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Achievements in Public Health, 1900-1999: Fluoridation of Drinking Water to Prevent Dental Caries

Fluoridation of community drinking water is a major factor responsible for the decline in dental caries (tooth decay) during the second half of the 20th century. The history of water fluoridation is a classic example of clinical observation leading to epidemiologic investigation and community-based public health intervention. Although other fluoride-containing products are available, water fluoridation remains the most equitable and cost-effective method of delivering fluoride to all members of most communities, regardless of age, educational attainment, or income level.

Dental Caries

Dental caries is an infectious, communicable, multifactorial disease in which bacteria dissolve the enamel surface of a tooth (1). Unchecked, the bacteria then may penetrate the underlying dentin and progress into the soft pulp tissue. Dental caries can result in loss of tooth structure and discomfort. Untreated caries can lead to incapacitating pain, a bacterial infection that leads to pulpal necrosis, tooth extraction and loss of dental function, and may progress to an acute systemic infection. The major etiologic factors for this disease are specific bacteria in dental plaque (particularly *Streptococcus mutans* and lactobacilli) on susceptible tooth surfaces and the availability of fermentable carbohydrates.

At the beginning of the 20th century, extensive dental caries was common in the United States and in most developed countries (2). No effective measures existed for preventing this disease, and the most frequent treatment was tooth extraction. Failure to meet the minimum standard of having six opposing teeth was a leading cause of rejection from military service in both world wars (3,4). Pioneering oral epidemiologists developed an index to measure the prevalence of dental caries using the number of decayed, missing, or filled teeth (DMFT) or decayed, missing, or filled tooth surfaces (DMFS) (5) rather than merely presence of dental caries, in part because nearly all persons in most age groups in the United States had evidence of the disease. Application of the DMFT index in epidemiologic surveys throughout the United States in the 1930s and 1940s allowed quantitative distinctions in dental caries experience among communities--an innovation that proved critical in identifying a preventive agent and evaluating its effects.

History of Water Fluoridation

Soon after establishing his dental practice in Colorado Springs, Colorado, in 1901, Dr. Frederick S. McKay noted an unusual permanent stain or "mottled enamel" (termed "Colorado brown stain" by area residents) on the teeth of many of his patients (6). After years of personal field investigations, McKay concluded that an agent in the public water supply probably was responsible for mottled enamel. McKay also observed that teeth affected by this condition seemed less susceptible to dental caries (7).

Dr. F. L. Robertson, a dentist in Bauxite, Arkansas, noted the presence of mottled enamel among children after a deep well was dug in 1909 to provide a local water supply. A hypothesis that something in the water was responsible for mottled enamel led local officials to abandon the well in 1927. In 1930, H. V. Churchill, a chemist with Aluminum Company of America, an aluminum manufacturing company that had bauxite mines in the town, used a newly available method of spectrographic analysis that identified high concentrations of fluoride (13.7 parts per million [ppm]) in the water of the abandoned well (8). Fluoride, the ion of the element fluorine, almost universally is found in soil and water but generally in very low concentrations (less than 1.0 ppm). On hearing of the new analytic method, McKay sent water samples to Churchill from areas where mottled enamel was endemic; these samples contained high levels of fluoride (2.0-12.0 ppm).

The identification of a possible etiologic agent for mottled enamel led to the establishment in 1931 of the Dental Hygiene Unit at the National Institute of Health headed by Dr. H. Trendley Dean. Dean's primary responsibility was to investigate the association between fluoride and mottled enamel ([see box](#)). Adopting the term "fluorosis" to replace "mottled enamel," Dean conducted extensive observational epidemiologic surveys and by 1942 had documented the prevalence of dental fluorosis for much of the United States (9). Dean developed the ordinally scaled Fluorosis Index to classify this condition. Very mild fluorosis was characterized by small, opaque "paper white" areas affecting less than or equal to 25% of the tooth surface; in mild fluorosis, 26%-50% of the tooth surface was affected. In moderate dental fluorosis, all enamel surfaces were involved and susceptible to frequent brown staining. Severe fluorosis was characterized by pitting of the enamel, widespread brown stains, and a "corroded" appearance (9).

