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# Fluorides and the Changing Prevalence of Dental Caries

Dennis H. Leverett

Dental caries is a disease associated with increasing acculturation. Along with crowding and pollution, it is one of the prices we have paid for our social and industrial development. Dental caries was not prevalent in primitive societies apparently because their diets lacked easily fermentable carbohydrates. Although caries is clearly a disease with multiple causes (*1*), the principal mode of caries initiation is acid dissolution of tooth enamel. This acid is produced by several different microorganisms, most notably *Streptococcus mutans*, with fermentable carbohydrates, especially sucrose, as the nutrient source. Although this is a simplification of a complex process, availability of sucrose in the diet is clearly the key factor in dental caries initiation.

Theoretically, the dental caries process can be interrupted or terminated in one of three ways: (i) reduction in the numbers of cariogenic bacteria or disruption of their ability to metabolize fermentable carbohydrates, (ii) dietary control of carbohydrate intake, or (iii) enhancement of the ability of tooth structure to withstand acid dissolution.

To reduce or disrupt the action of cariogenic bacteria, various antimicrobial agents have been incorporated in dentifrices and mouth rinses, and improved methods of personal oral hygiene have been recommended. A great deal of effort is also being placed on the development of an effective vaccine. Since the role of carbohydrates is well understood, it would seem relatively straightforward to restrict sucrose in the diet and substitute noncariogenic sweeteners. Both of these approaches to controlling the dental caries process, however, have serious limitations, which have already been described (*2*). It is the third approach, enhancing the ability of the tooth structure to withstand acid dissolution particularly through the use of fluorides, which has been most successful and which I will discuss in this article.

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## Fluorides for Dental Caries Prevention

Fluoride therapy as a means of preventing dental caries has been used since 1945, when the fluoride concentrations of community water supplies in two U.S. cities and one Canadian city were adjusted upward to 1 part of fluoride ion per 1 million parts of water (*3, 4*). Naturally fluoridated water supplies had been protecting those who drank it for generations, but it was only in the late 1930's, with improved microanalytical techniques and large-scale epidemiological studies, that the relation between fluoride in water supplies and reduced prevalence of dental caries was recognized (*5*).

During the past 40 years a large body of research has attested to the efficacy, cost-effectiveness, and safety of fluoride therapy in community water fluoridation, school water fluoridation, fluoridated dentifrices, professional topical application, and self-administered rinses and tablets (*6, 7*). A former U.S. Surgeon General called fluoridation, along with pasteurization, water purification, and immunization, one of the four most important public health measures of our time (*8*).

*Summary.* Community water fluoridation and individual use of fluorides have brought about a marked reduction in the prevalence of dental caries in the United States during the past 35 years. There is evidence that the prevalence of caries is declining in communities with unfluoridated water as well as in those with fluoridated water. This phenomenon may be related to an increase of fluoride in the food chain, especially from the use of fluoridated water in food processing, increased use of infant formulas with measurable fluoride content, and even unintentional ingestion of fluoride dentifrices. This trend should encourage reevaluation of research priorities and previously accepted standards for optimal fluoride use.

### Trends in Dental Caries Prevalence

In order to place the beneficial effects of fluoride therapy in proper perspective it is important to understand the natural history of dental caries in Western civilization. Although dental caries has been noted in the skulls of the earliest hominids, it became widespread only with the growth of civilization and can be linked most clearly to increasing consumption of sucrose. In England, for instance (*9*), there was a sharp increase in the prevalence of dental caries during the Roman occupation. There was a decline in dental caries after the departure of the Romans in the early 5th century A.D., and it did not significantly increase again until the second half of the 19th century, when sucrose became widely available to all levels of society. The relation between the availability of sucrose and an increase in dental caries is supported by observations of the effects of war on dental caries in children. Data available from several European countries during World War II (*10*) show sharp declines in dental caries during the war years, with subsequent reversal of the trend within 3 to 4 years after the end of the war. Changing dietary patterns, especially reduced consumption of sucrose, are considered to be the causes of this phenomenon (*11*).

