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Fluoride Revolution and Dental Caries: Evolution of Policies for Global Use

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Abstract

Epidemiological studies over 70 y ago provided the basis for the use of fluoride in caries prevention. They revealed the clear relation between water fluoride concentration, and therefore fluoride exposure, and prevalence and severity of dental fluorosis and dental caries. After successful trials, programs for water fluoridation were introduced, and industry developed effective fluoride-containing toothpastes and other fluoride vehicles. Reductions in caries experience were recorded in many countries, attributable to the widespread use of fluoride. This is a considerable success story; oral health for many was radically improved. While previously, water had been the only significant source of fluoride, now there are many, and this led to an increase in the occurrence of dental fluorosis. Risks identified for dental fluorosis were ingestion of fluoride-containing toothpaste, water fluoridation, fluoride tablets (which were sometimes ingested in areas with water fluoridation), and infant formula feeds. Policies were introduced to reduce excessive fluoride exposure during the period of tooth development, and these were successful in reducing dental fluorosis without compromising caries prevention. There is now a much better understanding of the public perception of dental fluorosis, with mild fluorosis being of no aesthetic concern. The advantages of water fluoridation are that it provides substantial lifelong caries prevention, is economic, and reduces health inequalities: it reaches a substantial number of people worldwide. Fluoride-containing toothpastes are by far the most important way of delivering the beneficial effect of fluoride worldwide. The preventive effects of conjoint exposure (e.g., use of fluoride toothpaste in a fluoridated area) are additive. The World Health Organization has informed member states of the benefits of the appropriate use of fluoride. Many countries have policies to maximize the benefits of fluoride, but many have yet to do so.

Keywords: fluoride(s), dental public health, epidemiology, prevention, remineralization, health policy

Introduction

While the global epidemic of dental caries, which began about 140 y ago, was very largely caused by the rise in sugar consumption (Rugg-Gunn and Nunn 1999), the more recent decline in caries, during the past 50 y, has been due largely to the use of fluoride. Appropriate fluoride policies have radically improved oral health, enhancing general health and quality of life for populations across the world. Its use varies from population-level interventions to individual-level home oral care measures and targeted clinical preventive measures. This article focuses on population-level interventions, which have been predominantly delivered through fluoridation of water supplies and the widespread use of fluoride toothpaste.

In this article, we look at the genesis of the idea of fluoridating water supplies and how landmark research up to 80 y ago shaped early public policy. Because of its effectiveness in combating dental caries, fluoride was added as an active ingredient in consumer products, including toothpaste and mouth rinses; in professionally applied products such as varnishes and dental restorative materials; and, for areas where water fluoridation is not feasible, in salt and milk.

Observations over 70 y ago related enamel developmental defects, now known as dental fluorosis, to high concentrations of fluoride occurring naturally in water supplies, but very quickly investigations turned to achieving a balance between maximizing caries control without the occurrence of unacceptable dental fluorosis. While policy has constantly evolved, this balance has remained the central issue for population-level interventions using fluoride. The key scientific challenges in informing present-day policy and future research needs are identified.

The Impact of Fluoride on Population Caries Levels

Purchase and consumption of sugar were particularly high in more developed countries during most of the 20th century, and it

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was in these countries that the caries epidemic hit hardest. In the 1950s and 1960s, edentulousness was the norm for older adults (U.S. Department of Health and Human Services 1960; Gray et al. 1970; O'Mullane and Whelton 1994) and it was usual for 12-y-olds to have 8 to 12 caries-affected teeth (Murray 1986).

The decision to adjust the concentration of fluoride in drinking water upward to around 1 mg/L (1 ppmF) in the mid-1940s in the United States had a profound effect on population oral health. Caries experience in children who had consumed fluoridated water was halved. The World Health Organization (WHO) recommended water fluoridation and many countries with high caries experience implemented water fluoridation programs (WHO 1958). By 2012, it was estimated that 370 million people in 27 countries were supplied with fluoridated drinking water, with about 50 million drinking naturally fluoridated water (British Fluoridation Society 2012).

The oral health care industry soon recognized the potential to market products, largely toothpastes, which would contain fluoride for the prevention of dental caries. However, formulating an effective fluoride-containing toothpaste was not easy, and it took 25 to 30 y for such toothpastes to be widely available. Issues dominating early research were incompatibility of abrasives included in toothpastes, different fluoride compounds, effective concentrations, and stability of fluoride compounds during storage. In 1970, less than 5% of toothpastes sold in the United Kingdom contained fluoride; by 1976, over 90% contained fluoride (Murray et al. 1991). Fluoridated toothpastes became the norm throughout the world for those who could afford to buy it (Goldman et al. 2008). In 2000, it was estimated that at least 1.5 billion people worldwide used a fluoride-containing toothpaste. Much smaller numbers, around 0.1 billion, used fluoride-containing mouthrinses (Rugg-Gunn 2001).