Dean compared the prevalence of fluorosis with data collected by others on dental caries prevalence among children in 26 states (as measured by DMFT) and noted a strong inverse relation (10). This cross-sectional relation was confirmed in a study of 21 cities in Colorado, Illinois, Indiana, and Ohio (11). Caries among children was lower in cities with more fluoride in their community water supplies; at concentrations greater than 1.0 ppm, this association began to level off. At 1.0 ppm, the prevalence of dental fluorosis was low and mostly very mild.

The hypothesis that dental caries could be prevented by adjusting the fluoride level of community water supplies from negligible levels to 1.0-1.2 ppm was tested in a prospective field study conducted in four pairs of cities (intervention and control) starting in 1945: Grand Rapids and Muskegon, Michigan; Newburgh and Kingston, New York; Evanston and Oak Park, Illinois; and Brantford and Sarnia, Ontario, Canada. After conducting sequential cross-sectional surveys in these communities over 13-15 years, caries was reduced 50%-70% among children in the communities with fluoridated water (12). The prevalence of dental fluorosis in the intervention communities was comparable with what had been observed in cities where drinking water contained natural fluoride at 1.0 ppm. Epidemiologic investigations of patterns of water consumption and caries experience across different climates and geographic regions in the United States led in 1962 to the development of a recommended optimum range of fluoride concentration of 0.7-1.2 ppm, with the lower concentration recommended for warmer climates

(where water consumption was higher) and the higher concentration for colder climates (13).

The effectiveness of community water fluoridation in preventing dental caries prompted rapid adoption of this public health measure in cities throughout the United States. As a result, dental caries declined precipitously during the second half of the 20th century. For example, the mean DMFT among persons aged 12 years in the United States declined 68%, from 4.0 in 1966-1970 (14) to 1.3 in 1988-1994 (CDC, unpublished data, 1999) ([Figure 1](#)). The American Dental Association, the American Medical Association, the World Health Organization, and other professional and scientific organizations quickly endorsed water fluoridation. Knowledge about the benefits of water fluoridation led to the development of other modalities for delivery of fluoride, such as toothpastes, gels, mouth rinses, tablets, and drops. Several countries in Europe and Latin America have added fluoride to table salt.

Effectiveness of Water Fluoridation

Early studies reported that caries reduction attributable to fluoridation ranged from 50% to 70%, but by the mid-1980s the mean DMFS scores in the permanent dentition of children who lived in communities with fluoridated water were only 18% lower than among those living in communities without fluoridated water (15). A review of studies on the effectiveness of water fluoridation conducted in the United States during 1979-1989 found that caries reduction was 8%-37% among adolescents (mean: 26.5%) (16).

Since the early days of community water fluoridation, the prevalence of dental caries has declined in both communities with and communities without fluoridated water in the United States. This trend has been attributed largely to the diffusion of fluoridated water to areas without fluoridated water through bottling and processing of foods and beverages in areas with fluoridated water and widespread use of fluoride toothpaste (17). Fluoride toothpaste is efficacious in preventing dental caries, but its effectiveness depends on frequency of use by persons or their caregivers. In contrast, water fluoridation reaches all residents of communities and generally is not dependent on individual behavior.

Although early studies focused mostly on children, water fluoridation also is effective in preventing dental caries among adults. Fluoridation reduces enamel caries in adults by 20%-40% (16) and prevents caries on the exposed root surfaces of teeth, a condition that particularly affects older adults.

Water fluoridation is especially beneficial for communities of low socioeconomic status (18). These communities have a disproportionate burden of dental caries and have less access than higher income communities to dental-care services and other sources of fluoride. Water fluoridation may help reduce such dental health disparities.

