SPECIAL CONTRIBUTIONS

A Half-century of Community Water Fluoridation in the United States: Review and Commentary

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Abstract

The nearly 50-year history of community water fluoridation is reviewed with the major emphasis on the benefits and safety of fluoridation. Other aspects of water fluoridation also described include the apparent reduction in measurable fluoridation benefits because of the abundance of other fluoride sources, the diffusion of fluoridation effects into fluoride-deficient communities, preeruptive and posteruptive effects, technical and cost aspects, sociopolitical and legal issues that affect the successful fluoridation of communities, and alternatives to community water fluoridation. The majority of studies have evaluated the effectiveness of water fluoridation on the permanent teeth of children, while there are fewer studies on deciduous teeth and in adults; the relationship between fluoride ingestion and bone health needs further clarification; the sociopolitical issues of fluoridation need to be better understood.

Key Words: fluoride, fluoridation, caries prevention, coronal caries, review article, root caries, antifluoridationists.

This paper was prepared at the request of the Executive Council and the Oral Health Committee of the American Association of Public Health Dentistry. It is a review of the published scientific literature concerning the benefits and risks of community water fluoridation, as well as other aspects of fluoridation that have been recognized during the nearly 50 years of use of this public health method of caries prevention. This review is meant to be a retrospective of fluoridation's past and to serve as a resource for charting fluoridation's future.

Normally, this type of work is referenced principally with primary sources. However, there have been many excellent reviews of the early and later history of community water fluoridation, and it would be imprudent not to take advantage of them (Table 1). Therefore, while the accompanying reference list demonstrates that primary sources are adequately represented, secondary sources have been cited when appropriate, and readers will need to consult them if they wish to be referred to other primary works. Although this is a review of community water fluoridation in the United States, reports from other countries are also cited.

History of Community Water Fluoridation

The history of community water fluoridation lies within three distinct periods (1). The first (ca. 1901–33) was concerned with the cause of a developmental enamel defect, described in the United States initially by Frederick McKay, and called "Colorado brown stain." This defect was identified as mottled enamel, or, more specifically, chronic endemic enamel fluorosis. The second period (ca. 1933–45), encompassing the classical epidemiologic studies of H. Trendley Dean, focused on the relationships among the naturally occurring fluoride concentration in the drinking water, enamel fluorosis, and dental caries. Later, by balancing the caries-preventive benefit achieved by fluoride and the risk of fluorosis, the limits of optimal fluoridation were set between 0.7 and 1.2 ppm F, based on the average of maximum daily air temperature (2). The third period, designated as the "moment of truth in fluoridation history" by Frank McClure (3), began on January 25, 1945, when Grand Rapids, Michigan, became the first city in the world to adjust its water fluoride concentration to a level expected to promote dental health. Sodium fluoride was added to the water supply of Newburgh, New York, on May 2, 1945, and on June 20, 1945, to the water supply of Brantford, Ontario. Sheboygon, Wisconsin, and Midland, Michigan, were fluoridated in 1946, and in February 1947 Evanston, Illinois, was fluoridated (3). The third period in the history of community water fluoridation continues to this day with nearly 10,000 US communities and numerous foreign countries using adjusted and naturally fluoridated water (4).

Status of Community Water Fluoridation

The 1989 fluoridation census, reported by the Centers for Disease Control, found that 135 million Americans—53.9 percent of the population and 62.1 percent of those on public water supplies—were served by drinking water containing fluoride that was adjusted to optimal

TABLE 1
Principal Secondary Sources Used in the Preparation of this Review

BOOKS

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National Health and Medical Research Council. The effectiveness of water fluoridation. Australian Government Publishing Service, 1991.

REVIEW ARTICLE

Kaminsky LS, Mahoney MC, Leach J, Melius J, Miller MJ. Fluoride: benefits and risks of exposure. Crit Rev Oral Biol Med 1990;1:261-81.

levels or that had fluoride already present to a level considered at or above optimal (4). Table 2 presents the 1989 fluoridation figures by geographic area. Region III (Midwest) had the highest proportion of the population with access to fluoridated water and Region VII (Pacific) the lowest. Of the 135 million people whose drinking water is fluoridated, 93 percent have had their water supply adjusted to the recommended fluoride concentration. This figure represents the fluoridation of 9,411 public water systems in 8,081 communities (4). The remaining 7 percent reside in 1,869 communities that are served by 3,463 water systems with natural fluoridation (4). Most of the cities with populations greater than 250,000 have adjusted or naturally optimal fluoride levels (5). Four of the five largest US cities (New York, Chicago, Philadelphia, and Detroit) were fluoridated in the 1950s and 1960s (5). Los Angeles, with a population of 3 million, is the exception (6).

Eight states, the District of Columbia, and the Commonwealth of Puerto Rico have mandated the addition of fluoride to the public water supplies (5,7), although in Puerto Rico there has not been vigorous execution of the mandate. The Minnesota and Illinois legislation has the greatest scope, requiring that all public water supplies be fluoridated. Some of the other states have restrictions in their laws that limit the scope of the mandate. Four states—Georgia, Michigan, Nebraska, and Ohio—allow a community to exempt itself from compliance if it does not wish to institute fluoridation. Two of these states—Michigan and Ohio—placed a time limit, which has already expired, on the period allowed for a referendum on fluoridation. Four states—Michigan, Ohio, Connecticut, and South Dakota—set lower limits on the size of the community that must comply. Table 3 demonstrates the success of water fluoridation in those states where it is mandated. All eight rank in the top half of states, based on the percentage of the population with public water supplies who are served by fluoridated water. Moreover, for seven of the eight states the percentage is between 80 and 100 percent, compared with a national average of 62.1 percent (4).

Since community water fluoridation was initiated in 1945, the US population receiving optimal levels of fluoride in their drinking water generally has grown apace with the overall population growth and with the growth of the population on public water systems (Figure 1). Nevertheless, the gap between the total population supplied by public water and the population served by community water fluoridation has not narrowed significantly since 1965 (7). A goal of the US Public Health Service was that by 1990 at least 95 percent of the population on piped water supplies would be serviced with optimally fluoridated water (8). This goal was not realized and the currently revised goal for the year 2000 stated in *Healthy People 2000*, establishes a more modest and realistic target of 75 percent (9).

Of the 52 jurisdictions (50 states, District of Columbia, Puerto Rico) included in the Centers for Disease Control's 1989 fluoridation census, nine of the lowest ranking in terms of the percent of the public water supply population drinking fluoridated water were in the western one-third of the country (Washington, Idaho, Wyoming, Montana, Oregon, Arizona, California, Nevada, and Utah). The other lowest ranking states were Kansas, New

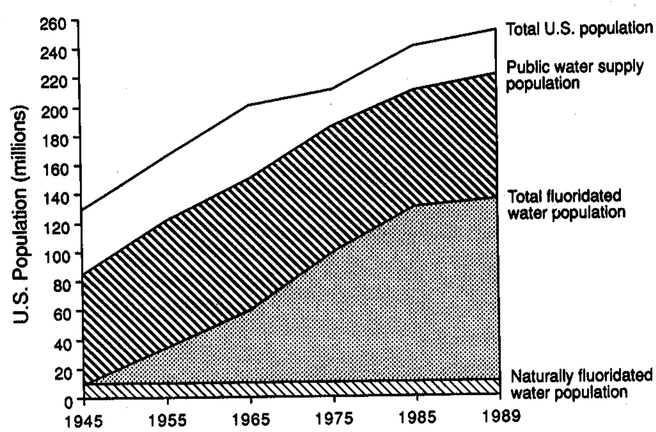
TABLE 2
Extent of Community Water Fluoridation in the United States (1989) (4)

Region	States	Population: Total	Population: Served by Public Water	Population: On Adjusted/ Naturally Fluoridated Water	% Pop. Receiving Adjusted/ Naturally Fluoridated Water: % of Total	% Pop. Receiving Adjusted/ Naturally Fluoridated Water: % Served by Public Water
I (New England)	ME, VT, NH, MA, CT, RI	13,046,000	11,453,000	7,175,756	61.4	62.7
II (Northeast)	NY, PA, NJ	37,726,000	34,502,000	17,997,284	47.7	52.2
III (Midwest)	MN, WI, MI, IA, MO, IL, IN, OH	54,650,000	44,534,000	40,069,901	73.3	89.9
IV (Southeast)	AR, LA, KY, TN, MS, AL, GA, FL, WV, VA, NC, SC, MD, DE	64,706,000	54,590,000	39,750,863	61.4	72.8
V (Southwest)	CO, AZ, NM, TX	25,392,000	23,658,000	15,403,185	60.6	65.1
VI (Northwest)	NV, UT, ID, MT, WY, ND, SD, NB, KS, OK	13,836,000	11,853,000	5,082,616	36.7	42.8
VII (Pacific)	WA, OR, CA	36,644,000	32,477,000	6,559,949	17.9	20.2
Other	HI, AK, DC, PR	5,534,000	5,370,000	3,589,203	64.8	66.8
United States	—	251,534,000	218,437,000	135,628,757	53.9	62.1

TABLE 3
Status of Water Fluoridation in those States in which it is Mandated (4)

State (Year of Legislation)	% of Pop. Served by Public Water Supply Receiving Adjusted/ Naturally Fluoridated Water	Rank (among 50 States)
Illinois (1967)	100.0	1
South Dakota (1969)	98.4	4
Michigan (1968)	90.2	7
Ohio (1969)	89.0	10
Connecticut (1965)	86.6	13
Georgia (1973)	85.7	15
Minnesota (1967)	83.5	17
Nebraska (1973)	71.3	23

FIGURE 1
US Population and Water Fluoridation



Hampshire, New Jersey, and Hawaii (4). If the year 2000 fluoridation goal is to be met, these states should be targeted for a special fluoridation effort.

Dental Benefits of Community Water Fluoridation

The inverse relationship between higher fluoride concentration of the drinking water and lower levels of dental caries experience, first demonstrated a half-century ago by Dean, continues to be true today. The results of community water fluoridation studies have been summarized in several comprehensive reviews. The reports of the first fluoridation studies conducted in the United States, Canada, the United Kingdom, and New Zealand between 1945 and 1965 were reviewed by McClure in 1970 in his book "Water Fluoridation. The Search and the Victory" (3). In the second edition of "Fluorides in Caries Prevention," published in 1982, Murray and Rugg-Gunn reviewed the literature through 1980 and summarized the results of 95 fluoridation studies conducted in 20 countries (10). Most recently, Newbrun, participating in a University of Michigan Workshop on the cost effectiveness of caries prevention in public health, reviewed the results of water fluoridation studies published between 1979 and 1988 (11).

There have also been several summary reports on water fluoridation, including those by the National

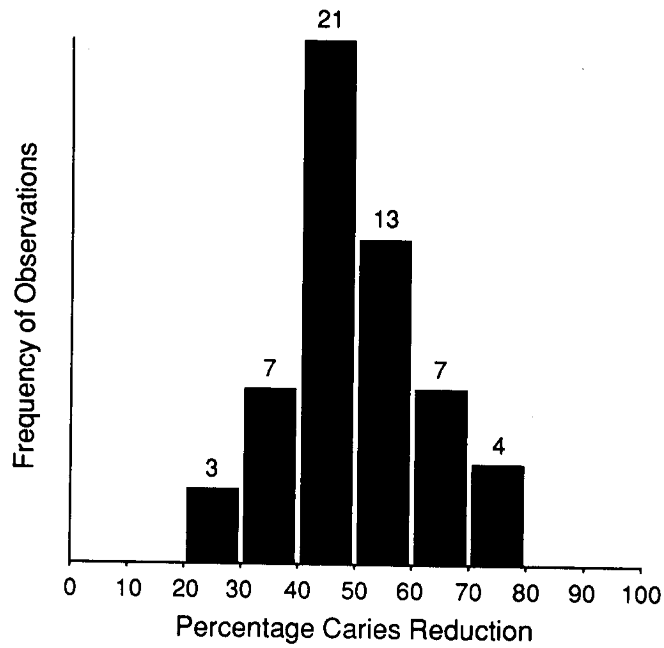
Health and Medical Research Council of Australia (12,13), the New York State Department of Health (14), and the US Department of Health and Human Services (15). Because of the thoroughness of the reviews and summary publications, reevaluation of individual water fluoridation studies would not be productive. The effectiveness of community water fluoridation will be discussed principally using the resources cited above, to which the reader is referred for specifics.

Children. *Deciduous Dentition.* Both Murray and Rugg-Gunn (10) and Newbrun (11) remarked on the paucity of reports detailing the effects of communal water fluoridation on the deciduous dentition, compared with the many reports on the permanent dentition. Nevertheless, sufficient clinical evidence is available to conclude that there are decided benefits to deciduous teeth from water fluoridation.

All three initial US fluoridation studies reported advantages to the deciduous teeth from communal water fluoridation. After 10 years (1945–54), the deft prevalence for Grand Rapids' six-year-olds, the peak caries prevalence age for the deciduous teeth, was reduced by 54 percent compared to the prefluoridation level (3). After 10 years of fluoridation in Newburgh, six- to nine-year-old children had almost six times as many caries-free primary cuspids and molars as children of the same age in fluoride-deficient Kingston (5). During the period from 1946 to 1960, there was a 13.7 percent decrease in the annual caries increment of six-, seven-, and eight-year-old Evanston children's deciduous teeth, compared to a 3.9 percent decrease in the nonfluoridated control city of Oak Park (3).