It took time for the effect of this "fluoride revolution" to be appreciated. The first signs of improving dental health of children in the United Kingdom became evident in the late 1970s (Palmer 1980; Anderson 1981). Two international conferences were held in the early 1980s in response to these reports (Glass 1982; WHO/FDI 1985). At both conferences, it was generally agreed that the prevalence of dental caries had declined substantially in developed countries and that the most probable reasons were fluoride in toothpastes, rinses, and/or community water supplies. More recent reviews have supported these conclusions (Bratthall et al. 1996).

After 50 y, the impact of fluoride-related prevention on caries experience in many countries has been transformative. While in 1954, Australian 12-y-olds had an average of over 9 caries-affected teeth (Barnard 1956), by 2012 to 2014, this had fallen to 0.9 (Do and Spencer 2016). During this time, adults' oral health also improved enormously; while changes in attitudes and behaviors are likely to have been a factor, exposure to any fluorides and water fluoridation also played a part (Griffin et al. 2007).

The path to implementing universal coverage of appropriate use of fluorides has not always been smooth, and key moments along this journey will now be described.

Policy on Naturally Occurring Fluoride Levels in Drinking Water

The research of Dean and others in the 1930s and early 1940s was initially focused on fluoride and dental fluorosis (Dean and Elvove 1936, 1937). An understanding of the "dose-response" relationship between fluoride concentration occurring naturally in water supplies and dental fluorosis emerged from data across 22 cities in 10 U.S. states.

This population-level epidemiology was aided by the development of Dean's classification of fluorosis (Dean 1934). Dean defined the degrees of dental fluorosis in children as normal (0), questionable (0.5), very mild (1), mild (2), moderate (3), and severe (4). Dean classified the fluorosis observed at a population level into 7 levels based on the frequency distribution of these degrees of fluorosis. Crucially, towns with less than 10% of children with very mild or more severe fluorosis were classed as "negative" for endemic dental fluorosis (Dean 1935).

These data seem crucial to the first policy around fluoride in water supplies. This emerged in terms of drinking water standards. McClure (1943) described 1.0 mg F/L as the "permissible" level naturally occurring in water supplies, citing the U.S. Drinking Water Standards (U.S. Department of Health and Human Services 1943).

Dean and colleagues quickly moved from studies of dental fluorosis to fluoride and dental caries (Dean et al. 1942) and then to dental fluorosis and caries simultaneously. A dose-response relationship between fluoride concentration in water supplies, dental fluorosis, and caries was established in the famous 21 cities in and around Chicago and a further 4 states in the United States (Dean 1946). The dose-response relationship for fluoride concentration and dental caries from the 21 cities data redrawn using modern methods is presented in Figure 1.

These caries and the accompanying dental fluorosis data from the 21 cities informed a broader policy for the balance between caries prevention and avoidance of fluorosis of public health concern. Dean introduced a summary measure for measurement of dental fluorosis in a population, a weighted average score, the Community Fluorosis Index (CFI).

Dean described CFI scores of 0.0 to 0.4 of "no" and 0.4 to 0.6 of "little" public health concern in the development of fluorosis. Figure 2 presents the fluoride levels in water supplies, caries, and the CFI.

A threshold score of 0.4 fitted well with the earlier statements that fluoride levels of up to 1.0 mg F/L were "negative" for endemic dental fluorosis and of no public health concern. This category also encompassed a sizable portion of benefit in the prevention of caries. Dean (1944) stated, "There seemingly is little if any advantage gained in further caries reduction by using a water higher than about 1 part per million [or mg/L]. And, as this concentration is sufficiently low to eliminate the complicating problem of dental fluorosis the question of markedly reducing the dental caries incidence [sic] through low fluoridation of domestic water supply warrants thoughtful

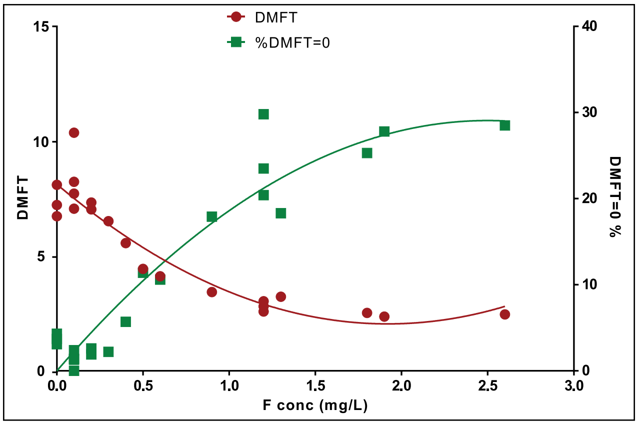

Figure 1. Relationship between fluoride concentration (F conc) and dental caries measured by per cent caries free and mean Decayed, Missing and Filled Teeth (DMFT) score. Lines of best fit were generated with a second-order polynomial (quadratic) equation. Source: Dean et al. (1941, 1942).