Biologic Mechanism

Fluoride's caries-preventive properties initially were attributed to changes in enamel during tooth development because of the association between fluoride and cosmetic changes in enamel and a belief that fluoride incorporated into enamel during tooth development would result in a more acid-resistant mineral. However, laboratory and epidemiologic research suggests that fluoride prevents dental caries predominately after eruption of the tooth into the mouth, and its actions primarily are topical for both adults and children (1). These mechanisms include 1) inhibition of demineralization, 2) enhancement of remineralization, and 3) inhibition of bacterial activity in dental plaque (1).

Enamel and dentin are composed of mineral crystals (primarily calcium and phosphate) embedded in an organic protein/lipid matrix. Dental mineral is dissolved readily by acid produced by cariogenic bacteria when they metabolize fermentable carbohydrates. Fluoride present in solution at low levels, which becomes concentrated in dental plaque, can substantially inhibit dissolution of tooth mineral by acid.

Fluoride enhances remineralization by adsorbing to the tooth surface and attracting calcium ions present in saliva. Fluoride also acts to bring the calcium and phosphate ions together and is included in the chemical reaction that takes place, producing a crystal surface that is much less soluble in acid than the original tooth mineral (1).

Fluoride from topical sources such as fluoridated drinking water is taken up by cariogenic bacteria when they produce acid. Once inside the cells, fluoride interferes with enzyme activity of the bacteria and the control of intracellular pH. This reduces bacterial acid production, which directly reduces the dissolution rate of tooth mineral (19).

Population Served by Water Fluoridation

By the end of 1992, 10,567 public water systems serving 135 million persons in 8573 U.S. communities had instituted water fluoridation (20). Approximately 70% of all U.S. cities with populations of greater than 100,000 used fluoridated water. In addition, 3784 public water systems serving 10 million persons in 1924 communities had natural fluoride levels greater than or equal to 0.7 ppm. In total, 144 million persons in the United States (56% of the population) were receiving fluoridated water in 1992, including 62% of those served by public water systems. However, approximately 42,000 public water systems and 153 U.S. cities with populations greater than or equal to 50,000 have not instituted fluoridation.

Cost Effectiveness and Cost Savings of Fluoridation

Water fluoridation costs range from a mean of 31 cents per person per year in U.S. communities of greater than 50,000 persons to a mean of \$2.12 per person in communities of less than 10,000 (1988 dollars) (21). Compared with other methods of community-based dental caries prevention, water fluoridation is the most cost effective for most areas of the United States in terms of cost per saved tooth surface (22).

Water fluoridation reduces direct health-care expenditures through primary prevention of dental caries and avoidance of restorative care. Per capita cost savings from 1 year of fluoridation may range from negligible amounts among very small communities with very low incidence of caries to \$53 among large communities with a high incidence of disease (CDC, unpublished data, 1999). One economic analysis estimated that prevention of dental caries, largely attributed to fluoridation and fluoride-containing products, saved \$39 billion (1990 dollars) in dental-care expenditures in the United States during 1979-1989 (23).

Safety of Water Fluoridation

Early investigations into the physiologic effects of fluoride in drinking water predated the first community field trials. Since 1950, opponents of water fluoridation have claimed it increased the risk for cancer, Down syndrome, heart disease, osteoporosis and bone fracture, acquired immunodeficiency syndrome, low intelligence, Alzheimer disease, allergic reactions, and other health conditions (24). The safety and effectiveness of water fluoridation have been re-evaluated

frequently, and no credible evidence supports an association between fluoridation and any of these conditions (25).

21st Century Challenges

Despite the substantial decline in the prevalence and severity of dental caries in the United States during the 20th century, this largely preventable disease is still common. National data indicate that 67% of persons aged 12-17 years (26) and 94% of persons aged greater than or equal to 18 years (27) have experienced caries in their permanent teeth.