Patterns of increasing dental caries prevalence during the 20th century have to be viewed within the context of social and economic development. Looking first at the developing nations of the world, patterns of dental caries are somewhat analogous to those described above in the example of Great Britain. There are numerous reports (*12*) of isolated population groups with low dental caries prevalence which, when exposed to Western dietary patterns, especially with regard to availability of sucrose, have developed substantially increased rates of dental caries. The general pattern in developing nations is that urbanization and improved socioeconomic status coincide with increased accessibility of sucrose in the diet and thus lead to increases in dental caries prevalence (*13*).

Eventually dental treatment and, to a lesser extent, preventive measures become available to the urbanized populations, especially in higher socioeconomic groups. At this stage dental caries still tends to be higher in the higher socioeconomic groups, but there is a shift toward higher numbers of filled and extracted teeth and lower numbers of decayed teeth in groups that can afford treatment (*14*).

The pattern of caries prevalence found in developed nations tends to be an extension of the continuum described for developing nations. As a nation becomes more developed and most segments of its society gain access to sucrose and to processed foods, dental caries becomes ubiquitous. For instance, a 1936–1937 survey in Denmark (*14*) showed that caries was increasing more among urban children than among rural children. However, when this population was surveyed in 1972 (*15*), dental caries was uniformly high throughout the population. In Hungary (*16*) there was a 43 percent increase in dental caries prevalence between 1955 and 1975, which paralleled a 54 percent per capita increase in sucrose consumption during the same period.

As effective preventive measures, particularly the use of fluorides, become available to a population, the early benefits accrue more to the affluent and to the urbanized segments of the population (*17*). With community water fluoridation, dental caries may be reduced by as much as 50 to 70 percent (*4, 6, 7*).

### Increasing Use of Fluorides in Developing Nations

Fluorides began to be used about 40 years ago for the prevention of dental caries in children, and their use has become widespread in the developed nations of the world in the last 20 years. Fluorides are systemically added to community and school water supplies and given in the form of chewable tablets. In the United States 110 million people and another 90 million throughout the world drink water which is optimally fluoridated, either naturally or by the addition of fluoride. Australia and New Zealand as well as nations in Europe and North America report that 80 to 95 percent of all dentifrices sold contain fluoride. Most dentists provide a topical application of fluoride for children and young adults as a preventive measure in the office. Approximately 10 million children in the United States also participate in supervised fluoride mouth-rinsing programs in schools. The reduction in the prevalence of dental caries, which can be directly attributed to this increased use of fluorides, is well documented (*4, 6, 7*).

Within the past 2 or 3 years there has been increasing evidence from several developed nations of a drop in the prevalence of dental caries which cannot be attributed directly to intentional fluoride use. The data are becoming available as epidemiologists and clinical researchers review the patterns of dental caries prevalence in communities which do not have fluoridated water. The data cover children from the ages of 5 to 17 for various periods of up to 30 years; caries reductions as high as 60 percent have been observed (Table 1). Possible reasons for this unanticipated decline in dental caries prevalence will be discussed later.

### Systemic Fluoride Dosage

Studies by Dean (*18*) and McClure (*19*) established the rationale for setting the optimum level of fluoride in drinking water at approximately one part fluoride ion per million parts (ppm) of water. On the basis of epidemiological studies from the American Midwest, Dean showed that the prevalence of dental caries was

Table 1. Decline in dental caries prevalence in communities with unfluoridated water.

| Location | Time interval | Age of subjects (years) | Caries reduction (%) | Reference |
|---|---|---|---|---|
| New Zealand | 1950–1977 | 5 | 44 | (*39*) |
| Northwestern England | 1969–1980 | 11 to 12 | 40 | (*40*) |
| Isle of Wight | 1971–1980 | 11 to 12 | 18 | (*41*) |
| Brisbane, Australia | 1954–1977 | 6 to 14 | 50 | (*42*) |
| Geneva, New York | 1965–1977 | 12 to 14 | 41 | (*43*) |
| Brockport, New York | 1952–1975 | 12 | 60 | (*43*) |
| Boston, Massachusetts | 1950–1980 | 5 to 17 | 40 to 50 | (*44*) |
| Massachusetts | 1958–1978 | Not stated | > 50 | (*45*) |
| Ohio | 1972–1978 | 6 to 12 | 17 | (*46*) |
| United States* | 1972–1979 | 5 to 17 | 32 | (*47*) |

*Includes communities with fluoridated, as well as unfluoridated, water.