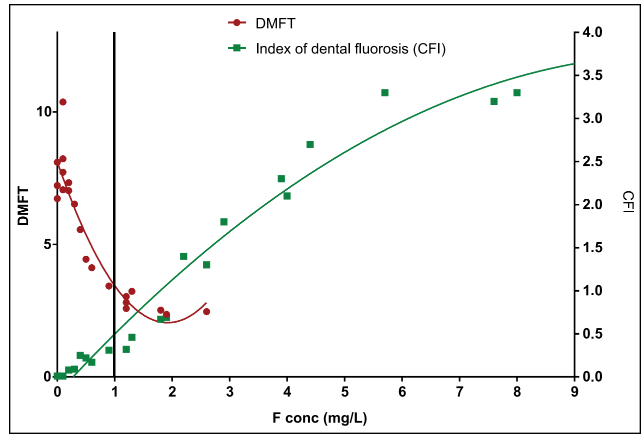

Figure 2. Relationship between fluoride concentration (F conc), dental caries measured by mean Decayed, Missing and Filled Teeth (DMFT) score, and dental fluorosis measured by the Community Fluorosis Index (CFI). Lines of best fit were generated with a second-order polynomial (quadratic) equation. Source: Dean et al. (1942).

consideration." A rationalization for 1.0 mg F/L as the target for water fluoridation trials had begun to emerge.

Moving from "Permissible" Fluoride Concentration to "Optimum" Fluoride Intake

At the same time that the dose-response relationships for fluoride in water supplies was being finalized, research was conducted to estimate fluoride intake. An indirect approach was adopted to convert exposure to water supplies with a known concentration of fluoride to population estimates of fluoride intake from drinking water and food in the diet (McClure 1943). McClure (1943) stated that at 1.0 mg F/L in drinking water fluoride intake "probably would rarely exceed 0.1 mg per kilogram of body weight. As a rule this average would equal about 0.05 mg daily per kilogram of weight for children." This intake "appears instrumental in reducing dental caries to a great degree." He suggested that "serious thought can be given to the use of this 'optimum' quantity of supplemental fluorine in children's diets for the partial control of dental caries" (McClure 1943). McClure's research has provided a backdrop to all subsequent research around an optimal fluoride intake (Farkas and Farkas 1974; Ophaug et al. 1980) and the specification of Nutrient Reference Values such as an Adequate Intake right through to today (Institute of Medicine 1997; Environmental Protection Agency 2010; Spencer et al. 2018).

Trials of Water Fluoridation

Dean wrote on the implications of the research up to that time. He stated that those domestic waters carrying naturally the "optimal" concentration of fluoride (about 1 ppm) would require no treatment, but those deficient in fluoride might have fluoride added to bring their concentration up to the optimal to inhibit dental caries attack (Dean 1944). Ast (1943) had already suggested to study the relationship between fluoridation and tooth decay by "deliberately placing nontoxic doses of sodium fluoride in the public drinking water of a community, and using a comparable community with fluoride-free water as a control."

Dean (1944) had outlined the community fluoridation trials that would soon follow, and research entered a phase of foundational community fluoridation trials: 3 in the United States and 1 in Canada:

- Grand Rapids (1945), Michigan, paired with nearby Muskegon, with the naturally fluoridated Aurora, Illinois (1.2 mg F/L), as a positive control
- Newburgh (1945), New York, paired with Kingston, New York
- Evanston (1946), Illinois, paired with Oak Park, Illinois
- Brantford (1945), Ontario, paired with Sarnia, Ontario, with the naturally fluoridated Stratford, Ontario, as a positive control

These trials were designed as before-and-after nonrandomized controlled trials. They were epidemiological studies, with long follow-up periods planned to observe people who had lived their whole lives exposed or not to fluoride in the water supply. Field examinations were to be conducted each year allowing for the progressive release of findings.

