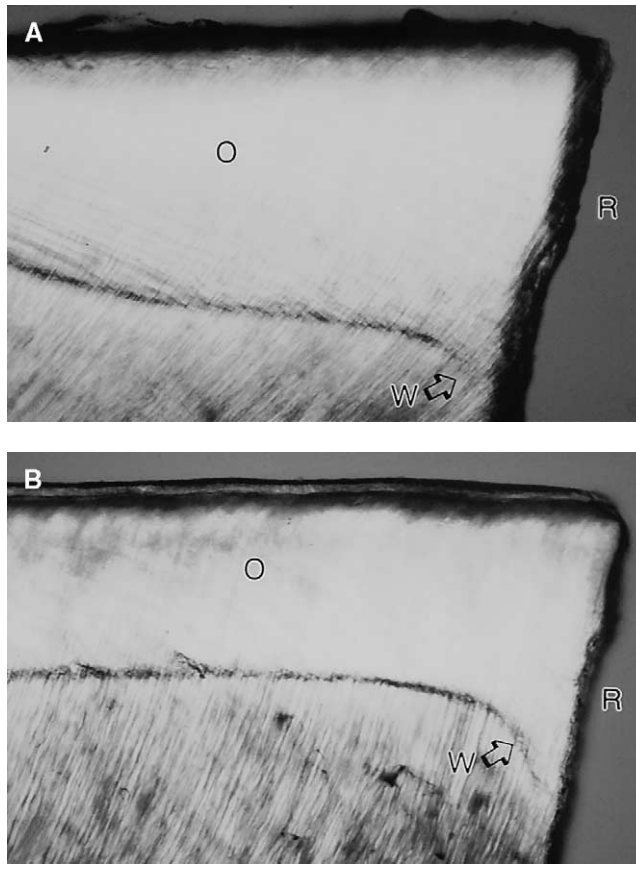

Fig. 4. Fluoride-releasing amalgam restorative material and *in vitro* secondary caries formation in root surfaces. Caries formation in the root surface (**O**) adjacent to a conventional amalgam restoration (A) is quite extensive and considerably greater than that for the primary outer root surface lesion (**O**) adjacent to a fluoride-releasing amalgam (B). (**R** = restored cavity where material was lost during the sectioning procedure; arrow = wall lesion).

Placement of amalgam, nonfluoride-releasing composite resin, and conventional glass ionomer class II restorations in extracted teeth in contact with other teeth possessing well-defined proximal lesions provided insight into the effects of these restorative materials on adjacent interproximal surfaces. After a 2-week exposure to a cyclic demineralizing-remineralizing artificial caries system, differences were identified among the lesions adjacent to glass ionomer restorations compared with those in contact with fluoride-releasing composite resins and nonfluoridated amalgams. The lesions next to glass ionomers had regressed slightly in area (−2%), whereas the lesions adjacent to amalgams and fluoride-releasing resins had increased by 64% and 28%, respectively. Fluoride release into the local environment by the glass ionomer

Table 4
Remote effect of fluoride-releasing dental materials

Fluoride uptake from glass ionomer (6 months after placement)

Distance from ionomer (mm)	Enamel surface (ppm)	Root surface (ppm)
1.5	2745	6465
3.5	2283	6061
5.5	2106	5952
7.5	2102	5862

Mineral loss (volume %, microradiography)

Distance from restoration (mm)	Composite resin	Glass ionomer	Reduction (%)
0.2	8365	1875	78
0.5	7731	2344	70
1.0	7691	3280	57
2.0	6268	2809	55
4.0	6446	3317	49
7.0	6951	4360	37

Primary (outer) lesion depth and mineral loss (% reduction, microradiography)

	Lesion Depth (%)	Mineral Loss (%)
Fluoride-releasing resin		
Adjacent to restoration	35	24
3 to 4 mm from restoration	0	<1

Primary (outer) outer lesion depth (polarized light microscopy)

Distance from glass ionomer restoration (mm)	Primary tooth enamel (μm)	Root surface (μm)
0.5	128	139
1.0	148	173
2.0	228	232
4.0	256	292

Caries development in proximal surfaces of teeth adjacent to restored teeth (clinical studies)

	Year 1 (%)	Year 2 (%)	Year 3 (%)	Total (%)
Amalgam restoration	36	18	27	82
Glass ionomer tunnel restoration	0	18	9	27
	Caries at 2 years (%)			
Resin-modified glass ionomer-resin restoration	6			
Resin restoration	11			
Primary dentition	Caries at 3 years (%)			
Amalgam	21			
Glass ionomer	12			

Data from references [28], [47], [62], [63], [78], [109], [114], and [115].

restorations resulted in no caries progression with the lesion in the opposing tooth surface.