Table 2. Recommended supplemental fluoride dosage schedule according to fluoride concentrations of drinking water (*23*).

| Age (years) | Fluoride dosage (mg/day) for drinking water with fluoride concentrations (ppm) of | | |
|---|---|---|---|
| | < 0.3 | 0.3 to 0.7 | > 0.7 |
| Birth to 2 | 0.25 | 0 | 0 |
| 2 to 3 | 0.50 | 0.25 | 0 |
| 3 to 13 | 1.00 | 0.50 | 0 |

negatively correlated within the fluoride concentration of drinking water and that mottling of tooth enamel (fluorosis) was positively correlated with fluoride concentration (*20*). The fluoride concentration at which prevention of dental caries approached its maximum and enamel fluorosis ceased to be an esthetic problem was 1 ppm; mild fluorosis was detectable in only 10 percent of the population at this concentration. Although fluorosis, even at severe levels, is of no consequence to health, it does serve as an indicator that fluoride was consumed during the age of calcification of the teeth (up to about 8 years of age) in concentrations above that necessary for optimal dental caries prevention. The fluoride concentration at which fluorosis becomes apparent in a population (2.0 ppm) corresponds to a daily intake of about 0.1 milligram per kilogram of body weight up to the age of 12.

From studies of diets and dental caries prevalence in children up to the age of 12 in communities with naturally fluoridated drinking water, McClure determined that the average daily fluoride intake of a child in a community with water fluoridated at 1 ppm was approximately 0.05 mg per kilogram of body weight; this seemed to be a reasonable amount, being 50 percent of the amount likely to cause fluorosis. And for the past 35 years, the optimum fluoride concentration for drinking water has been set at 1 ppm.

In the early 1950's there was interest in the use of dietary fluoride supplements for children in communities with unfluoridated or suboptimally fluoridated water (*21*), and effort was made to make dosages mimic the daily intake of fluoride in a community with optimally fluoridated water. In 1958, the American Dental Association (ADA) recommended the following dosages of dietary fluoride supplements (*22*) in communities with less than 0.2 ppm fluoride in the drinking water: (i) for children less than 2 years of age, one tablet (1 mg) dissolved in one quart of water to be used for drinking and for preparation of formula and other foods; (ii) for children 2 to 3 years of age, one tablet (1 mg) with fruit juice or water every other day; and (iii) for children over 3 years of age, one tablet (1 mg) each day with fruit juice or water. In communities with 0.2 to 0.7 ppm of fluoride in the drinking water, the ADA recommended that the dosages be adjusted downward to compensate for the fluoride in the water, and in communities with over 0.7 ppm of fluoride in drinking water, no fluoride supplements were recommended.

In 1979, the ADA recommended modified dosages (*23*), which were endorsed by the American Academy of Pediatrics and the American Academy of Pedodontics (Table 2). The new dosage recommendations differ from those of 1958 in two important respects: (i) the recommendation for children up to 2 years was decreased from an average dosage of 0.5 mg daily (*19*) to 0.25 mg daily; and (ii) the previously recommended dosage of 1 mg every other day for children between 2 and 3 years (although mathematically equivalent to 0.5 mg/day) probably produced bidaily blood concentrations of fluoride that exceeded the threshold for causing some fluorosis (*24*).

### Fluoride in the Food Chain

In the mid-1960's, Marier and Rose (*25*) found that the effect of processing foods and beverages with fluoridated water produced an average fluoride intake in the range of 1.0 to 2.0 mg/day, which is an increase of about 0.5 mg/day over the 0.5- to 1.5-mg range estimated by Hodge and Smith (*26*) for fluoride-free areas. It was reported in 1974 (*27*) that a large proportion of Canadian food-processing plants used fluoridated water in food processing. It was clear that more data were needed to determine the actual fluoride content of foods and to define concentrations, especially for infants, that would be unlikely to contribute to fluorosis in later erupting teeth.

Kumpulainen and Koivistoinen (*28*) also investigated the fluoride content of foodstuffs. They reported that the mean fluoride content of the diet is three times higher in communities with fluoridated water than in those where the water is not fluoridated (2.7 versus 0.9 mg/day). Of commonly consumed vegetables, fresh spinach was found to have the highest amount of fluoride. Gelatin also is a potent source of fluoride, as are bone meal and fish protein concentrate.