Murray and Rugg-Gunn plotted the frequency distribution of the percentage of caries reductions for the deciduous teeth from 55 fluoridation studies reported between 1956 and 1979 (10). The modal percentage caries reduction was 40–50 percent (Figure 2).

FIGURE 2
Distribution of Percentage Caries Reductions (deft) in Deciduous Teeth from 55 Community Water Fluoridation Studies Reported between 1956–79 (10)*



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Newbrun reported only one US study during the period of his review (1979–88) in which the effects of communal water fluoridation on the deciduous teeth were reported (11). Based upon examinations conducted in 1984, there was a 30 percent lower caries prevalence (defs) in three-and-a-half- to five-year-old Ohio Head Start children from fluoridated urban and nonurban sites compared to those from fluoride-deficient sites. Newbrun noted that these children were from low socioeconomic homes and were not representative of all children in this age group. Newbrun also cited data for five-year-olds from NIDR's 1986–87 National Survey of Dental Caries in US Schoolchildren. Five years is the last age when children still have only a deciduous dentition. There was a 39 percent lower caries prevalence (dfs) for five-year-old children with a history of continuous residence in optimally fluoridated communities, compared to those residing in fluoride-deficient communities.

Because of the paucity of information on the effects of communal water fluoridation on the deciduous teeth of US children during the period of his review, Newbrun included eight reports from the United Kingdom, which were published between 1979 and 1988. Caries reductions in the deciduous dentition of 40–60 percent were consistently reported in four- to five-year-old children from fluoridated communities compared with those from fluoride-deficient ones. Most of the UK studies included only children with life-long residence in the communities.

O'Mullane et al. (16) reported the results of an extensive caries survey of children in the Republic of Ireland. Between 1964 and 1972, most of the larger public piped water supplies were fluoridated; by 1986, 65 percent of the population was serviced by fluoridated water. Caries examinations of five-year-old children conducted in 1984 provided information on the deciduous teeth. A comparison was made between children whose home water supply had been fluoridated continuously since birth (and who also may have been exposed to other fluoride sources) and children who had never had any type of fluoride exposure. O'Mullane and coworkers reported the mean dmft score of the children residing in fluoridated communities was 1.8 compared to 3.0 for those residing in fluoride-deficient communities, a difference of 40.0 percent. Fifty-two percent of children from the fluoridated communities had a caries-free deciduous dentition compared to 38 percent of children in the fluoride-deficient communities.

FIGURE 3
Distribution of Percentage Caries Reductions (DMFT) in Permanent Teeth from 73 Community Water Fluoridation Studies Reported between 1956–79 (10)*

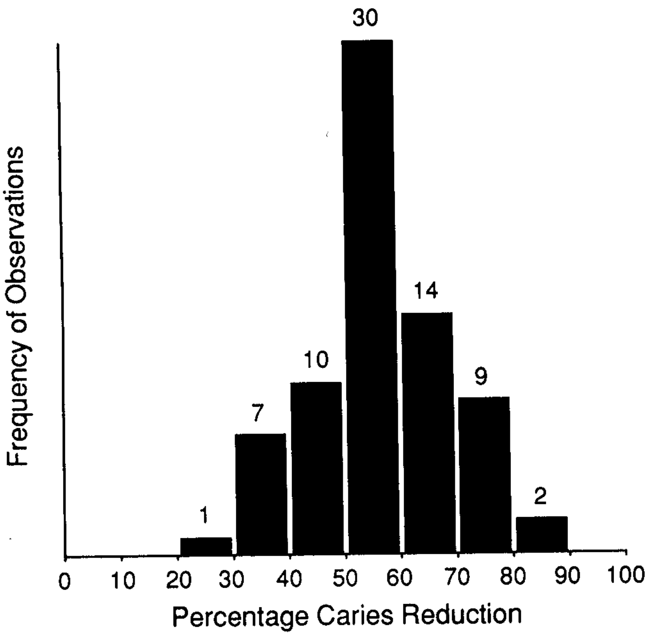

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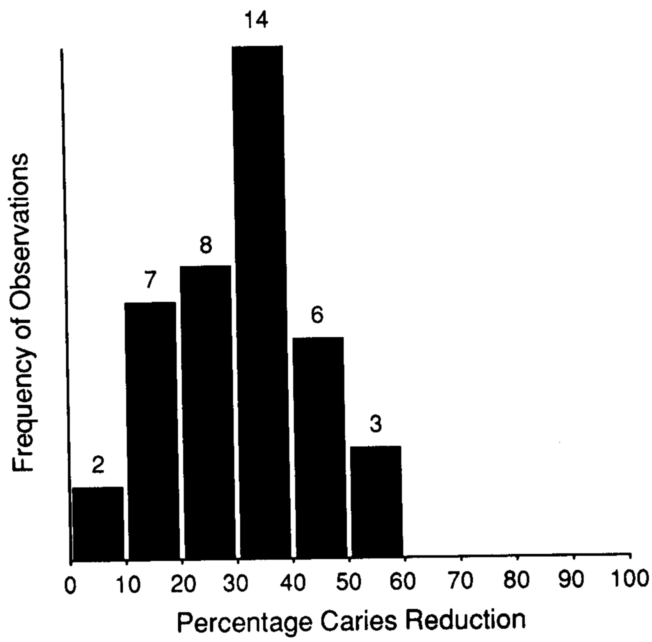
FIGURE 4
Distribution of Percentage Caries Reductions (DMFT or DMFS) in Permanent Teeth from 20 Community Water Fluoridation Studies Reported between 1979–89 (11)



A comparison was also made between the 1984 data and similar data collected in 1961–63, before fluoridation. There was a substantial caries decline in Irish children during the 20 years, with the decline being greatest among the residents of fluoridated communities. The dmft of five-year-olds in 1961–63 was 5.6. In 1984, it was 3.0 for those residing in fluoride-deficient communities (46.4 percent reduction) and 1.8 for those residing in fluoridated communities (67.8 percent reduction). O'Mullane and coworkers attributed the caries decline in fluoride-deficient communities to the widespread use of fluoride dentifrices, which, of course, also contributed to the caries decline in fluoridated communities, and to the diffusion of water fluoridation benefits, caused by such factors as the consumption in fluoride-deficient communities of soft drinks bottled in fluoridated communities.

Permanent Dentition. After 10 years, the results of fluoridation in Grand Rapids, Newburgh, and Evanston demonstrated caries reductions of between 40 to 65 percent in permanent teeth (3). The percentage decline was greatest for proximal surfaces. These highly favorable findings prompted Arnold and coworkers, who were evaluating fluoridation in Grand Rapids, to comment that, with the exception of the decrease in caries in European children caused by World War II sugar restrictions, "no such dramatic and persistent inhibition of caries in large population groups has ever been demonstrated by any other means than fluoridation of a domestic water supply" (3).

Murray and Rugg-Gunn plotted the frequency distribution of the percentage caries reductions in the permanent dentition resulting from water fluoridation (10). Of the 73 studies that they reviewed, published between 1956 and 1979, 46 were from the United States and the other 27 were from 16 other countries. The modal percentage caries reduction was 50–60 percent (Figure 3). Murray and Rugg-Gunn commented that this figure "is in agreement with the oft-quoted statement that 'water fluoridation reduces dental decay by half.'"

Newbrun reviewed the results of 20 reports on the effectiveness of communal water fluoridation in inhibiting dental caries in the permanent dentition (11). The reports, published between 1979–89, were based on studies conducted in the United States, Britain, Canada, Ireland, and New Zealand. When the results of these reports were averaged, a mean caries reduction of 30.4 percent was obtained. When the results of fluoridation studies in the US and in other countries were each averaged separately, the mean caries inhibitions were 26.5 percent for the US and 36.1 percent for the other countries. Figure 4 presents a frequency distribution of the percentage caries reductions from the reports in Newbrun's review. For these reports published between 1979 and 1989, the modal percentage caries reduction was 30–40 percent compared to the 50–60 percent found earlier by Murray and Rugg-Gunn (Figure 3).

Newbrun (11) and others (15,17,18) have commented on the narrowing of the relative caries difference between children living in fluoridated and those living in fluoride-

TABLE 4
Coronal and Root Caries Prevalence in Adults Based on Fluoride Concentration of Water Supply (11)

Reference	Water Fluoride Concentration (ppm)	Age (Mean or Range)	# of Subjects	DMFT DFS*	% Diff.
Coronal caries†					
Russel and Elvove (1951)	0.1	20–44	155	17.2	56
	2.5	20–44	385	7.5	
Eklund et al. (1987)	0.7	40.1	502	10.9	20
	3.5	39.8	164	8.7	
Hunt et al. (1989)	<0.5	74.1	174	15.6	21
	0.7–1.0	75.2	101	12.4	
Stamm et al. (1990)	0.2	43.0	465	15.1	28
	1.6	40.2	502	10.9	
Root caries†					
Brustman (1986)	<0.3	>60	162‡	11.9§	35
	1.0–1.2	>60	103	7.7	
Burt et al. (1986)	0.7	39.8	164	0.69	88
	3.5	43.2	151	0.08	
Hunt et al. (1989)	<0.5	74.1	174	2.3	17
	0.7–1.0	75.2	101	1.9	
Stamm et al. (1990)	0.2	43.0	465	3.0	17
	1.6	40.2	502	2.5	

*DMFT for coronal caries, DFS for root caries.
†These articles are cited by Newbrun (11) and do not necessarily appear in the references for the current article.
‡The only study listed in which some subjects did not have a continuous residence history.
§Lower 6 anterior teeth.

deficient communities. The reasons for this reduction in the measurable benefits of water fluoridation are discussed in the section of this review that addresses the issues of the dilution and diffusion of fluoridation benefits.

Adults. Adults also benefit from water fluoridation. Earlier studies on the effects of fluoridation on dental caries in adults have been reviewed extensively by Murray and Rugg-Gunn (10). Newbrun's review has brought the topic up to date (11). Newbrun stressed that in studies of adults, the comparison was often between those living in fluoride deficient or optimally fluoridated communities and those living in *above*-optimally fluoridated communities. More studies are needed on the caries levels of adults in which the conventional comparison is made between residents of optimally fluoridated communities and residents of communities that are fluoride deficient.

Table 4 presents the results of reports from Canada and the United States comparing the prevalence of coronal or root caries in adults living in communities with different water fluoride concentrations. The coronal and root caries prevalence rates of adults residing in the communities with the higher water fluoride concentrations were consistently lower than the rates for adults living in communities with lower levels of fluoride in their water.

In a recently completed study of approximately 600 adults 20 to 34 years old, the investigators found a 25.1 percent lower mean coronal caries score (DFS) in subjects who resided in optimally or naturally fluoridated communities compared to subjects who had no exposure to fluoridated water (19). Pre- and posteruptive fluoride exposure patterns relative to caries activity were also assessed, but the sample size of the preeruptive exposure group was too small for meaningful comparison.

Dilution and Diffusion of Fluoridation Benefits

As cited above, comparisons of the caries prevalence rates between optimally fluoridated and fluoride-deficient communities conducted during the last decade show less of a difference than comparisons reported before 1980. The decrease in the magnitude of the difference in caries prevalence between these two types of communities probably is not the result of an abatement of the ability of water fluoridation to inhibit caries. Rather, it appears to be the result of what may be called "dilution" and "diffusion" effects.

Dilution is the apparent reduction in measurable water fluoridation benefits resulting from the ubiquitous availability of fluoride from other sources. Beginning in the 1950s, each succeeding decade has seen the introduction of new fluoride products, including professionally applied topical agents, fluoride toothpastes, dietary fluoride supplements, fluoride mouthrinses, and self-applied fluoride gels. This abundance of readily available fluoride has contributed to a lowering of the "background" caries levels, both in fluoridated and fluoride-deficient communities, from which the effectiveness of communal water fluoridation is measured (20,21). Kaminsky and coworkers listed 14 studies in fluoride-deficient communities in the US and elsewhere, which collectively covered about 30 years from the 1950s to the 1980s, in which the prevalence of dental caries had declined 17 to 60 percent (14). Undoubtedly, these declines resulted partly from the availability and use of both professional and consumer fluoride products.

Diffusion is the extension of the benefits of community water fluoridation to residents of fluoride-deficient communities. Diffusion can result from the consumption of commercial beverages and foods that were processed in optimally fluoridated communities and transported to fluoride-deficient ones (22). It can also occur when children or adults who live in fluoride-deficient communities travel to optimally fluoridated communities where they attend child care centers, school, or work. (Presumably, reverse diffusion can also occur when beverages bottled in fluoride-deficient communities are consumed in fluoridated communities, or when children or adults who reside in optimally fluoridated communities routinely travel to school or work in a community that is fluoride deficient. Reverse diffusion would have the same leveling effect when caries rates in the two types of communities are compared, although in this situation, fluoride benefits are being denied rather than extended).

Brunelle and Carlos analyzed the data from the second NIDR national survey of caries in US schoolchildren, completed in 1987, in order to determine the effect of exposure to community water fluoridation (18). They reported an 18 percent difference in caries prevalence between schoolchildren who were life-long residents of optimally fluoridated and those who were residents of fluoride-deficient communities. However, to control for the dilution effects of other sources of fluoride, they excluded from their analysis those children with histories of exposure to dietary fluoride supplements or topical fluorides received in dental offices or school programs. After eliminating these children, the difference in caries prevalence was 25 percent.