Similarly, resin-modified glass ionomer has been shown to provide protection against *in vitro* lesion progression and to induce remineralization to a similar extent as that found with fluoride dentifrices, but less than that for a low-concentration (0.05%) sodium fluoride rinse. [113] Lesional areas of artificial caries have been noted to be reduced by 2.45-fold when placed adjacent to resin-modified glass ionomers, by 2.23-fold when exposed to a

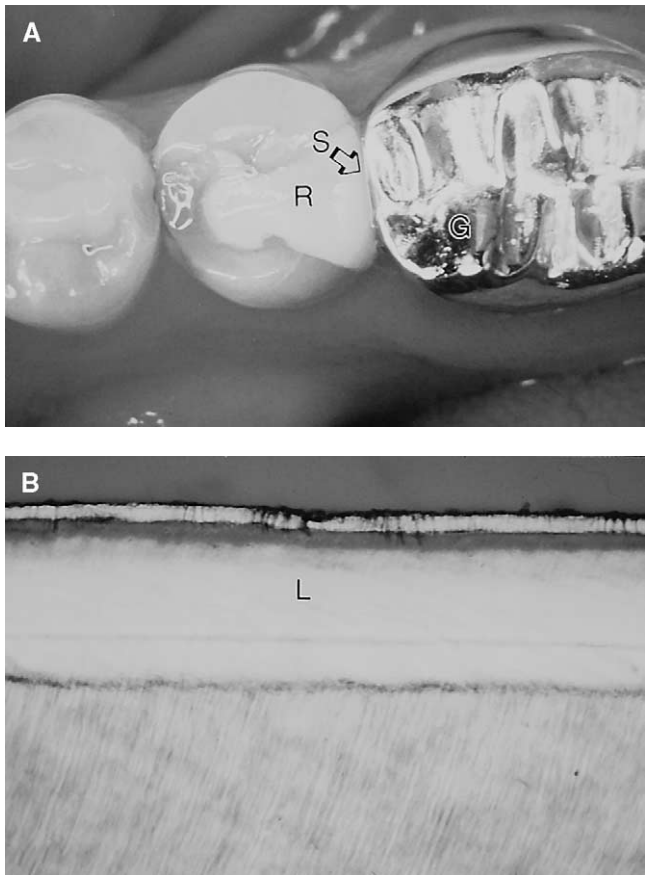

Fig. 5. An intraoral method for testing the effect of a fluoride releasing restorative material (**R**) employs the temporary placement of a gold crown (**G**) with a mesial slot (**S**) for retaining sections of human tooth enamel or root surfaces. Development of the intraoral caries in the tooth sections (B, C) is influenced by the release of fluoride from the adjacent restoration into the oral environment. A nonfluoride-releasing dental material allows for more extensive caries formation (**L** = body of lesion) in a previously sound root surface (B), compared with a lessened degree of caries formation (**L** = body of lesion) in a previously sound root surface (C) in close proximity to a fluoride-releasing dental material.

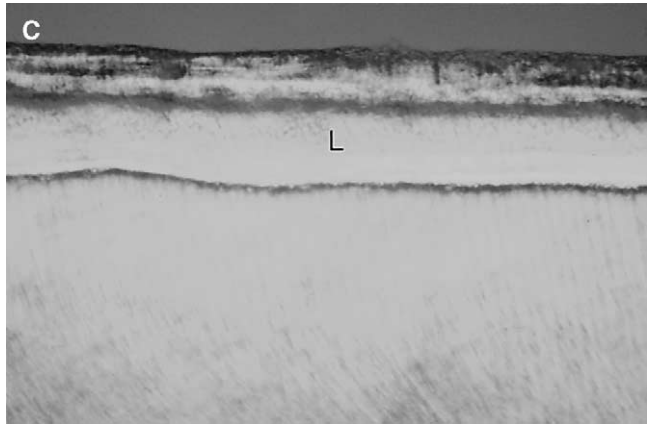

Fig. 5 (*continued*)

fluoridated dentifrice, and by 3.74-fold when exposed to a 0.05% sodium fluoride mouth rinse.