The first results from the Grand Rapids trial were released in 1950 (Dean et al. 1950), providing data on baseline and the 4-y follow-up. This early release of findings created a difficulty. Control sites quickly became aware of the reductions in caries in the fluoridated sites and sought to implement fluoridation. Muskegon fluoridated in mid-1951, eliminating the paired negative control. Longer-term findings were frequently reported as before-and-after studies.

Findings for the Grand Rapids trial were published up to the 15-y follow-up results, comparing the outcome to the baseline data. Caries experience had reduced by 50% to 63% in children aged 12 to 14 y and by 48% to 50% in children aged 15 to 16 y (Arnold et al. 1956). Slightly more impressive findings came from Newburgh after 15 y of fluoridation establishing the benchmark 50% to 60% reduction so often claimed (Moore 1960). Caries reductions after 16 y of follow-up in Evanston were of a similar magnitude to those for Grand Rapids (Blayney and Hill 1967). The Brantford trial reported follow-up over a 17-y period of fluoridation (Brown and Poplove 1965). The similarity of the findings across these "original 4" adds weight to their veracity, despite criticism of methodological shortcomings (Sutton 1960).

A crucial but somewhat overlooked finding from these trials was the reporting on dental fluorosis. In Grand Rapids, at the 15-y follow-up, the prevalence of dental fluorosis among 12- to 16-y-old children was 11%, but most of this was of questionable or very mild severity (Arnold et al. 1962). This fit well with the earlier dose-response relationship for fluoride occurring naturally in water supplies and served well for benchmarking what prevalence and severity to expect if further cities were fluoridated.

From the 1970s and 1980s, fluoride cessation studies and observations of the impact of fluoride on caries in children who received only posteruptive fluoride exposure were reported. This contributed to the recognition that water fluoridation provided a local intraoral, or "topical," caries-preventive effect. These observations changed the debate on the mode of action of fluoride, as discussed by ten Cate and Buzalaf (2019).

Policy Adopted in the United States

By 1950, the U.S. Public Health Service (USPHS) had given its endorsement to water fluoridation, stating that "communities desiring to fluoridate their communal water supply should be encouraged to do so" (Dunning 1962). The U.S. Surgeon General reaffirmed fluoridation as an official policy of the USPHS in testimony before the Senate in April 1951 (McClure 1970). The number of U.S. towns and the population numbers covered with water fluoridation rapidly grew, reaching more than 1,500 cities and towns by the late 1950s (WHO 1958).

Replication and the Emergence of International Policy

There are 2 aspects to the replication phase. First, the dose-response relationship between fluoride occurring naturally in water supplies and caries experience was replicated in the United States and other countries in the late 1940s and 1950s (Murray et al. 1991). The curvilinear relationship was confirmed, and around 1.0 mg F/L was confirmed as the level at which near-maximal reduction in caries experience was achieved in children.

Second, water fluoridation trials and community programs were implemented in Australia, Belgium, Brazil, Canada, Chile, Columbia, El Salvador, Germany, Great Britain, Japan, Malaya, Netherlands, New Zealand, Panama, Sweden, and Venezuela (WHO 1958).

WHO formed an Expert Committee on Water Fluoridation, which delivered its first report (WHO 1958). The report concluded that drinking water at about 1 mg F/L fluoride had a marked caries-preventive action, maximum benefits were obtained if such water was consumed throughout life, there was no evidence that water containing this concentration of fluoride impaired general health, and automatic fluoridation of drinking water was seen as a practicable and effective public health measure.

Notable water fluoridation trials were also commenced in the 1950s. Caries reductions were subsequently reported, notably from the Tiel-Culemborg study in the Netherlands (Kwant et al. 1973). In 1953, Tiel's water supply was fluoridated at 1.1 ppm (mg/L); Culemborg with a water fluoride level of 0.1 ppm served as the control. Clinical examinations of 11- to 15-y-old children in 1952 showed similar levels of caries in the 2 areas. In 1969, clinical and radiographic examination of 15-y-old children born in the first year after introduction of fluoridation was carried out at both sites. Tooth surface-level analysis revealed 56% less caries among Tiel children, and the impact of fluoridation was greater on the smooth surfaces, with an 86% difference compared with 31% on pit and fissure surfaces.

Hastings, New Zealand, was fluoridated in 1954, and a baseline survey was carried out at the time to measure caries among 15-y-olds. In 1970, an examination of 15-y-old children born after fluoridation revealed similar caries reductions and the differential surface impact as found in the Dutch study (Ludwig 1971).