The effects of diffusion on the benefits of water fluoridation can be deduced by comparing the caries prevalence of schoolchildren in optimally fluoridated and those in fluoride-deficient communities according to the seven US geographical regions. Table 5 ranks the US geographical regions according to the percentage of the population served by communal water fluoridation (18). Comparing mean DMFS scores of children who are lifelong residents of optimally fluoridated communities and those without communal water fluoride exposure, the magnitude of the percentage difference is lowest in the region (Region III, Midwest) with the greatest percentage of the population having community water fluoridation. In fact, in Region III, there is actually less caries in the children with no residence history of communal water fluoridation. Brunelle and Carlos (18) suggest that the negative percentage difference in DMFS scores for Region III may be due to sampling limitations. Because so much of this region is fluoridated, the number of children who never had contact with fluoridated water was small.

Conversely, the percentage difference between mean DMFS scores is greatest in the region (Region VII, Pacific) with the lowest percentage of its population on communal water fluoridation. The difference of 60.6 percent in Region VII is consistent with the reports of the magnitude of the caries inhibition from water fluoridation in the 1950s prior to the introduction of other fluoride interventions. The regions that are intermediate in their extent of fluoridation have differences in caries scores between

TABLE 5
Comparison of the Caries Prevalence of US Schoolchildren with or without Residence Histories of Fluoridated Water Exposure, Relative to the Geographic Region in which They Live (18)

Region	% of Pop. Receiving Adjusted/Naturally Fluoridated Water (1988)*		DMFS—Residence History of Water Fluoridation: Lifelong	None	Difference in Mean DMFS Scores: %	Rank	
III (Midwest)	72.2	(greatest)	2.86	2.69	–5.6	1	(lowest)
I (New England)	66.2	↑	3.11	3.45	9.8	3	↓
IV (Southeast)	57.5		2.75	3.60	23.6	6	
V (Southwest)	57.4		2.49	2.71	8.1	2	
II (Northeast)	48.1		3.08	3.42	9.9	4	
VI (Northwest)	35.9		2.36	3.07	23.1	5	
VII (Pacific)	17.8	(lowest)	1.42	3.61	60.6	7	(greatest)
	53.2		2.79	3.39	17.7		

*1988 figures, rather than 1989 figures (Table 2), are used here, since they more closely conform to the date of the caries examinations.

residents of fluoridated and fluoride-deficient communities that also are intermediate, although irregular. While the limitations in attempting to correlate the water fluoridation status of a region with the caries status of individuals within the region must be recognized, the comparisons in Table 5, nevertheless, suggest that the extent of water fluoridation in a region determines the magnitude of the diffusion effect and its influence on the relative difference in caries prevalence between optimally fluoridated and fluoride-deficient communities.

Failure to consider fluoride residence history, inaccurate reporting of residence histories, and intermittent compliance with exact standards of water fluoride concentration in fluoridated communities also can lead to improper assumptions concerning the true value of water fluoridation, generally underestimating its benefits (18,23,24). Brunelle and Carlos found that of the approximately 36,000 subjects participating in the NIDR national caries survey for whom residence histories were available, 23 percent had life-long exposure to fluoridated water, 23 percent had never lived in a fluoridated community, and 54 percent had lived in both fluoridated and fluoride-deficient communities (18). Thus, more than five of every 10 US schoolchildren have intermittently consumed fluoridated water because of residence changes. Burt et al. (25) and Clovis et al. (26) have shown that for American and Canadian children, respectively, a limited residence exposure to fluoridated water will impart dental benefits. A highly mobile American society, compared to a relatively stable society when water fluoridation was introduced in the 1940s, also serves to blur the distinction between populations that have or have not been exposed to water fluoridation.

It is evident that a variety of factors—principal among them being the dilution effects of other sources of fluoride, the diffusion of the benefits of water fluoridation beyond the geographic limits of the community being served, and the mobility of contemporary US society—have confounded the traditional distinction between communities that are fluoridated and communities that are fluoride deficient. It is no exaggeration to say that, for all practical purposes, the phrase "not exposed to fluoridated water" now is a misnomer in the United States and, possibly, in other developed countries that employ fluoridation widely.

Effect on Dental Benefits of Discontinuing Water Fluoridation

Several studies have evaluated the effect of discontinuing water fluoridation. Two of the earliest studies were in Galesburg, Illinois, and Antigo, Wisconsin (27,28). Galesburg's water, which contained a natural fluoride concentration of 2.0 ppm, was replaced by fluoride-deficient water (<0.1 ppm F) in 1959. Within two years there was a 10 percent decrease in the number of caries-free [illegible] and their DMFT scores increased from 2.02 to 2.79 (27). In Antigo, fluoridation of the water supply was discontinued in 1960 after 11 years. Six years later, the DMFT scores of second, fourth, and sixth grade children had risen by 70, 41, and 48 percent, respectively (28). The water fluoride concentrations were also reduced to suboptimal levels in Austin, Minnesota, in 1956 (29) and Wick, Scotland, in 1979 (30). In both communities the caries prevalence of the children increased. In the more recent episode in Wick, defluoridation in 1979 resulted in a downward adjustment of the water fluoride concentration from 1.0 ppm to the natural level of 0.02 ppm. Five- and six-year-old children received clinical and radiographic caries examinations in 1979, after life-long exposure to optimally fluoridated water, and similar aged children received caries examinations in 1984, after life-long exposure to fluoride-deficient water. The dmft index rose from 3.14 in 1979 to 4.30 in 1984, a difference of 27.0 percent, and the dmfs index went from 8.42 to 13.93, a difference of 39.6 percent.

In Karl-Marx-Stadt (now Chemnitz), Germany, technical problems reduced the adjusted fluoride concentration from 1.0 ppm to a low of 0.2 ppm (31). From 1959 to 1970 the water fluoride concentration had been maintained at a constant 1.0±0.1 ppm. There was an interruption in water fluoridation from 1970 to 1971 that lasted 1.5 years, followed for the next five years by suboptimal levels of water fluoridation until, in 1977, the optimal fluoride level was restored. During this 18-year period all schoolchildren in Karl-Marx-Stadt received regular visual-tactile caries examinations from the same dental examiner. For 3- to 15-year-old children, dmft and DMFT scores showed a reduction during the original period of optimal fluoridation, increased during the period when the water fluoride concentration fell, and then were reduced again when fluoridation was fully restored.

A recent study that determined the effect of defluoridation was conducted in Stranraer, Scotland, which was fluoridated in 1970 and then defluoridated in 1983 because of a judgment by the Scottish court (32-34). The consequences of defluoridation in Stranraer, as well as those described for Wick, are of particular interest since they happened during the overall secular caries decline occurring throughout the United Kingdom, which has been attributed largely to the use of fluoridated toothpastes.

In 1980, after 10 years of fluoridation, the DMFT of 10-year-olds was 1.66, compared with 3.35 for 10-year-olds in Annan, a comparable fluoride-deficient community. This was a difference of 50.4 percent. After defluoridation, the mean DMFT of Stranraer 10-year-olds increased, despite the secular decline that continued in Annan. In 1986, three years after defluoridation, the DMFT of 10-year-olds in Stranraer was 39 percent lower than in the same aged children in Annan. By 1988, the mean DMFT of Stranraer 10-year-olds was 2.28 compared with 2.56 in Annan, a difference of only 11 percent

(34). At the same time, dental treatment needs and costs rose in Stranraer. Between 1980–86, the costs associated with restorative care had risen by a dramatic 115 percent, compared to a 9 percent rise in Annan.

Salivary fluoride levels are low in individuals who reside in communities where the water fluoride concentration is low (35-38). When the fluoride concentration in drinking water is reduced to suboptimal levels, the concentration of fluoride in dental plaque can decrease to almost nonmeasurable levels (39). Inasmuch as the permanent teeth of the 10-year-old Stranraer children who were examined in 1988 were largely formed during the period of optimal fluoridation, the decreased caries protection might be attributed to the lack of posteruptive fluoride contact that, presumably, reduced salivary and plaque fluoride concentrations (40).

In its review of the benefits and risks of communal water fluoridation, the Ad Hoc Subcommittee on Fluoride of the US Public Health Service proposed that one criterion for conferring effectiveness of an agent is the disappearance of effects when the agent is removed (15). The report cites the studies described above in which increases in caries scores are associated with discontinuation of communal water fluoridation as additional evidence of a causal relationship between optimal concentrations of fluoride in drinking water and caries resistance.

Mechanism of Action of Fluoride in Drinking Water

The mechanisms by which fluoride provides caries resistance have been reviewed by Newbrun (41), Murray and Rugg-Gunn (42), and Mellberg and Ripa (43). The latter state that fluoride mechanisms can be grouped into five categories: increased enamel resistance to acid demineralization, increased rate of posteruptive maturation, remineralization of incipient lesions, interference with microorganisms, and improved tooth morphology. Furthermore, it is customary to classify fluoride therapy and mechanisms under two broad categories: systemic and topical. Systemic methods are those in which fluoride is ingested and the unerupted teeth are the targets of fluoride activity. Topical fluorides are not meant to be ingested and act posteruptively on the teeth. Fluoridated water provides topical contact to erupted teeth as it passes through the oral cavity and systemic contact to unerupted teeth after it is absorbed and circulated. Despite nearly 50 years of fluoride use, the relative importance of these two modes of contact in the prevention of dental caries and, by implication, the mechanisms involved are still uncertain.

When water fluoridation began, most scientists believed that the anticaries activity of fluoride was principally a result of its incorporation into the apatite crystals of developing enamel, thus increasing the stability and reducing the solubility of the apatite structure. However, the correlation between enamel fluoride concentration and caries experience was inconsistent (21,43). Perhaps this equivocal finding should have been expected, considering that the effects of some preeruptive mechanisms of fluoride, such as improved crystallinity (42,43) and octacalcium phosphate conversion (44), cannot be measured by an enamel biopsy. Since a conclusive relationship between fluoride levels in sound enamel and caries protection could not be established, the emphasis in research about fluoride mechanisms shifted from the creation of high levels of fluoride in sound enamel (systemic effect) to the presence of low concentrations of fluoride in the intraoral environment (topical effect) and to the role of fluoride in remineralization (45,46). In 1991, the Ad Hoc Subcommittee on Fluoride stated, "The theory of preeruptive fluoride incorporation as the sole or principal mechanism of caries prevention has been largely discounted" (15). Data from both early and recent clinical studies of water fluoridation and other systemic fluoride methods support the view of *both* a preeruptive and a posteruptive influence on caries (21).

Preeruptive Effects. The Grand Rapids, Newburgh, and Evanston water fluoridation studies all demonstrated greater percentage reductions in the younger age groups of children, who had the greatest amount of preeruptive fluoride contact (3). Of more recent vintage, Driscoll et al. reported greater caries protection to teeth that were unerupted at the start of a fluoride supplement program compared to teeth already in the mouth (47). In that study children received 1 or 2 mg F/day as tablets for six school years. The control group was given placebo tablets. Four years after discontinuing the study the mean DMFS increments for early erupting teeth in children using 1 mg F/day and 2 mg F/day were 15.0 percent and 23.3 percent less than in the control children, respectively. For late erupting teeth the mean DMFS increments were 38.6 percent and 33.6 percent less. However, Thylstrup believes that the most critical period for caries protection from fluoride is when the teeth are emerging into the oral cavity (48), and Driscoll and coworkers' findings could reflect the effect of topical fluoride contact at the time of tooth emergence. Burt and coworkers' findings are less subject to antithetical interpretations (25). These investigators compared the DMFS increments of children, initially six and seven years old, who lived in a fluoride-deficient community (0.2 ppm F), but who had resided in fluoridated communities prior to the eruption of their permanent teeth with children of similar age who were life-long residents of the fluoride-deficient community. The native residents had a three-year DMFS increment of 2.35 compared with 1.72 for the fluoride-exposed group, a difference of 26.8 percent. Burt and coworkers concluded: "Despite evidence that the benefits of limited ingestion of fluoridated water are topical in nature, the fact that many of the affected teeth in this study were unerupted at the time of the fluoride exposure means that preeruptive benefits cannot be ruled out."

Posteruptive Effects. In addition to indicating a preeruptive effect, findings from the original US fluoridation studies also demonstrated posteruptive benefits (21). In his review of these studies, McClure stated, "The evidence strongly suggested that there were beneficial effects on teeth which were formed or erupted prior to the initiation of water fluoridation" (3). Beltran and Burt (21) cite recent studies from Britain (49) and Denmark (37,50) that provide additional evidence of posteruptive benefits from systemic fluoride. In the British study, the four-year mean caries increment of children who were 12 years old when fluoridation (1.0 ppm F) began was compared with that of a control group residing in a fluoride-deficient community (<0.1 ppm F) (49). Children were transported to a central facility so that the examinations were conducted without the examiner knowing to which group the children belonged. The four-year mean DMFS increments of the fluoride and control groups were 6.73 and 9.19, respectively, representing a difference of 27 percent. Since all or most of the permanent teeth had erupted prior to the initiation of fluoridation, the difference was attributed to "substantial topical effects on teeth already erupted at the start of fluoridation."

Other, less direct, arguments may be considered to support the claim of posteruptive benefits from water fluoridation. For instance, it is known that when contact ceases, caries protection diminishes (see section "Effect on Dental Benefits of Discontinuing Water Fluoridation"). It may be inferred, therefore, that the continued caries protection in fluoridated areas into adulthood is the result of repeated topical contacts.