Krugel and Field (*29*), who investigated the effect of mechanically deboning meat on the fluoride content of the resultant meat products, found that frankfurter, for instance, containing up to 10 percent mechanically deboned meat, would contain about 1.7 mg of fluoride per kilogram of product.

Singer and Ophaug (*30*) noted that 0.05 to 0.07 mg of fluoride per kilogram of body weight is generally regarded as the optimum daily intake. They found wide variations in the fluoride concentrations of different infant foods, which were not usually related to the fluoride content of the water in the communities where the foods were processed (Table 3). The high fluoride content in strained chicken, for example, might be related to the incorporation of bone chips in the product. They found that the fluoride content of dried cereals, however, was strongly influenced by the fluoride content of the water in which they were processed (Table 4). The fluoride content of ready-to-drink fruit juices increased 5 to 20 times when fluoridated water was used in the processing (Table 5). Fluoride in milk formulations for infants, both concentrates and ready-to-drink types, ranged from 0.15 mg/liter in communities without fluoridated water to 0.58 to 0.67 mg/liter in communities with fluoridated water (*31*). Human and bovine milk generally contain less than 0.1 ppm of fluoride regardless of the fluoride content of the drinking water. They determined that the intake of fluoride in typical diets of infants between 2 and 6 months averaged about 0.1 mg per kilogram of body weight from foods processed in a community with fluoridated water. Diets consisting mainly of food processed in communities without fluoridated water contained about one-tenth that amount of fluoride. Since fluorosis can occur with a fluoride intake as low as 0.1 mg per kilogram of body weight per day, this finding suggests that the optimal intake may have been exceeded.

When the same research team (*32*) looked into the estimated fluoride intake of 2-year-olds in several cities of the United States, they found that the amount of fluoride, in milligrams per kilogram of body weight, ranged from 0.025 in a community with unfluoridated water to 0.049 in one with fluoridated water. These findings are more within the acceptable range of optimum daily fluoride intake.

Another form of fluoride consumption, albeit unintentional, is from fluoridated dentifrices. As pointed out above, 80 to 95 percent of all dentifrices sold in Europe, North America, Australia, and New Zealand contain fluoride, at a concentration of 1000 ppm. All age groups are known to ingest dentifrice, but the highest average values of about 0.3 gram, equivalent to 0.3 mg of fluoride, are reported for children under the age of 5 (*33*). Almost half of the children in Britain have been reported to begin brushing their teeth by the age of 12 months and three-quarters by the age of 18 months (*34*). However, the magnitude of toothpaste ingestion among children under 2 years is not known.

## Increasing Prevalence of Fluorosis

If there are increasing concentrations of fluoride in the food chain, particularly food for infants, then we would expect fluorosis to be increasing in the population as well. This is, indeed, the case. In a study of the effects on a population of the use of fluoride supplements from shortly after birth (intake, 0.5 mg/day up to 3 years of age and 1 mg/day thereafter), in a community without fluoridated water, Aasenden and Peebles (*35*) found that 63 percent of the children had very mild to mild fluorosis by the time they were between 7 and 12 years of age. According to standards defined first by McClure (*19*) and Dean (*18*), no fluorosis should have resulted from such supplementation. Forsman (*36*) found that 32 percent of formula-fed children, without fluoride supplements, had mild fluorosis in a community without fluoridated water. Fluorosis increased in frequency and severity where fluoride supplements had been introduced at birth. In a study in Minnesota (*37*), children in nonfluoridated communities were found to have high levels of fluorosis if they received fluoride supplements soon after birth, if they were bottle-fed, or if they were breast-fed for less than 3 months. These findings were even more pronounced in fluoridated communities. In our own prevalence studies (*38*), we found mild fluorosis in 28 percent of children 11 to 13 years of age from communities with fluoridated water, whereas 12 percent would have been expected from Dean's studies. It should be emphasized that in our research, as well as in the reports of other investigators, this level of mottling from fluorosis is, for the most part, not discernible by the layman.