The ability of glass ionomers to release fluoride to adjacent tooth surfaces accounts for hypermineralization of enamel and dentinal lesions seen in microradiographic investigations and inhibition zones with polarized light microscopy. [79,80] With an *in vitro*, pH-cycling, demineralizing-remineralizing system and an *in vivo*, intraoral, partial denture model, it has been noted that enamel and dentinal lesions in contact with glass ionomers possess increased calcium content and mineral volume percentage compared with enamel and dentinal lesions adjacent to nonfluoridated amalgams and composite resins. The mineral content of the glass ionomer-associated hypermineralized layer was reported to be more than three-fold greater than those for the lesions adjacent to amalgams and resins. In addition, the hypermineralized area extended up to 300 μm into the underlying tooth structure. In contrast, the carious lesions adjacent to the amalgams and resins progressed and increased in depth by four-fold and three-fold, respectively. The glass ionomer material induced remineralization and hypermineralization of adjacent enamel and dentinal lesions, whereas the nonfluoridated amalgam and resin restorations were associated with progressive demineralization.

Plaque and fluoride-releasing dental materials

Although dental plaque is intimately involved in caries development, this organic film may act as a fluoride reservoir and provide a means to affect the demineralization-remineralization process. Glass ionomer materials release fluoride into the oral environment and are in direct contact with the overlying dental plaque. Clinical studies have shown that plaque adjacent to glass ionomers has increased fluoride concentrations compared with

nonfluoridated composite resins. [68,88,91,115,118] The plaque fluoride content ranges from 15.0 to 21.2 μg/g for glass ionomers compared with 0.4 to 3.5 μg/g for nonfluoridated resins. Although these levels seem to be relatively low, only small concentrations of fluoride in plaque, saliva, or calcifying fluids are necessary to shift the equilibrium from demineralization to remineralization. In fact, remineralization of enamel lesions begins with only 0.03 ppm fluoride in artificial saliva, plaque, and calcifying fluids. [4,82,83,112] Remarkably, optimal remineralization requires a fluoride concentration of only 0.08 ppm. Children in communities either with or without water fluoridation have similar baseline salivary fluoride levels of between 0.02 to 0.04 ppm, which is less than optimal for remineralization. In a 4-year longitudinal study, [4,112] it was reported that children with high salivary fluoride levels ($\geq$0.075 ppm) are more frequently caries-free than those with lower salivary fluoride concentrations. A child's salivary fluoride level, regardless of whether fluoridated drinking water is available, is associated with the child's caries status. It is apparent that water fluoridation has less of an effect on caries than the availability of other sources of fluoride, such as dietary fluoride, fluoridated dentifrices, and fluoride mouth rinses.

The importance of relatively frequent exposure to low-dose fluoride sources is emphasized by clinical studies that have shown that caries around orthodontic brackets and in xerostomic patients may be eliminated or greatly reduced with fluoridated dentifrice usage or daily sodium fluoride (0.05%) rinsing. [4,54,82,83,112] Such preventive agents increase the fluoride content of saliva and plaque above the level necessary to facilitate remineralization for at least 2 to 6 hours. The levels may be prolonged and higher if the individual does not rinse after toothbrushing or fluoride mouth rinsing.

As noted previously, glass ionomers may induce remineralization of carious lesions and hypermineralization in enamel and dentin adjacent to the restorative material. These materials release small amounts of fluoride on a continuous basis into the local environment. This fluoride is then taken up by plaque and saliva. [3,4,82,83,86] In many ways, these materials may be seen as slow-release fluoride devices. Not only is fluoride available to inhibit demineralization of sound tooth structure and facilitate remineralization of hypomineralized and carious tooth structure, but the released fluoride also affects bacteria within dental plaque. Several clinical studies [3,4,88,114,115,118] have shown substantial reductions (46–77%) in cariogenic bacteria (mutans streptoccci, lactobacillus) within plaque adjacent to glass ionomers. This effect has been observed up to 6 months after restoration placement. Dental plaque fluoride, even in small concentrations, inhibits bacterial metabolism by diffusion of hydrogen fluoride from the plaque into the bacteria. Once inside the bacteria, the hydrogen fluoride acidifies the bacterial cytoplasm and leads to release of fluoride ions. These ions interfere with enzymes essential for bacterial metabolism (enolase, acid

phosphatase, pyrophosphatase, pyrophosphorylase, peroxidase, catalase, proton-extruding adenosine triphosphatase). In addition, increased plaque fluoride decreases adherence of bacteria to hydroxyapatite, which results in reduced plaque formation.