Beltran and Burt (21) proposed that if the major effect of fluoride is a posteruptive one, then caries experience in communities with long-standing comprehensive topical fluoride programs should approach that of communities where the drinking water is fluoridated. However, they admitted that the clinical results they presented lacked consistency and failed to resolve the issue. Ripa (51) reviewed the results of three US fluoride mouthrinse programs that used historical controls to assess the effectiveness of this topical intervention (52-54). In all three studies, the results showed that when the children began rinsing as kindergartners, there was a caries reduction of approximately 50 percent, which is similar to that reported in water fluoridation studies. Ripa believed that since the children were five to six years old when they entered the mouthrinse programs, the fluoride solution contacted most of the permanent teeth as they emerged into the mouth and this was a major factor determining the caries reductions achieved. This interpretation agrees with Thylstrup's contention that the most important time for fluoride to contact the teeth is when they are erupting into the mouth (48).

Pre- vs Posteruptive Effects. Groeneveld et al. analyzed the results of caries examinations between 1953 and 1971 in the Tiel (1.0 ppm F)–Culemborg (0.1 ppm F), Netherlands, water fluoridation study (55). Children were followed longitudinally and examined every two years from seven to 18 years of age, until water fluoridation ended. Those living in fluoridated Tiel received fluoride continuously from birth. The analysis is too complex to describe here, but their conclusions concerning the relative benefits of pre- and posteruptive fluoride contact are summarized:

(1) The initiation of enamel lesions is hardly affected by water fluoridation. However, lesion progression is slowed by posteruptive fluoride contact.

(2) For 15-year-olds exposed to water fluoridation since birth, the DMFS reduction was half due to the preeruptive effect and half to the posteruptive effect.

(3) The best protection is achieved if fluoridation is available from birth, but 85 percent of the maximum protection will occur if fluoride consumption starts between ages three and four.

(4) About two-thirds of the caries protection imparted to pits and fissures from water fluoridation comes from preeruptive contact. For smooth surfaces, the effect of preeruptive contact accounts for 25 to 50 percent of the caries protection. Groeneveld et al.'s analysis needs verification by others (55). Nevertheless, it indicates that the cariostatic activity of water fluoridation includes both systemic and topical mechanisms.

Safety of Communal Water Fluoridation

Fluoride metabolism studies have consistently established that the principal fate of ingested fluoride is either urinary excretion or retention by the skeleton and teeth. Because of the affinity of the fluoride ion for calcified tissue and its concentration in the kidneys, the safety of fluoride in relation to the skeleton, the teeth, and renal function specifically will be discussed. Because of the importance of the relationship between cancer mortality and fluoridation, this will be an additional safety topic. For a discussion of fluoride safety concerning other issues, such as the effects on other organs and tissues, hypersensitivity and allergy, reproductive toxicity and birth defects, readers are referred elsewhere (12,14,15,56). Several reviews of fluoride safety over the last decade constitute the principal source material for this section (12,14,15,56). Additional primary sources are cited where appropriate.

Skeletal Fluorosis and Osteosclerosis. Endemic skeletal fluorosis is confined largely to tropical climates with very high levels of at least 10 ppm fluoride in the water (12). Skeletal fluorosis also has been observed in workers exposed to high levels of fluoride in industry, such as aluminum production. Skeletal fluorosis has several stages and is usually characterized by generalized bone pain, stiffness and pain of the joints, and arthritic symptoms. Radiographic findings have shown osteosclerosis of the pelvis and vertebral column (12,14,15).

There have been five reported cases of crippling skeletal fluorosis in the United States. These individuals were exposed to natural levels of fluoride in the drinking water ranging from 3.9–8.0 ppm, and, in the two cases with an established history, the daily water consumption was excessively high (15). Radiographically detectable osteosclerosis has been reported in other individuals exposed to 4.0–8.0 ppm F, but there were no clinical symptoms of skeletal fluorosis (14). Skeletal fluorosis has not been reported in the US at water fluoride concentrations below 3.9 ppm, nor is skeletal fluorosis a public health problem in the US (15).

Bone Fracture and Osteoporosis. Sodium fluoride is used sometimes in the United States and other countries to treat osteoporosis. The minimum daily dose is about 40 mg NaF, and although the US Food and Drug Administration has never approved NaF treatment for osteoporosis, it is approved in other countries. People on the regimen have displayed an increase in the density of the vertebrae (trabecular bone) by as much as 35 percent over four years. Some studies have shown that there is a simultaneous decrease in cortical bone, such as the shaft of the radius, causing concern that the observed increase in bone density may be at the expense of other portions of the skeleton losing calcium.

The incidence of vertebral fracture is the most important outcome in osteoporosis treatment using fluoride (15). While studies have consistently shown that a daily NaF regimen will increase vertebral bone mass, the findings on reduced vertebral fracture are mixed, with two well-controlled recent studies failing to show a reduction in bone fracture rates (57,58). In 1989, an FDA Advisory Committee concluded that NaF has not been shown to be effective in reducing the incidence of vertebral fractures resulting from osteoporosis (15).

Because of the effect of fluoride in increasing trabecular bone mass and apparently reducing cortical bone mass, interest also has focused on the relationship between the concentration of fluoride in water supplies and both the prevalence of osteoporosis and the prevalence of fractures, especially the hip. Simonen and Laitinen compared the incidence of femoral-neck fracture over a decade in two Finnish towns, one with an adjusted water fluoride concentration of 1.0 ppm and the other with 0.0 to 0.1 ppm F (59). They found that the risk of fracture in both men and women was significantly higher in the fluoride-deficient community. A study in North Dakota reported that residents, especially women, exposed to water containing about 4.0 ppm F had less osteoporosis and vertebral collapse than a comparable group in a low-fluoride area (60).

Three studies have failed to find a relationship between water fluoride levels and hip and long bone fracture (61-63), whereas other studies have found a relationship (64,65). Cooper et al. evaluated hospital discharge records for 1978–82 in 39 counties in England and Wales (63). Approximately 20,000 men and women above aged 45 years were admitted with hip fractures (fracture of the proximal femur). The water fluoride concentrations in the counties under study ranged from almost none (0.005 ppm) to approximately 1.0 ppm. No significant correlation was found between water fluoride concentration and the prevalence of hip fracture. In the United States, Jacobsen et al. analyzed nationwide hospital discharge records from the Health Care Financing Administration and the Department of Veterans Affairs of white women aged 65 years and older for the period 1984–87 (64). They found a distinct north to south pattern for hip fracture, with the lower rates in the North and the higher rates in the South. Although they stated that no presently recognized factor or factors adequately explained the geographic variation, they nevertheless found an increased prevalence of hip fracture associated with the availability of fluoridated water. The report of Jacobsen et al. caused Cooper and Jacobsen to reevaluate the data from the UK In a letter to the editor of the *Journal of the American Medical Association,* they said that after weighting their data for each county by the size of the population aged 45 and older, they found a positive correlation between water fluoride levels and the prevalence of hip fractures, i.e., the higher the fluoride level, the greater was the risk of hip fracture (66). In a prospective five-year study of women in three Iowa communities conducted between 1983–84 and 1988–89, Sowers et al. also reported an association between water fluoride concentration and bone fractures (65). They reported a twofold increased risk of fracture of the wrist, spine, and hip in 55- to 80-year-old women in the higher fluoride community (4.0 ppm) compared with the control community (1.0 ppm).

Phipps and Burt reported no difference in cortical bone mass when the density of the distal radius was measured in post-menopausal women who were life-long residents of communities with either 3.5–4.2 ppm F or 0.7 ppm F in the water (67). However, they concluded that one predictor of cortical bone mass was fluoride exposure, with the higher fluoride level associated with lower bone mass. Considering the conflicting reports, it must be concluded that the question concerning the role of water fluoride exposure in both osteoporosis and bone fracture is unresolved (15).

Renal Effects. The kidneys are potential targets of acute and chronic fluoride toxicity because they remove fluoride from the blood, and the kidney cells that concentrate urine are exposed to high fluoride concentrations. The National Kidney Foundation has attested that water fluoridation does not harm the kidneys (56). Despite the importance of the kidneys as waystations for the disposal of fluoride from the body, there is no evidence that the incidence of mortality from any renal disorder is increased by water containing 1.0 ppm F(12). Furthermore, in several epidemiologic studies, long-term consumption of water containing fluoride as high as 8.0 ppm was found not to be associated with the induction or exacerbation of kidney dysfunction (14,15). While higher fluoride concentrations are definitely found in calcium oxalate kidney stones from residents of fluoridated compared with kidney stones from residents of fluoride-deficient communities, the effect of fluoride on stone formation is poorly understood. At least one group of investigators believes that there might be a dose-dependent fluoride inhibition of kidney stone formation. Increasing fluoride concentration, for instance from 0 to 10 ppm, inhibits the growth of calcium oxalate crystals (68). However, concentrations as high as 10 ppm are not relevant to controlled water fluoridation.

Studies have shown that persons with renal insufficiency have decreased fluoride clearance and will have elevated plasma levels of fluoride compared with unaffected individuals (14). For these people, the need is recognized to use water for hemodialysis that has a low fluoride concentration, as well as a low concentration of other ions. Recently, Bello and Gitelman showed that hemodialysis patients who received dialysis fluids from a fluoridated tap-water source purified by reverse osmosis had a higher plasma fluoride level than those who used a commercially prepared peritoneal dialysis fluid (69). They attributed this difference to the fact that although reverse osmosis systems remove most of the fluoride from water, this process cannot produce dialysis fluid from a fluoridated water source that is as low as the fluoride concentration in a commercial preparation. They speculated that since municipal water fluoridation and the reliance on reverse osmosis systems for water purification are both commonplace, many hemodialysis patients are being overexposed to fluoride, which may accumulate in their skeleton. In general, patients with impaired kidney function have an increased risk of skeletal fluorosis and in young children whose teeth are forming there is a risk of dental fluorosis. Cases of both, usually associated with high fluid intake, have been reported (14).

Hyperfluoridation of a water supply can occur due to "overfeeds" involving equipment malfunction (70,71) or to "accidents" in which equipment is not directly involved (72). There has been one report of a hyperfluoridation accident in a municipal water supply. In that instance, fluoride was accidentally added to the water supply of Annapolis, Maryland, at a level of over 30 ppm for several days (72). As a result, a resident undergoing kidney dialysis with softened tap water instead of purified water died and seven other dialysis patients became extremely ill. These individuals were in end-stage renal disease and were not receiving the recommended dialysis procedure. No untoward effects were documented in the population at large.

Cancer Mortality. After the introduction of communal water fluoridation, five reports appeared in the 1950s that evaluated general mortality rates in US communities with different concentrations of water-borne fluoride (15). No relationship between fluoride concentration and cancer was detected. Two studies from the UK, which appeared in the early 1970s, also reported no significant association between cancer rates and water fluoridation (15).

In a series of publications and public announcements beginning in 1975, Yiamouyiannis and Burk claimed that their analysis of cancer mortality statistics showed that fluoridation significantly increased the risk of cancer and that 10 US cities that had instituted controlled fluoridation programs had a rapid increase in cancer mortality rates compared with 10 nonfluoridated US cities over the same time period. The methodology of Yiamouyiannis and Burk was criticized, mainly for failure to adjust for confounding variables such as age and sex differences that affect cancer rates. The National Cancer Institute and others who reanalyzed the same cancer mortality data, using different methods, failed to find significant increases in cancer deaths in the cities with fluoridated water. The consensus of the scientific community is that the studies of Yiamouyiannis and Burk do not support the conclusion that fluoridation causes cancer (15).

Additional epidemiologic studies that investigated a possible link between water fluoridation and cancer morbidity and mortality have been conducted in several countries including the United States (73-77), the United Kingdom (78-81), Canada (82,83), and Australia (84). In all, over 50 epidemiologic studies have evaluated the possibility of an association between cancer mortality or morbidity and water fluoridation. The overall conclusion from these studies is that there is no credible evidence that water fluoridation increases the risk of cancer. Several independent commissions have reviewed the scientific literature on a cancer–fluoridation link and all came to a similar conclusion (85-87). The report of one of these commissions, reads, in part (85):

> We have found nothing in any of the major classes of epidemiological evidence which could lead us to conclude that either fluoride naturally in water, or fluoride added to water supplies, is capable of inducing cancer, or of increasing the mortality from cancer. This statement applies both to cancer as a whole, and to cancer at a large number of specific sites. In this we concur with the great majority of scientific investigators and commentators in this field. The only contrary conclusions are in our view attributable to errors in data, errors in analytical technique, and errors in scientific logic.