Table 3. Fluoride content of infant foods (*30*).

| Food item | Mean fluoride content (mg/kg) |
|---|---|
| Strained meats with broth | |
| Chicken | 5.29 |
| Liver | 0.14 |
| Pork | 0.23 |
| Turkey | 0.39 |
| Vegetables | |
| Carrots | 0.23 |
| Spinach | 0.43 |
| Squash | 0.15 |
| Fruits | |
| Pears | 0.057 |
| Peaches | 0.017 |
| Applesauce | 0.078 |

Table 4. Fluoride content of dried cereals processed in fluoridated and unfluoridated water (*30*).

| Cereal | Mean fluoride content (mg/kg) | |
|---|---|---|
| | Unfluoridated water | Fluoridated water |
| Mixed | 0.93 | 3.85 |
| Oatmeal | 0.98 | 4.87 |
| Rice | 2.11 | 6.35 |
| Barley | 1.99 | 4.30 |

Table 5. Fluoride content of fruit juices processed in fluoridated and unfluoridated water (*30*).

| Juice | Mean fluoride content (mg/liter) | |
|---|---|---|
| | Unfluoridated water | Fluoridated water |
| Orange | 0.029 | 0.15 |
| Mixed | 0.014 | 0.38 |
| Apple-cherry | 0.14 | 1.48 |

## Conclusions

On the basis of the available evidence, it appears that the prevalence of dental caries in the United States, as well as several other nations, is declining. This decline is caused primarily by the increasing availability of fluoride intentionally introduced in drinking water and in various systemic and topical forms of supplementation. Fluorides also are being introduced unintentionally and secondarily by increasing use of fluoridated water in food processing, by increasing use of infant formulas with high fluoride content, and by ingestion of fluoride intended for topical use, especially fluoridated dentifrices.

The decline in caries prevalence in communities without fluoridated water in various countries is well documented (*39–47*). The cause or causes are, at this time, a matter of speculation. Only fluorides, of all preventive approaches available, have experimentally demonstrated a capability for reducing dental caries on a community-wide basis, strongly indicating that the decline in caries is due to the use of fluorides, systemic and topical, intentional and unintentional.

The relative importance of various modes of fluoride application probably varies from place to place. For instance, in a nation with relatively little water fluoridation, increased fluoride in the food chain may not be a factor in reducing caries, although extensive use of dietary fluoride supplements and fluoride dentifrices (both topically and accidentally ingested) may play a major role.

The widespread use of fluorides may have created a situation in which we are approaching a critical mass of fluoride in the environment, which is eliminating dental caries as a public health problem in the United States and some other nations of the world (*48*). This situation has important implications for the continuing use of fluorides and for the direction of dental caries research in the United States.

For instance, we may be rapidly approaching a situation in which basic research into new caries-preventive measures is of declining importance. A practical anticaries vaccine may not be available before the 1990's (*49*). If, however, prevalence of dental caries continues to decline, such a vaccine may have little practical importance in the United States and other developed nations. On the other hand, it seems that the following types of research will take on increasing importance.

1) Epidemiological studies need to be conducted which will confirm the preliminary evidence described here. These studies need to look not only at dental caries prevalence, but also at fluorosis, the history of known fluoride exposure, and evidence of ambient fluoride in the environment.

2) There needs to be extensive research addressing the issue of increased fluoride in the food chain. This research should include studies of the bioavailability of fluorides found in foodstuffs (*50*).

3) On the basis of the findings described in this article, the definition of the optimum concentration of fluoride in community water supplies needs to be reassessed. It is important to remember that efficacy of fluoridation and standards for its implementation were established when water fluoridation was the exception, rather than the rule. The redefinition of standards may be indicated.

4) More clinical research needs to be conducted to evaluate the efficacy and the cost-effectiveness of topical fluoride regimens such as fluoridated dentrifices, supervised fluoride mouth-rinsing programs, and individual topical application.

5) The dosage of fluoride supplements for infants in communities without fluoridated water needs to be reassessed in light of evidence regarding the fluoride content of formulas and baby foods.

The National Caries Program of the National Institute of Dental Research, established in 1971, set as its goal the elimination of dental caries as a public health problem in the United States. It now appears that this goal may be near attainment, and it is incumbent upon those of us in biomedical research to recognize this fact in our planning for the future.

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