Among the most striking results of water fluoridation is the change in public attitudes and expectations regarding dental health. Tooth loss is no longer considered inevitable, and increasingly adults in the United States are retaining most of their teeth for a lifetime (12). For example, the percentage of persons aged 45-54 years who had lost all their permanent teeth decreased from 20.0% in 1960-1962 (28) to 9.1% in 1988-1994 (CDC, unpublished data, 1999). The oldest post-World War II "baby boomers" will reach age 60 years in the first decade of the 21st century, and more of that birth cohort will have a relatively intact dentition at that age than any generation in history. Thus, more teeth than ever will be at risk for caries among persons aged greater than or equal to 60 years. In the next century, water fluoridation will continue to help prevent caries among these older persons in the United States.

Most persons in the United States support community water fluoridation (29). Although the proportion of the U.S. population drinking fluoridated water increased fairly quickly from 1945 into the 1970s, the rate of increase has been much lower in recent years. This slowing in the expansion of fluoridation is attributable to several factors: 1) the public, some scientists, and policymakers may perceive that dental caries is no longer a public health problem or that fluoridation is no longer necessary or effective; 2) adoption of water fluoridation can require political processes that make institution of this public health measure difficult; 3) opponents of water fluoridation often make unsubstantiated claims about adverse health effects of fluoridation in attempts to influence public opinion (24); and 4) many of the U.S. public water systems that are not fluoridated tend to serve small populations, which increases the per capita cost of fluoridation. These barriers present serious challenges to expanding fluoridation in the United States in the 21st century. To overcome the challenges facing this preventive measure, public health professionals at the national, state, and local level will need to enhance their promotion of fluoridation and commit the necessary resources for equipment, personnel, and training.

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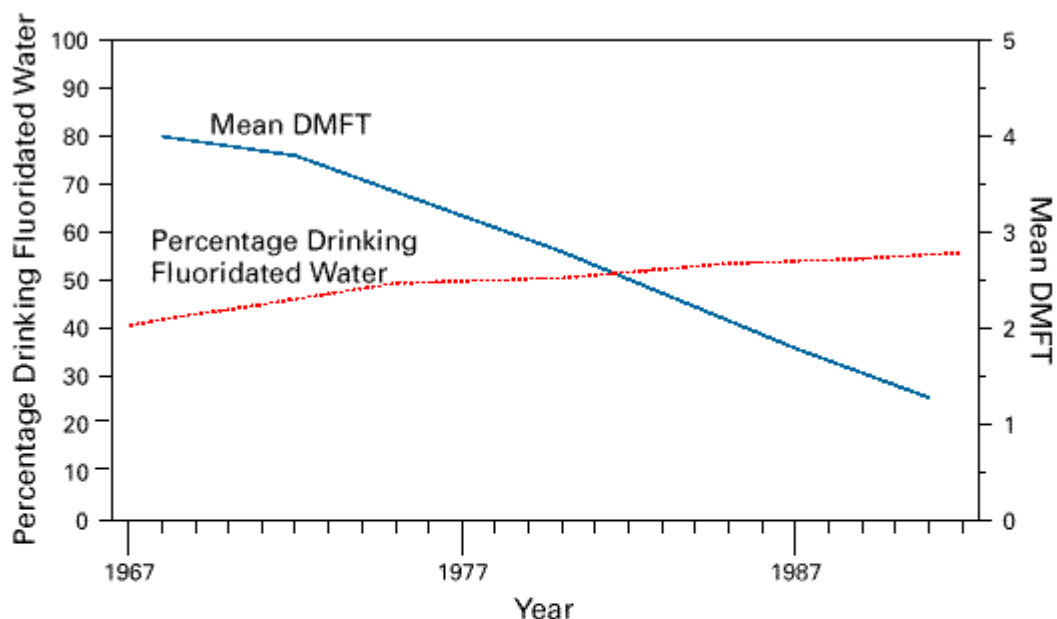
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Figure 1

FIGURE 1. Percentage of population residing in areas with fluoridated community water systems and mean number of decayed, missing (because of caries), or filled permanent teeth (DMFT) among children aged 12 years — United States, 1967–1992



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