The issue of cancer and water fluoridation resurfaced in late 1989 with the premature release of data from a study of chronic toxicity and carcinogenicity of NaF in laboratory animals, conducted by the National Toxicology Program (NTP) of the National Institute of Environmental Health Sciences. In the NTP study, fluoride, as NaF, was administered to male and female rats and mice

TABLE 6
Doses and Number of Animals in the NTP Study of the Toxicity and Carcinogenicity of Sodium Fluoride (15)

Dose (ppm)		Daily Dose of NaF in mg/kg/Body Weight		# of Animals			
				Rats		Mice	
NaF	F	Rats	Mice	Male	Female	Male	Female
0	0	0.0	0.0	80	80	80	80
25	11	1.3	2.4–2.8	50	50	50	50
100	45	5.2	9.6–11.2	50	50	50	50
175	79	8.6–9.5	16.7–18.8	80	80	80	80

TABLE 7
Fluoride Concentrations in Bone Ash and Incidence of Osteosarcomas in the NTP Study of the Toxicity and Carcinogenicity of Sodium Fluoride (15)

Dose (ppm)		F Concentration in Bone Ash in μg F/mg Ash		Incidence of Osteosarcomas			
				Rats		Mice	
NaF	F	Rats	Mice	Male	Female	Male	Female
0	0	0.45–0.50	0.72–0.92	0	0	0	0
25	11	0.98–1.35	1.52–1.61	0	0	0	0
100	45	3.65–3.73	3.59–4.37	1	0	0	0
175	79	5.26–5.55	5.69–6.24	4*	0	0	0

*Includes one extraskeletal osteosarcoma.

in concentrations of 0, 11, 45, and 79 ppm (Table 6). Osteosarcomas were found in one high-dose (45 ppm F) and four highest dose (79 ppm F) male rats (Table 7). In the latter group, one of the osteosarcomas was extraskeletal—that is, it did not originate in bone. There were no osteosarcomas in the female rats or in the mice of either sex. Oral squamous cell neoplasms also were diagnosed in the dosed and control rats, but the incidence rates between dosed and control animals were not statistically significantly different (15).

The results of the NTP study were reviewed in April 1990 by the NTP Peer Review Panel. The panel concluded that, under the conditions of the two-year study, there was "equivocal" evidence of carcinogenic activity of NaF in male rats, based upon the small number of osteosarcomas in dosed animals. "Equivocal" is a classification for uncertain findings demonstrated by studies that are interpreted as showing a marginal increase of neoplasms that may be chemically related. The panel also concluded that there was no evidence of carcinogenic activity from NaF in the female rats or in the male or female mice.

The doses of fluoride in the NTP study were extremely high when contrasted to optimally adjusted or above-optimal naturally occurring levels of fluoride in US drinking water. In the two-year NTP study, the fluoride concentration in the bones of the dosed animals increased by a factor of approximately 2 to 10 (Table 7). Both rats and mice had dose-related fluorosis of the teeth and female rats had osteosclerosis of the long bones.

In a separate carcinogenicity study, commissioned by the Procter & Gamble Company and conducted from 1981 to 1983, rats and mice received daily doses of 0, 1, 4, 10, and 25 mg NaF/kg body weight. Two osteosarcomas were identified in low-dose (4 mg NaF) female rats that died before the end of the study; one fibroblastic sarcoma, possibly with osteoid formation, was found in a mid-dose (10 mg NaF) male rat; and one osteosarcoma was found in a high-dose (25 mg NaF) male rat. Benign osteomas increased in high-dosed male and female mice (15). The Carcinogenicity Assessment Committee, Center for Drug Evaluation and Research, of the US Food and Drug Administration observed that, under the conditions of the study, malignant tumors were not related to fluoride ingestion in rats or mice, but that a significant increase in the incidence of benign osteomas was observed in high-dose mice.

The Ad Hoc Subcommittee on Fluoride of the US Public Health Service characterized the combined results of these two animal studies as follows (15):

> When the NTP and the Procter & Gamble studies are combined, there is a total of eight individual sex/species

groups examined. Seven of these groups showed no significant evidence of malignant tumor formation. One of these groups, male rats from the NTP study, showed "equivocal" evidence of carcinogenicity, which is defined by NTP as a marginal increase in neoplasms — i.e., osteosarcomas — that may be chemically related. Taken together, the two animal studies available at this time fail to establish an association between fluoride and cancer.

In view of the NTP findings, the National Cancer Institute in 1990 conducted a study of cancer incidence in fluoridated and fluoride-deficient US communities (see Ref. 15 for a full description). Cancer incidence rates between 1973 and 1987 were evaluated in whites in Iowa and the Seattle metropolitan area. A county was considered exposed to fluoride if the proportion of the population served by fluoridated water increased from less than 10 percent to greater than 60 percent within a three-year period. Control counties had less than 10 percent of the population served by adjusted or naturally fluoridated water through 1987. Expected numbers of cancer cases were derived from the rates in nonexposed counties and the measure of risk was the ratio of observed to expected cases. For none of the cancers surveyed, including osteosarcoma, could a consistent link between cancer incidence and water fluoridation be established (15).

In a separate case control study involving 22 matched pair cases of osteosarcoma and controls from Iowa and Nebraska, McGuire et al. did not find the development of osteosarcoma to be associated with fluoridated water exposure (88). Although the investigators emphasized that the sample size of their study was small, they detected a negative relationship between fluoridation and osteosarcoma, suggesting that water fluoridation at recommended levels might have a protective, or antimutagenic, effect. The investigators indicated that they are currently investigating this hypothesis in a larger, nationwide study.

Dental Fluorosis. Dental fluorosis is a developmental defect of enamel that occurs when an excessive amount of fluoride is ingested during the period of enamel formation. The severity of the defect depends upon the amount of fluoride ingested, the duration of exposure, and the age(s) when exposure occurs. In humans, the defect consists of subsurface hypomineralization—that is, an increase in the porosity of subsurface enamel (89). The structural arrangement of the enamel crystals appears normal, but the width of the intercrystalline spaces is increased. Clinically, the enamel appears opaque or matte white, in contrast to the glossy translucence of normal enamel. In animals exposed to very high doses of fluoride, hypoplastic enamel lesions, seen clinically as surface malformations or pitting, can also occur (90). In humans, the pitting present in severe cases of dental fluorosis is the result of posteruptive breakdown of porous surface enamel (89,91-94). However, Richards believes that, with extremely high doses of fluoride during enamel development, preeruptive pitting might also occur (90). Posteruptive staining of the white areas also occurs in severely affected enamel (94).

TABLE 8
Dean's Dental Fluorosis Classification (5,95)

Classification	Dental Fluorosis Score	Description of Enamel
Normal	0	Smooth, glossy, pale creamy-white translucent surface
Questionable	0.5	A few white flecks or white spots
Very mild	1	Small opaque, paper-white areas covering <25% of tooth surface
Mild	2	White opaque areas covering <50% of tooth surface
Moderate	3	All tooth surfaces affected; brown stain; marked wear on biting surfaces
Severe	4	All tooth surfaces affected; brown stain; discrete or confluent pitting

Historically, the term "mottled enamel" has been used as a designation for enamel fluorosis. Its use is unfortunate, since "mottled" means colored spots or blotches, and it inaccurately indicates that all affected teeth have unesthetic blemishes. Actually, the degree of fluorosis runs a continuum from barely noticeable white striations that may affect a small portion of the enamel to confluent pitting and unesthetic dark brown or black staining that affects almost the entire enamel surface (95). Early researchers who examined children exhibiting the milder forms of fluorosis felt that the teeth were cosmetically more attractive than teeth that developed in areas with fluoride-deficient water. In fact, in 1970, McClure commented, "there is a consensus that an optimum quantity of fluoride may actually enhance the appearance of the teeth" (3). Because "mottled enamel" inaccurately describes the less severe forms of the condition and gives the erroneous impression that all affected teeth are cosmetically compromised, its use should be discontinued in favor of dental fluorosis or enamel fluorosis.

Dean developed a dental fluorosis classification that categorized the condition according to its severity (Table 8) (96,97). With Dean's method, an individual fluorosis score or a community fluorosis index (CFI) could be obtained. The fluorosis classification of an individual was based on the two most affected teeth. If the two teeth were not equally affected, the classification was determined by the lesser involved tooth. The CFI was calculated from the mean of the individual scores within a community:

TABLE 9
Public Health Significance of Community Fluorosis Index, According to Dean (95)

Community Fluorosis Index Range	Public Health Significance
0.0–0.4	Negative
0.4–0.6	Borderline
0.6–1.0	Slight
1.0–2.0	Medium
2.0–3.0	Marked
3.0–4.0	Very marked

$$F_{ci} = \frac{\Sigma\,(\text{frequency} \times \text{individual fluorosis score})}{\text{number of individuals}}$$

When the CFI reached 0.6, Dean believed it warranted consideration as a public health concern (Table 9).

Since Dean's classification system was published, other fluorosis indices have been developed, including ones by Moller (3,98), Thylstrup and Fejerskov (93), and the NIDR (tooth surface index of fluorosis) (TSIF) (99). These have been reviewed by Horowitz (95), who, along with others (100-102), has emphasized the problem of distinguishing dental fluorosis from nonfluoride enamel defects. Enamel opacities can be classified into three categories: fluoride-induced opacities, i.e., dental fluorosis; nonfluoride-induced opacities of known etiology; and idiopathic opacities (101). Some believe that the clinical appearance and the distribution of the enamel defects can enable experienced examiners to correctly identify dental fluorosis from other conditions (15,95,102). However, others believe that a positive clinical diagnosis can be supported only by an adequate history of exposure to fluoride. Cuttress and Suckling, who developed a flowchart for the differential diagnosis of dental fluorosis, indicated that only when the condition is encountered in an endemic fluorosis area where above-optimal water fluoride conditions prevail, can a diagnosis of dental fluorosis be made confidently, without recourse to an individual's medical/dental history or laboratory analysis of enamel, hair, nails, or urine (101). Confidence in the diagnosis of fluorosis increases as the prevalence and severity of the defects increase. Diagnostic uncertainty increases with lower prevalence and severity, which is generally the situation in the United States (101).

Assessment of whether the prevalence or severity of enamel fluorosis in the United States has changed over time is based on three types of time-related comparisons: (1) a comparison of different cities with similar fluoride concentrations using the same fluorosis index but different examiners, (2) a comparison of the same cities using the same fluorosis index but different examiners, (3) a comparison of the same cities using the same fluorosis index and the same examiners. Studies concerned with these three types of assessments have been reviewed by the Ad Hoc Subcommittee on Fluoride of the US Public Health Service and the conclusions of the subcommittee will be presented here (15). In addition, Brunelle has reported the only national US survey of dental fluorosis, which was conducted in 1986–87 on schoolchildren (103).

TABLE 10
Percent Prevalence of Dental Fluorosis in 1939–40 and in 1978–82 Using Dean's Index (15)

Water Fluoride Concentration	Total # of Cities		% Fluorosis Prevalence (Mean)	
(ppm F)	1939–40	1978–82	1939–40	1978–82
<0.4	10	5	0.9	6.4
0.4–0.6	3	1	5.6	2.4
0.7–1.2	4	4	13.6	22.2
1.3–1.7	1	3	30.2	25.7
1.8–2.2	2	1	44.0	53.2
2.3–2.7	1	5	73.8	78.5
2.8–3.2	0	3	—	74.0
3.3–3.7	0	0	—	—
>3.7	0	2	—	83.4

Different Cities/Same Fluorosis Index/Different Examiners Comparisons. Comparisons were made between the prevalence and severity of fluorosis in 1939–40 in 21 US cities and the prevalence and severity in 1978–82 in 24 different cities (Table 10). Dean's index was used as the measure of fluorosis.

In cities with less than 0.4 ppm F, the mean prevalence of fluorosis increased from less than 1 percent to approximately 6 percent. Nearly all of the increase occurred in the very mild and mild categories. In cities with optimal water fluoridation (0.7–1.2 ppm F), the mean dental fluorosis prevalence increased from 14 to 22 percent, and the increase was limited almost entirely to the milder forms. Except for the 1.3–1.7 ppm F category, cities with above-optimal fluoride concentrations showed a slight increase in fluorosis prevalence, from 44 to 53 percent where the water fluoride concentration was 1.8–2.2 ppm, and from 74 to 79 percent in cities with 2.3–2.7 ppm F. If moderate dental fluorosis has increased since the 1940s, the increase most likely has occurred in communities with fluoride concentrations of 1.8–2.2 ppm F (15).

Same Cities/Same Fluorosis Index/Different Examiners Comparisons. During the 1980s, Driscoll et al. (104) surveyed children for fluorosis in Kewanee, IL (1.06 ppm F), and Kumar et al. (105) conducted a similar survey in Newburgh (1.0 ppm F) and Kingston, NY (0.3 ppm F). Both groups compared their results to historical data from the same communities, reported in 1942 and 1955, respectively (106,107). Dean's CFI was used as the index.

In 1980 Driscoll and coworkers found the CFI of Kewanee was 0.39 compared to 0.31 reported in 1942

(104). Approximately 85 percent of children were diagnosed as normal (no or questionable fluorosis) in 1942 and 1980. The investigators found eight out of 336 children (2.4%) with moderate or severe fluorosis compared with none with those classifications in the earlier survey; however, they could not ascertain the cause. Comparing Dean's findings of nearly half a century earlier to their own, Driscoll et al. concluded, "No important changes in the prevalence and severity of fluorosis had taken place between the two periods."

Kumar and coworkers reported that for seven- to 12-year-olds in optimally fluoridated Newburgh, the CFI scores were 0.14–0.21 in 1986, compared to 0.11–0.18 in 1955 (105). For fluoride-deficient Kingston, the CFI was 0.00 in 1955 and 0.13–0.23 in 1986. The investigators concluded that for the fluoridated community, over the three-decade span, "the differences over time were negligible" and "no change of consequence" had occurred. There was an increase in the prevalence of fluorosis in fluoride-deficient Kingston, principally in the very mild and mild categories, to approximately the same level as fluoridated Newburgh. While the CFI was well below 0.6, the level Dean felt might prompt public health concern, the findings indicated "the availability of fluorides in nonfluoridated areas."