Recharging of fluoride-releasing dental materials

Most of the fluoride-release studies performed with fluoridated dental materials have evaluated the amount of fluoride released over varying lengths of time without the material being exposed to exogenous sources of fluoride. From the information presented previously, it is quite obvious that certain materials release fluoride for long periods (up to 8 years). This is not equivalent to what happens in the oral environment. Most individuals in developed and developing countries have access to fluoridated toothpastes, over-the-counter low-dose fluoride rinses, and prescription high-dose fluoride rinses and toothpastes. Exposure of fluoride-containing dental materials to exogenous fluoride sources replenishes the fluoride within the dental material and provides a continuing, renewable source of fluoride for the oral environment. [57,90,92, 97,98,102,103,111–113,117,119] This is particularly true for all glass ionomer-based restorative materials and less so for composite resin-based materials. Professionally applied fluoride treatment provides a 2.5 to 4.0 fold increase in fluoride release from fluoride-releasing dental materials. Even with commercially available fluoridated toothpastes, the fluoride uptake and release by fluoride-containing materials is substantial and adequate to increase plaque and saliva fluoride to levels sufficient to inhibit demineralization and facilitate remineralization. Significant increases in fluoride release (two-fold) may be achieved when conventional and resin-modified glass ionomers are exposed for short periods to only a 50-ppm fluoride solution.

The benefit of recharging glass ionomers and fluoride-releasing composite resins has been demonstrated *in vivo* using well-defined artificial lesions placed in the interproximal aspects of crowns and opposing fluoridated restorative materials. [111] Changes in the lesional areas due to the fluoride-releasing materials were determined in the absence and presence of fluoridated toothpaste. In a relatively short time period in the oral cavity, twice-daily exposure to the fluoridated toothpaste for 1 minute resulted in a reduction in lesional area of approximately 10% for a fluoride-releasing composite resin and about 5% for a glass ionomer. In another laboratory study, [117] fluoridated toothpaste used in concert with a fluoride-releasing resin and glass ionomer reduced the lesional areas by 18% and 14%, respectively. The ability to recharge fluoride-containing restorative materials with fluoridated dentifrices provides continuous low-level fluoride release that may prevent secondary caries in the restored tooth and primary caries in both the restored tooth and the neighboring tooth, and remineralize existing caries and hypomineralized tooth structure.

Caries-preventive mechanisms of fluoride-releasing materials

Fluoride-releasing dental materials prevent secondary caries by several different mechanisms (Box 2). [3,4,35,64,66,82–86] The release of fluoride into the local environment may inhibit or slow the process of demineralization. As little as 1 ppm fluoride in demineralizing, acidic, and plaque fluids reverses the demineralization process. Fluoride released from restorative materials may coat hydroxyapatite crystals that form the mineral substance of enamel, dentin, and cementum. Although fluorapatite has the greatest degree of acid resistance, the acid solubility of hydroxyapatite with a fluoride coating or veneer approaches that of fluorapatite. Such fluoridated hydroxyapatite may be formed in the presence of fluoride-releasing dental materials and provide even greater caries resistance than native tooth structure. Remineralization of lesions and hypomineralized tooth structure is facilitated by low levels of fluoride (>0.03 ppm) in saliva and plaque fluid. As noted previously, bacteria in dental plaque have several enzyme systems that are dysregulated by hydrogen fluoride derived from plaque. These enzyme systems are necessary for glycolysis and energy production by the bacteria. Fluoride-releasing materials provide a source for continuous fluoride that elevates salivary and plaque levels and adversely affects plaque bacteria. Fluoride-releasing materials may act as continuous low-level fluoride-delivery systems, especially when ''recharged'' by readily available exogenous fluoride sources. Finally, an intimate interface with minimal to no microspace between the restorative material and cavosurface may be enhanced by physicochemical bonding with glass ionomer-based materials and by mechanical bonding with composite resins.

Caries-preventive mechanism with fluoride-releasing dental materials

- Demineralization inhibited by release of fluoride into local environment
- Fluoride absorption to hydroxyapatite crystal surface enhanced (fluoride veneer)
- Remineralization of lesions and hypomineralized tooth structure facilitated
- Dental plaque bacterial enzyme systems affected
- Salivary and plaque fluoride concentrations elevated
- Continuous low-level fluoride-delivery system with ''recharging'' by exogenous fluoride sources
- Physicochemical bonding (glass ionomer--based materials)
- Mechanical bonding (composite resins)

Data from references [3], [4], [35], [64], [66], and [82–86].

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