Same Cities/Same Fluorosis Index/Same Examiners Comparisons. Heifetz and coworkers examined eight- to 10-year-old and 13- to 15-year-old children in four Illinois communities with optimal and two, three, or four times the optimal levels of fluoride (108). The examinations were conducted in 1980 and repeated in 1985. The TSIF index was used. The study was cross-sectional, except for the eight- to 10-year-olds in 1980 who were available as 13- to 15-year-olds for the second examination.

There was little difference in the distribution of TSIF scores between 1980 and 1985 for all tooth surfaces of eight- to 10-year-olds, at all fluoride levels. In contrast, in 1985, there was a greater prevalence and severity of fluorosis for the 13- to 15-year-olds, at every fluoride level, compared with 1980. However, the most severe categories of fluorosis were not detected at either survey, and the fluorosis that occurred at the optimum fluoride level was characterized as "only whitish discolorations" (108).

From their data, Heifetz et al. hypothesized about the changes in fluoride ingestion that may have occurred during the lifespan of the children in their study (108). A similar analysis was conducted by the Ad Hoc Subcommittee on Fluoride (15). The following represents the combined conclusions from these independent analyses:

(1) Fluoride ingestion was lowest from 1965–70.

(2) Fluoride ingestion began to increase in the early 1970s.

(3) There was little or no additional change in fluoride intake between 1970–77.

(4) Fluoride ingestion continued to remain about constant through 1982.

TABLE 11

Comparison by Geographic Region of Percentage of Population Receiving Fluoridated Water with Mean DMFS Scores of Schoolchildren and Mean CFI Scores (18,103)

Region	% of Pop. Receiving Adjusted or Naturally Fluoridated Water (1988)	Mean DMFS Schoolchildren (1986–87)	Mean CFI (1986–87)
III (Midwest)	72.2 (1) [1]	2.91 (3) [1]	0.53 (2) [1]
I (N. England)	66.2 (2) [2]	3.60 (7) [5]	0.38 (5) [3]
IV (Southeast)	57.5 (3) [3]	3.08 (4) [2]	0.44 (3) [2]
V (Southwest)	57.4 (4)	2.39 (1)	0.72 (1)
II (Northeast)	48.1 (5) [4]	3.43 (6) [4]	0.36 (6) [4]
VI (N.west)	35.9 (6)	2.75 (2)	0.40 (4)
VII (Pacific)	17.8 (7) [5]	3.37 (5) [3]	0.27 (7) [5]

( )=rank; the left and right columns are ranked from greatest to least in keeping with the positive relationship expected between the status of community fluoridation and the community fluorosis index. The middle column is ranked from least to greatest in keeping with the negative relationship expected between the status of community fluoridation and caries prevalence.

[ ]=same, but omitting Regions V and VI.

The last conclusion, however, is surprising, since the late 1970s saw a reduction in the American Academy of Pediatric's supplemental fluoride schedule for children to age two, as well as a voluntary reduction in the fluoride content of baby formulas and foods to approximately 0.1 ppm F. Perhaps the consequences of these changes will become more apparent with time.

National Fluorosis Survey. In the first national survey of dental fluorosis among US schoolchildren, conducted in 1986–87, 78 percent were found to be normal (no or questionable fluorosis), 21 percent had very mild or mild fluorosis, 1 percent had moderate fluorosis, and 0.3 percent had severe fluorosis (103). (Refer to Table 8 for a description of Dean's fluorosis categories.) The highest prevalence of fluorosis, as well as the highest percentage of children with moderate or severe fluorosis, was found in Region V (Southwest), where natural fluoride concentrations are known to be above optimum in many communities.

Table 11 presents figures by geographic region for the percentage of the population with adjusted or naturally fluoridated water, the mean DMFS of schoolchildren in 1986–87, and the mean CFI from the same survey. Conventional wisdom dictates that there should be a direct positive relationship between the percentage of the regional populations receiving fluoridated water and the CFIs of the regions and a *negative* relationship between the percentage of the regional populations receiving fluoridated water and the mean caries prevalences of the regions. Notice that there is not an exact rank-order relationship between the percentage of the population consuming fluoridated water and either the mean caries scores or the mean CFI scores. One probable reason for the lack of a straightforward relationship is the consumption of water containing above-optimal natural concentrations of fluoride that tends to lower caries prevalence and to raise the CFI. Large percentages of the populations in Regions V and VI reside in communities with above-optimal fluoride levels. When Regions V and VI are omitted from consideration, thus reducing the confounding variable of naturally occurring high fluoride levels, the rank-order of the columns falls into closer agreement.

The analysis presented in Table 11 is only observational, and it is subject to the same limitations already discussed for Table 5, namely that regional fluoridation data are being linked with caries and fluorosis observations of individuals. Nevertheless, considering the ambient fluoride in the environment, the relationships presented in Table 11 are surprisingly strong. This suggests that, despite the many other sources of fluoride available, community water fluoridation still exerts a major influence on both caries and fluorosis and it is probably not surprising that, concomitantly, there has been a decrease in the prevalence of the former and an increase in the prevalence of the latter. Any explanation of these phenomena in the US must include the complex role of water-borne fluoride.

Nonwater sources of fluoride that can increase fluorosis risk include dietary fluoride supplements, the ingestion of fluoride toothpaste by preschool children, and the inadvertent ingestion of other topical fluorides. Fluoride dentifrices are the most ubiquitous of the topical fluoride methods and their use has been closely examined as a possible contributing factor to the fluorosis increase. Generally, preschool children will swallow some dentifrice when brushing(109), and although children's ages when dentifrice use began (110) and the amount of dentifrice used (111) have been identified as fluorosis risk factors, clinical studies so far have failed to confirm dentifrice ingestion as a primary cause for the increased prevalence of fluorosis (51). Conversely, the improper prescription and use of fluoride supplements has been identified as a major risk factor, indicating the need for close scrutiny of the prescriptive practices of physicians and dentists. Even proper fluoride supplement use may constitute a fluorosis risk factor in some children when other uncontrolled sources of ingested fluoride are considered (109,112,113). Further discussion of the relationship between dental fluorosis and these other fluoride modalities falls outside the scope of a review on water fluoridation and readers are referred elsewhere (15,51,114,115).

TABLE 12
Recommended Optimal Fluoride Levels According to Air Temperatures (4)

Annual Average of Max. Daily Air Temps. (°F)	Recommended Fluoride Concentration (ppm)	Recommended Control Range (ppm)
40.0–53.7	1.2	1.1–1.7
53.8–58.3	1.1	1.0–1.6
58.4–63.8	1.0	0.9–1.5
63.9–70.6	0.9	0.8–1.4
70.7–79.2	0.8	0.7–1.3
79.3–90.5	0.7	0.6–1.2

Technical and Cost Aspects

Liquid consumption is affected by the local ambient temperature and, therefore, the amount of fluoride ingested daily from fluids is influenced by climate (116,117). In 1962, the US Public Health Service established limits for optimal levels of fluoride in drinking water for the North American climate zones (3). The concentration standards, which were revised in 1982, range from 0.7 to 1.2 ppm F and are presented in Table 12 (4).

Three factors complicate the relationship between an assumed presence of a specific concentration of fluoride in the drinking water and caries protection: namely, variation in the municipal water fluoride concentration (118), the consumption of beverages or of water other than from the municipal water supply (118), and variable compliance with the accepted water fluoridation standards (119).

The use of home water purification systems, either reverse osmosis or distillation types, can reduce the concentration of fluoride in piped water sources to below optimal levels. Bottled water also has become a popular substitute for tap water. The amount of fluoride in bottled water varies and may result in individuals consuming too little or too much fluoride for their climate zone. Flaitz and coworkers reviewed the health histories of 1,126 children in a private pediatric dentistry practice in order to determine the prevalence of bottled water usage as a primary source of drinking water (118). The investigators asked the brands of bottled water used and determined the amount of fluoride they contained at that time. Of the 1,126 children, 1,070 (95%) lived in homes served by municipal water sources; the other 5 percent used well water. One hundred twenty-four children (11.0%) did not use their available drinking water source. Of these, 105 used bottled water and the other 19 had home water purification systems. Depending on the brand, the bottled water contained from 0.04 to 1.4 ppm F. The investigators concluded that of the 105 children using bottled water as their primary water source, 17 percent were receiving less than the recommended daily amount of fluoride, 72 percent were receiving more and 11 percent were receiving the correct amount. In this study, the bottled water came from nine different bottled water companies, six of which were located in Colorado. However, in another study of the fluoride content of 24 brands of bottled water from the US and abroad, 18 (75.0%) had fluoride concentrations of 0.34 ppm or less, two (8.3%) had a fluoride concentration of 0.55 ppm, and four (16.6%) had fluoride concentrations from 0.70 to 1.25 ppm (112).

Several studies have reported discrepancies between the intended and actual concentrations of fluoride in fluoridated water supplies (24,120-125). The state of Illinois enacted mandatory fluoridation legislation in 1967. Kuthy and coworkers reviewed monthly laboratory slips from 249 fluoridated public water systems in Illinois for a five-year period from 1977–81 (24). Compliance was not consistent. Municipalities with large populations and water plants with low chief operator turnover more consistently maintained the recommended fluoride level. Other characteristics that influenced compliance rates were the source of the water supply and the classification of the water plant operators. Thus, even though a community practices water fluoridation, the addition of optimal amounts of fluoride cannot be assumed.

The Centers for Disease Control reported that in 1988 there were nearly 9,000 municipal water systems with the fluoride concentration adjusted to an optimal amount (4), serving approximately 123,900,000 Americans. The three principal types of fluoridation distribution systems used in the US are the saturator, the dry-feeder, and the acid-feeder systems. The Indian Health Service uses another type, the Venturi fluoridator system, in some small rural communities. Descriptions of these systems have been published (126).

The three principal compounds used for fluoridation in the US are hydrofluosilicic acid, sodium silicofluoride, and sodium fluoride (4). The fluoride compound used as the fluoride source and the distribution system must be compatible. A saturator system is used with granular sodium fluoride, a dry-feeder system with sodium silicofluoride or sodium fluoride, and a solution-feeder with hydrofluosilicic acid (126).

Sodium fluoride was the first compound used in controlled fluoridation programs. Because of its low cost, sodium silicofluoride replaced sodium fluoride as the most frequently used compound for fluoridation. Within the last 20 years, hydrofluosilicic acid has become the preferred compound in the US. In 1975, hydrofluosilicic acid was used by 37.4 percent of the fluoridating municipalities (5). In 1989, it accounted for 57.3 percent (Table 13) (4). Several factors are responsible for the increased preference for hydrofluosilicic acid, including its low cost and relative ease in handling (5).

TABLE 13
Major Compounds Used for Community Water Fluoridation (1989) (4)

	Pop. Served		Systems	
Compound	#	%	#	%
Hydrofluorosilicic acid	75,295,924	62	5,187	57
Sodium silicofluoride	35,050,494	29	1,432	16
Sodium fluoride	11,474,400	9	2,431	27
Total	122,326,226	100	9,050	99

The chemical used was not indicated for all systems reporting, so data are incomplete.

Recent publications have addressed the economics of communal water fluoridation. Murray estimated the annual cost per person of fluoridation in 1981 for Hong Kong, Watford, England, and a series of US cities (126). He believed that assessments of fluoridation costs made by the US Public Health Service were inflated because of failure to amortize the costs of fluoridation equipment over a 10–15-year period. The costs of caries-preventive programs, including water fluoridation, were discussed at symposia held at the University of Michigan in 1978 and 1989 (127,128). Also in 1989, White and coworkers addressed issues associated with cost–benefit and cost-effectiveness analyses of communal water fluoridation (129).

The cost of communal water fluoridation is usually expressed as the annual cost per capita of the total population being served. Costs include amortization of initial capital expenditures and the annual operating costs for supplies, maintenance, and salaries. Costs vary according to a plant's capacity, the type of installation and fluoride compound, the number of injection points, and the existing natural fluoride concentration. Internationally, costs obviously will vary depending on the nature of the local economy in which fluoridation is introduced. However, a universal economic tenet for water fluoridation is that cost varies inversely with the size of the population being served.

In 1978, Newbrun estimated that the approximate annual cost of water fluoridation programs was $0.20 per capita in the US (127). He estimated that, after fluoridation had been operating for 12 years, a maximum annual savings in dental treatment expenditure would be $10.00 per capita, so that the approximate cost–benefit ratio for water fluoridation would be 1:50.

In 1989, Garcia reported that direct annual costs of fluoridation in the US ranged from $0.12–$1.31 per person with a mean of $0.54 (128). She presented costs based upon capitalization of existing equipment and on equipment replacement costs. Based upon the capital cost of existing equipment, she reported that the annual cost per person to fluoridate communities with populations of 2,000 or less was $0.77–$1.16; for communities between 2,800–20,000 it was $0.21–$0.95; and for communities with populations over 100,000 the cost was $0.12–$0.21.

The cost data on fluoridation collected by Garcia were reanalyzed separately by each of the five work groups at the Michigan Workshop (130). The results of the reanalysis are collectively summarized as follows:

Community Size	Range of Costs (per person/yr)
>200,000	$0.12–0.21
10,000–200,000	$0.18–0.75
<10,000	$0.60–5.41

The costs are in 1988 dollars using a 4 percent discount rate, and the range considers high and low estimates of assumptions on labor, capital, number of injection points, fluoride compound, and use of weighted and unweighted averages. The greatest variability was shown in the smallest cities because of their sensitivity to changes in the variables that comprise the analysis.

White et al. reviewed eight published reports that compared the cost of fluoridation with its benefit or effectiveness (129). The cost–benefit analyses all used treatment savings, expressed in dollars, as the measure of fluoridation success. The cost-effectiveness analyses used caries prevented or surfaces saved as the measure of effectiveness. In these studies, which were published between 1973 and 1987, the cost–benefit ratio varied from 1:2.5 to 1:11.5, and the cost was given as between $0.20–$1.22 per surface saved. They stated that the effectiveness of water fluoridation is influenced by at least three variables: (1) the baseline caries rate and change in disease pattern over time, (2) the mobility of the population of the community, and (3) the number of people at risk for caries. White et al. believed that, of the three, the most important is the disease fluctuation over time, which was not duly considered in other published analyses. They concluded that "water fluoridation is one of the most cost-effective preventive dental programs and, indeed, may be one of the most cost-effective preventive programs in health care."

Alternatives to Community Water Fluoridation

The principal requirement for communal water fluoridation is a centralized piped water system (126). As of 1988, 12.2 percent of the US population, approximately 30 million people, used private wells or other sources, rather than a municipal water supply (4). For these individuals, alternative sources of fluoride are recommended.

In the US, in lieu of communal water fluoridation, other community-based methods of supplying systemic fluoride to children are the fluoridation of an individual school's water supply and the establishment of a school-based fluoride supplement program. Also used in the US, as well as other countries, are school-based fluoride mouthrinsing programs that provide topical fluoride contact to the teeth.

Fluoridated salt has been sold in Switzerland since 1955 (131) and recently has been introduced into other countries, including France, Mexico, Jamaica, Colombia, and Costa Rica (17). This method is believed to be as effective as communal water fluoridation, provided the daily intake of fluoride, measured by urinary excretion levels, is similar (131). Fluoridated salt is useful in countries with a lack of centralized water supplies that make water fluoridation technically difficult and expensive. The addition of fluoride to salt is not indicated in the US because of its well-developed network of municipal water systems and because of the presence of naturally occurring optimal or higher levels of fluoride in many communities. Other considerations are the propriety of promoting salt ingestion with its known link to hypertension and the substantial variation in the ingestion of fluoride from salt.

Milk has also been used as a vehicle for fluoride and been proposed for use by children in areas where the water supply is fluoride deficient. However, studies of this particular method are limited (132,133).

School Water Fluoridation. School water fluoridation is well suited for rural areas where the schools are supplied by their own wells and especially where children in many grade levels from kindergarten through 12th grade may attend class in the same or adjacent buildings. Considering that the age group served may range from approximately five to 18 years, the teeth could receive both systemic and topical fluoride exposure.

In 1954 the first evaluation of school water fluoridation began in St. Thomas, US Virgin Islands (134). Since children have a limited exposure to their school's water, it was fluoridated at 2.3 ppm, slightly over three times the optimum indicated for the community. Other studies followed in Kentucky, Pennsylvania, and North Carolina (135-138). In Seagrove, NC, after 12 years of school water fluoridation adjusted to seven times the optimum for that locale (6.3 ppm F), students had 48 percent fewer DMF surfaces compared with children examined before the fluoridation program began (139). In 1976, after eight years of school water fluoridation at 6.3 ppm F, continuous participants in the seventh and eighth grades in Seagrove were examined for dental fluorosis of the canines, premolars, and second molars (138). These teeth were mineralizing at the time of the children's entrance into the program. Of 134 examined children, 11 had "questionable" fluorosis and the rest were classified as normal. Because the caries inhibition from adjusting to seven times the optimal fluoride level was only slightly greater than the caries inhibition from adjusting to 4.5 times optimal (137), the current recommendation is that the lower level, i.e., an adjustment to 4.5 times the optimal fluoride concentration for the area, be used for school water fluoridation programs (140).

Despite the documented effectiveness of this method, it has not been widely implemented. At its height, only 500 schools with slightly more than 200,000 schoolchildren participated (17). As of 1989, the Centers for Disease Control reported that 122,458 schoolchildren in 351 schools were involved in school water fluoridation programs, predominantly in Kentucky, North Carolina, and Indiana (4). Consolidation of school districts and extension of municipal water supplies may have contributed largely to the reduction in the number of programs.

Fluoride Supplement Programs. When it is not feasible to adjust water fluoride concentrations to optimal levels in a community or to initiate school water fluoridation, the use of dietary fluoride supplements in schools has been considered. School-based fluoride supplement programs use daily a 2.2 mg NaF tablet, which provides 1.0 mg F. This dosage for school-aged children is based on current American Dental Association and American Academy of Pediatrics recommendations where the water is fluoride deficient (0.3 ppm F or less) (141).

As with school water fluoridation programs, children may have their first contact with school-based fluoride supplement programs in kindergarten. However, supplement programs can begin earlier at age three or four in Head Start or at birth in individual home programs. The younger the children are when introduced to fluoride supplements, the greater will be the systemic contact to the teeth. Nevertheless, home-based programs are notorious for their lack of long-term compliance, which is a marked disadvantage to this caries-preventive approach.

Results of clinical trials of fluoride supplements have been reviewed by Driscoll (142) and Mellberg and Ripa (143). An average DMFS reduction of approximately 32 percent can be expected. Because the tablets are chewed, swished, and swallowed, both systemic and topical benefits accrue to the teeth when the children enter the program at age five or six. In school-based fluoride tablet studies, teeth that erupted during the study (144) or late-erupting teeth (145) received the most benefit. For instance, DePaola and Lax reported that use of acidulated NaF tablets for two school years produced an overall caries reduction of 23 percent (144). However, the caries reduction for teeth that erupted during the study was 53 percent. Fluoride tablets were part of a comprehensive fluoride regimen provided to schoolchildren in Nelson County, Virginia (146). In addition to the dietary fluoride supplement, the children were provided with a fluoride dentifrice for home use and rinsed once a week in school with a 0.2 percent NaF rinse (900 ppm F). Utilizing a historical control, the investigators reported a 65 percent lower DMFS prevalence in six- to 17-year-olds who, depending upon their school grade, had participated continuously in the program from one to 11 years. Since the Nelson County study relied upon a historical control, the results also reflect the general decline in caries that has occurred in US schoolchildren. This circumstance, coupled with the multiple fluoride regimen that was used, makes it impossible to separate the effects specifically attributable to the fluoride tablets. On the other hand, trials of fluoride tablets in the US that used concurrent placebo controls were all conducted more than a decade ago, before the major decline in caries prevalence had been documented. Presumably, studies conducted today would produce a lower absolute difference in teeth or surfaces saved as a result of the fluoride tablet intervention.

Garcia has reviewed the costs of school-based fluoride supplement programs in terms of 1988 dollars. She reported a mean cost of $2.53 per child with a range of $0.89–$5.40 (128). Differences in cost result principally from whether the personnel involved with the program are salaried or volunteers.

Fluoride Mouthrinse Programs. Fluoride mouthrinsing is a widely used public health method. In the US, it is second only to communal water fluoridation. The exact number of American children participating in school-based fluoride mouthrinsing is not clear, and the figure has been reported as low as 2–4 million (147) and as high as 12 million (148). School programs in the United States usually use a 0.2 percent NaF solution (900 ppm F). Children most often rinse once a week under supervision with 10 ml of solution for one minute. If kindergarten children participate, they rinse with 5 ml.

The results of fluoride mouthrinsing studies have been reviewed recently by Leverett (149) and Ripa (51). Both agree that studies of fluoride mouthrinsing have given consistently positive results, with few reporting caries inhibitions of less than 20 percent. Ripa found that for North American studies in which a mouthrinse concentration of 900–1,000 ppm F was used, DMFS reductions of 16 to 44 percent, with an average of 31 percent, were obtained in fluoride-deficient communities (51). Four studies have been conducted in fluoridated communities, of which three were positive (51). However, since the disease levels in fluoridated communities are usually lower than in fluoride-deficient ones, the number of surfaces saved per year from fluoride rinsing is less (150). Leverett discussed that while most fluoride mouthrinse studies yielded statistically significant caries inhibitions, those using a historical control design could be challenged because of the background decline in caries prevalence that was also occurring (149). He observed that even the more recent trials using appropriate control groups were reporting smaller differences in the caries incidence between the experimental and control groups. Leverett concluded that future fluoride mouthrinse programs were unlikely to result in annual savings in DMF increment greater than 0.4 surfaces, thus reducing the clinical importance of the result.

Ripa and coworkers found that participation in a school-based fluoride mouthrinsing program produced a greater percentage caries reduction in smooth proximal surfaces than in either occlusal or buccolingual surfaces (151). After seven years of rinsing, DF proximal surfaces accounted for 5.8 percent of the total caries prevalence, compared with 10.1 percent in children examined before the program began. Although this result was based upon a historical comparison, it is consistent with the known action of fluoride in smooth tooth surface caries.

The cost of supplies to conduct a fluoride mouthrinsing program have been estimated to range from $0.69 to $1.22/child/year (in 1988 dollars) (128). The material costs vary depending upon how the rinse is dispensed. The least costly method uses pump bottles to dispense the appropriate volume of solution; the most expensive uses premixed individual packets. If volunteers supervise the program, its cost tends to be low. Paid personnel will obviously increase the total cost. In an evaluation of 11 different school-based fluoride mouthrinse programs, Garcia calculated the average cost to be $1.30/child/year (128).

In a recent prospective study, kindergarten and first grade students in Springfield, OH, were assigned to one of three groups: one group rinsed once a week in school with a 0.2 percent NaF solution, the second group chewed and swallowed daily in school a 2.2 mg NaF tablet (1.0 mg F), and the third group did both procedures (152). For ethical reasons, there was no placebo control group. Eight-year DMFS increments were 3.6, 2.8, and 2.4 for the rinse, tablet, and combined programs, respectively. Even though the combined regimen showed increased caries protection compared with the mouthrinse, the investigators felt that "the additional cost, time, and effort required to carry out the procedure would appear to outweigh the small savings in DMF surfaces." Therefore, they recommended that ongoing fluoride mouthrinse programs should not be replaced with programs employing both procedures.

Sociopolitical and Legal Issues

McClure subtitled his 1970 book on water fluoridation "The Search and the Victory" (3). Yet, in 1985, an article appeared in a prestigious nondental journal entitled, "America's Longest War: The Fight over Fluoridation, 1950–" (153). This article described the militant resistance to fluoridation that began in 1949–50 in Stevens Point, Wisconsin, and that continues to this day. In a survey of state dental directors conducted in 1984, the American Dental Association found that, during the five years prior to the survey, there had been 255 challenges to dental programs (154). Of these, 82 percent concerned fluoridation and 13 percent involved school fluoride mouthrinse programs. As a result of the challenges, 14 percent of the programs were delayed or curtailed and 36 percent were terminated. McClure's claim of victory was premature.

The expansion of fluoridation in the United States has slowed (7). Issued in 1980, one of the US Public Health Service's objectives was that within 10 years, at least 95 percent of the US population with community water systems should be serviced with optimally fluoridated water (8). That objective was not met. According to the Centers for Disease Control, by December 31, 1989, only 62.1 percent of Americans living in areas with public water systems were drinking fluoridated water (4). Part of the lack of success was a result of a change in how federal funds were allocated to the states. Allocation changed from categorical grants, under which money could be designated specifically for fluoridation, to block grants, under which fluoridation competes with other uses for the money (7). The year 2000 oral health objectives propose a 75 percent target that is less than the 95 percent originally proposed (9). Considering the higher level, Easley stated, "Without a major increase in emphasis among national, state, and local health policy makers, it is questionable whether the proposed year 2000 fluoridation objectives ... will be able to be met" (155). That admonition also applies to the current level.

It would be ideal if health issues were decided by health experts. For water fluoridation, this is rarely the case, as the issue has found its way into the political arena (17). Authorization to fluoridate a public water supply can be made by administrative decision, such as by city or county executives or councils, public utility boards, or public health boards; by a voter initiative; or by legislative action. State legislation providing for water fluoridation is of two types. It may be mandatory, in which communities of a certain size are required to fluoridate their public water supplies, or it may be permissive, or enabling, in which a local authority is empowered to institute fluoridation (126,156). Eight states, the District of Columbia, and Puerto Rico have mandatory laws requiring the fluoridation of public water supplies. Unsuccessful attempts for mandatory fluoridation legislation were made within the last decade by Hawaii and Pennsylvania (155). States with enabling fluoridation legislation include Alaska, Nevada, and Massachusetts (126). Massachusetts' statute empowers the State Commissioner of Public Health to recommend fluoride adjustment of the public water supply of any city, town, or district. The commissioner is required to notify the local boards of health, and the boards may, if they consider doing so in the best interest of the residents under their jurisdiction, order fluoridation of the public water supply (126).

With either a mandatory or enabling statute, the legislation may also allow or require that a vote or referendum be taken on the issue (126). Nevada, for instance, requires that any proposal for fluoridation must be submitted to the voters within the affected community. Unfortunately, referenda have proved to be the nemesis of fluoridation. Easley found that between 1980–89, 63 percent of 163 community fluoridation referenda failed to pass. Conversely, of 281 fluoridation initiatives in which only a governing body was involved, 78 percent were successful (155). Easley concluded that, in the absence of a state mandate, the most effective means to implement community water fluoridation is to "pursue promotion with the local legislative body and hope that a referendum does not ensue" (155).

The reasons for the public's rejection of a proven health benefit have presented a quandary for dentistry since the issue first emerged in Wisconsin (157-159). To explain this phenomenon, a World Health Organization publication lists three factors (126): *First,* ignorance and confusion on the part of the public about the dental health benefits of fluoridation. In the late 1960s it was believed that during a fluoridation campaign, people were confused by exposure to conflicting arguments. However, in a 1977 national survey conducted by the Gallup Organization, 49 percent of adults correctly answered that the purpose of fluoridation was to reduce tooth decay, and in a 1980 Massachusetts survey, 76 percent of respondents correctly believed that the purpose of fluoridation was to improve dental health (160). In Massachusetts this knowledgeable public opinion did not translate into voter acceptance, since, of 14 referenda held between 1980 and 1983, local Massachusetts voters rejected fluoridation in 11 of them, and the pooled results showed that only 39 percent of those voting favored fluoridation (160). While these findings do not refute the contention that people may be confused during a fluoridation campaign, they indicate that simply understanding the benefits of water fluoridation may not be sufficient to make people favor it.

Second, ambivalence of the public toward science with greater reservations about scientific findings that concern the human body. Yet, in a 1980 survey conducted in three California communities that had or were scheduled for fluoridation referenda, the majority of respondents did not hold opinions against drinking fluoridated water (161). Moreover, in a survey of mothers of preschool children from low socioeconomic areas of Scotland, the mothers held more positive attitudes toward vaccinations against caries than toward water fluoridation (162), which seemed to indicate that ambivalence toward science was not a major concern.

Third, misrepresentation of the scientific and technical information involved, enabling the opposition to distort the issues and frighten the public. Sapolsky (163) proposed what Hastreiter later termed the "confusion hypothesis" (164). During a fluoridation campaign, voters are exposed to conflicting arguments by individuals who claim to be experts, and the voters have difficulty identifying correct information, misinformation, or disinformation. As catalogued by Horowitz, not only do antifluoridationists assert that fluoridation is not effective against caries, but they also allege that fluoride promotes cancer, sickle cell anemia, kidney and heart diseases, birth defects, Alzheimer's Disease, and Acquired Immune Deficiency Syndrome (AIDS) (17). They also have portrayed fluoridation as a communist plot, a conspiracy of the sugar and aluminum industries, and an invasion of freedom of choice since it forces medication on people who may not want it (17). Armed with these many accusations, the antifluoridationists can easily generate a modicum of doubt in voters' minds, which often is sufficient to sway them against fluoridation. Conversely, fluoridation's supporters need to try to prove, without any question of a doubt, that fluoride is safe and effective in order to gain the vote. Simply put, raising doubt is easier than suppressing it.

A fourth factor, not listed by the World Health Organization, but which may assume importance, is the issue of controlling one's destiny. It is of interest that in the Scottish study cited above, Kay and Blinkhorn found that the mothers whom they interviewed preferred methods of preventing disease that were dictated by their desire to retain some control of the situation (162). This sentiment echoes the statement of the leader of a successful 1983 campaign to defluoridate Levittown, NY, who explained that a strong element of the antifluoridationists' argument was that, "We're skeptical of government—we want control over what our children consume" (153).

The antifluoridationists have also taken their battle against community water fluoridation to local, state, and federal courts. Litigation against fluoridation began in the early 1950s in Northhampton, MA, and San Diego, CA. In both cases, the legality of fluoridation was upheld (165). Generally, the opponents of fluoridation contend that fluoride is biologically harmful and water fluoridation is an unreasonable exercise of police power, that fluoridation is a violation of religious freedom, that fluoridation violates constitutional guarantees of personal liberties and protection from harm to the public, and that fluoridation is a form of class legislation (see review by Block (165)). However, in all cases where a legal challenge to fluoridation has been made, no court of last resort has ever ruled against it (155). Block lists 13 fluoridation cases that reached the US Supreme Court between 1954 and 1984 (165). None was actually heard by the court. Either the case was dismissed for lack of a substantial federal question, or the court denied the *writ of certiorari* for which no reason need be given. Essentially, fluoridation has been upheld as a legitimate exercise of governmental authority.

The continued constitutional legitimacy of fluoridation upheld by US courts bodes favorably for the future of water fluoridation. There are other favorable signs, as well. Although the absolute number of fluoridation initiatives decreased during the 1980s, Easley's statistics show a higher percentage of favorable outcomes during the second half of the decade (155). For the first half, 28 percent of fluoridation referenda were favorable compared with 52 percent in the second half; likewise, favorable outcomes for fluoridation initiatives instituted by legislative action increased from 74 percent in the first half of the decade to 86 percent in the second half.

A successful outcome for a fluoridation initiative requires careful planning (166,167). The success of a La-Crosse, WI, fluoridation referendum in 1988 was attributed to a well-conceived plan that included broad-based community support led by citizens for a better health committee; consultation and support from concerned professional organizations; knowledgeable scientific reporting by the press; the timing of the ballot to coincide with the Wisconsin presidential primary election in order to ensure a large voter turnout; and the support of some local chiropractors, who, as a group, traditionally have been fluoridation opponents (166). Even the 1985 vote against fluoridation in San Antonio cannot be considered a complete failure. The organization and planning of the fluoridation advocates were excellent and fluoridation was narrowly defeated by a margin of 42,323 to 39,050, compared with a 2 to 1 margin when San Antonians were offered the same choice 19 years earlier (168).

Recently, Martin has analyzed the fluoridation debate at a social, rather than a dental scientific level (169). He emphasizes that his analysis is not concerned with the scientific merits of fluoridation, but rather with the elements that have contributed to making fluoridation an issue of unresolved public debate. He considers the public argument on fluoridation an "exercise of power" involving proponents and opponents, organized dentistry, individual researchers and the research establishment, and certain elements of industry including the aluminum and fertilizer industries, the sugar-food industry, and over-the-counter dental products manufacturers. Martin's book is unique, since it attempts to avoid the "rightness" or "wrongness" issue in favor of how scientific knowledge is used and shaped in the course of what he calls a bitter public debate.

Conclusions

Community water fluoridation is one of the most successful public health disease prevention programs ever initiated. It has the potential to benefit all age groups and all socioeconomic strata, including the lowest, which has the highest caries prevalence and is least able to afford preventive and restorative services. Community water fluoridation is also the most cost-effective of all community-based caries preventive methods (128).

Early water fluoridation studies produced caries reductions of approximately 40 to 60 percent for the permanent dentition, and slightly lower reductions for deciduous teeth (10). Recent studies have found a smaller difference in the caries prevalence between optimally fluoridated and fluoride-deficient communities (11). This change is believed to be due to the availability, beginning in the early 1950s, of a variety of fluoride products, including professionally applied gels and solutions, dentifrices, mouthrinses, and systemic supplements. Use of these products reduces the caries prevalence in both optimally fluoridated and fluoride-deficient communities and, therefore, decreases the magnitude of the caries difference between the two. The presence of fluoride in beverages and foods that are processed in fluoridated communities but transported to, and consumed in, fluoride-deficient ones further acts to blur the distinction in caries activity between fluoridated and fluoride-deficient communities.

Corbin has written that it is "virtually impossible to find 'nonfluoride' communities due to the many opportunities for alternative exposures to fluoride" (170). Communities in the United States still may be classified as being optimally fluoridated or fluoride-deficient based upon the concentration of fluoride in the drinking water. However, because fluoride is ubiquitous in food and dental health products, practically no American today is unexposed to fluoride. Therefore, to designate a US community as strictly fluoridated or fluoride-deficient may now be a spurious distinction and, in the future, should no longer be emphasized. Rather, the emphasis should be directed to the geographic and socioeconomic differences in caries prevalence in the United States. While it is desirable that initiatives continue to increase the number of Americans drinking optimally fluoridated water, the underlying goal should be to attain a *uniformly low* caries level for all geographic regions of the country and for all socioeconomic strata.

Along with analyses of the benefits of any health procedure should be studies of coincident risks that might be reasonable to expect. Because fluoride is primarily deposited in the bones and teeth or excreted in the urine, the effects on the body's hard tissues and kidneys have been especially well studied. In addition, fluoride risk assessment has also considered the relationship between fluoride in the drinking water and cancer.

At the time optimal fluoridation was introduced, it was known to result in about 10 percent of the population developing very mild fluorosis (5). In the 1940s and 1950s, this risk was considered acceptable, considering the substantial caries preventive benefits both in absolute and percentage terms. However, reports published in the 1980s found an increase in the prevalence of fluorosis in fluoride-deficient communities and, to a lesser extent, in fluoridated ones. This increase is principally in the milder forms of fluorosis, which was considered by some early investigators to enhance the appearance of the teeth rather than to be cosmetically detracting. Nevertheless, the increase in the prevalence of fluorosis is *prima facie* evidence that increased fluoride ingestion has occurred among young children. It has not been determined whether the observed increase in fluorosis is a necessary tradeoff for the reductions in caries prevalence that have been achieved or whether the same reductions could have occurred without the increase in fluorosis.

Leverett presented a graph comparing recent caries and fluorosis levels with water fluoride concentrations (171). When similar comparisons were first done some 40 to 50 years ago, using the data available then, the caries and fluorosis curves intersected at a water fluoride concentration of 1.2 ppm. The curves prepared by Leverett intersected at 0.8 ppm, a difference of 33 percent. Leverett attributed this difference to the increased ingestion of fluoride that has occurred as a result of fluoride becoming more ubiquitous in the environment than it was a half century ago. Prudence dictates that inadvertent and unnecessary fluoride ingestion should be avoided. This requires that dentists be aware of the indications and proper techniques for professional topical fluoride treatments; that consumer products, such as fluoride dentifrices and mouthrinses, be labeled regarding their proper use, especially for preschool-aged children; and that physicians, dentists, and pharmacists know when dietary fluoride supplements are indicated and what the recommended dosage is. In addition, further research is indicated to understand better the complexities of fluoride ingestion from multiple sources, especially from water and other beverages, dietary supplements and dentifrices, and their roles in fluorosis etiology and risk.

The effects of fluoride on bone need further clarification from epidemiologic and other studies. The problem is twofold. First, fluoride may behave differently in different types of bone. It appears to increase the density of trabecular bone, such as the vertebrae, and decrease the density of cortical bone, such as the hip and long bones. Second, it should be determined if the overall effects on the bones provide a health benefit or pose a health threat. Although fluoride may increase the bone mass of the vertebrae, there is not strong evidence of a concomitant reduction in the incidence of vertebral fracture or an alleviation of the clinical symptoms of osteoporosis. Likewise, the evidence of a relationship between drinking fluoridated water and the incidence of bone fracture is not clear, with different studies reporting more, less, or the same incidence of bone fractures in communities with naturally high, or adjusted, levels of fluoride in the drinking water compared with fluoride-deficient communities (15,61-67).

No untoward effects on the kidneys result from drinking water containing optimal levels of fluoride. Even when high concentrations of fluoride, as much as 30 ppm, were inadvertently added to the drinking water, healthy individuals did not suffer harmful kidney effects (72). Medically compromised patients undergoing hemodialysis require the use of water with a low concentration of fluoride as well as a low concentration of other ions.

The relationship between water fluoridation and cancer is especially important because of people's fear of cancer and because antifluoridationists' tactics capitalize on that fear in an effort to defeat fluoridation. The cancer/fluoride issue was exacerbated in 1989–90 by the release of the results of the National Toxicology Program's study of sodium fluoride in laboratory animals. An independent peer review panel concluded that there was "equivocal" evidence of carcinogenicity from sodium fluoride in male rats, based upon the findings of a small number of osteosarcomas in the NTP study. The panel found no evidence of carcinogenicity in female rats or in male or female mice (15). Another study, commissioned by the Procter & Gamble Company, failed to find an association between malignant tumors and sodium fluoride ingestion by mice and rats of either sex (15). The Ad Hoc Subcommittee on Fluoride of the US Public Health Service concluded that when the results of these two animal studies were considered together, they failed to establish an association between fluoride and cancer (15). Properly conducted epidemiologic studies also have failed to find a correlation between fluoride in the water supply and cancer. Every review of this evidence by expert committees has found naturally or adjusted levels of fluoride in drinking water not to be associated with cancer in humans.

Because water fluoridation provides proven dental benefits with minimal risks, the frequent success of antifluoridationists in preventing fluoridation or removing it from communities in which it had been established is perplexing. Reasons that have been proposed to explain the antifluoridationists' success were listed in the section "Sociopolitical and Legal Issues." The arguments of the antifluoridationists, which are designed to create doubts, are easier to advance than ones that must instill confidence in fluoridation. Nevertheless, the antifluoridationists' campaigns are usually well organized and often enlist the support of community leaders, politicians, and the media, and they have been successful in creating an aura of controversy where no scientific controversy exists.

The dental public health community's success rate in accomplishing the fluoridation of municipal water supplies must increase. Well-planned profluoridation campaigns have been successful (166,167), and the elements of these campaigns should be studied carefully. Considering the graying of the American population, the benefits of fluoridation for adults must be more fully documented and publicized. More research on the effects of fluoridation on bone is needed and, if the findings are positive, will support claims of general health benefits in addition to dental benefits. Finally, it must be made clear that water fluoridation is a near-ideal public health measure whose benefits can transcend all racial, ethnic, socioeconomic, and regional differences.

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