In the United Kingdom, fluoride was added to the water of Watford, Kilmarnock, and part of Anglesey in 1955 to 1956, with Sutton, Ayr, and the remaining part of Anglesey acting as control towns. In 1962, 5 y after fluoridation, caries levels among 5-y-olds was found to be 50% lower in the fluoridated areas than the nonfluoridated areas. A further study after 11 y confirmed effectiveness and safety (Department of Health and Social Security 1969).

Despite the major positive effect of fluoride on population caries levels and the reach of water fluoridation to all sectors of society in fluoridated communities, there are some who have raised concerns: suggesting that fluoride is a poison or medication, the aesthetic impact of fluorosis, civil liberties, and the right to choose. These issues have been debated at length and across many fora by ethicists, by the media, and in the courts.

The issues of fluoride as a harmful substance and fluoridated water as a medicinal product were considered in a case taken in 1979 in Glasgow, by Mrs Catherine McColl against Strathclyde Council; neither claim was upheld in the verdict of Lord Jauncey, the judge on the case (Jauncey 1983). This position has not changed; in the intervening period, the WHO has cited fluoride as an element with beneficial health effects in the prevention of dental caries.

Considering the argument that water fluoridation infringes on people's freedom of choice, because it is done without the explicit consent of the people who drink the water, reference is made to the UNESCO (2005) Universal Declaration on Bioethics and Human Rights, which specifically exempts laws for the protection of public health from seeking consent for public health.

This issue was considered, for example, in the Republic of Ireland. After hearing 67 d of evidence, the High Court held that fluoridation of water supplies was not unconstitutional or harmful, with the judge ruling that the personal rights of the citizen were not unlimited (Kenny 1963), and fluoridation of Dublin's water supplies began in 1964.

Aside from the ethical issues, the technical feasibility and affordability of fluoridating many small separate water supply systems was another area of concern. This issue was relevant to dispersed populations with separate water supply systems, as is the case in numerous European countries. This would impose high capital costs on small populations, making water fluoridation less affordable. One response was to mimic water fluoridation in terms of fluoride exposure and intake by school-based fluoride tablet programs, for example, in central and eastern Europe (Kunzel 1996), and fluoridating salt, which Switzerland successfully led (Marthaler et al. 1978).

So, when WHO articulated policy on fluorides, it accommodated both water fluoridation and the pursuit of alternatives (WHO 1969). The 28th World Health Assembly considered a report on the promotion of the fluoridation of community water supplies and other approved methods for the prevention of dental caries and noted that while optimizing the fluoride content of water supplies remained the most effective known means of preventing dental caries, other systems of securing some of the benefits of fluoride protection in areas where the fluoride content of drinking water was insufficient and fluoridation was not feasible were available (WHO 1975). This position has remained largely unchanged through to today. The Sixtieth World Health Assembly in 2007 issued a statement urging member states "to consider and develop fluoridation programmes, giving priority to equitable strategies such as the automatic administration of fluoride, for example, in drinking water, salt or milk, and the provision of affordable fluoride toothpaste" (Petersen 2008).

Currently, other than natural and artificial water fluoridation, delivery of fluorides for caries prevention occurs in a number of ways: some bottled waters (spring waters) have fluoride levels commensurate with water fluoridation, fluoridated salt is used extensively in some countries and marketed widely, widespread use of fluoridated toothpaste (including higher fluoride concentrations up to 1,500 ppm), use of fluoride mouthwashes, and the application of professional fluoride products in public health programs. This meant that some countries that did not pursue water fluoridation still faced policy issues around the balance in the prevention of caries and dental fluorosis.

Fluoride Concentration, Climate, and Water Consumption

The importance of variation in water consumption with ambient temperature was recognized (Galagan 1953). The variation in water consumption of 0- to 10-y-olds, measured over a 5-d period during different seasons across 2 different temperature zones in California, was examined (Galagan and Vermillion 1957). A relationship between water consumption and mean maximum daily temperature was subsequently proposed and led to the USPHS recommending a range of optimal fluoride concentrations of 0.7 to 1.2 mg F/L across the United States (U.S. Department of Health and Human Services 1962). This principle has remained internationally relevant but has come under recent scrutiny in the United States and other countries.

Fluoridated Toothpaste

Formulating effective fluoride-containing toothpastes was not simple. Early trials of adding sodium fluoride to toothpaste were unsuccessful (Bibby 1945). The first successful trial was reported 10 y later (Muhler et al. 1955) and was followed by a deluge of reports. These reports led to the acceptance of fluoride toothpastes by the Council on Dental Therapeutics of the American Dental Association (ADA) in 1964 (American Dental Association Council on Dental Therapeutics 1964). Health authorities in numerous countries and international bodies such as WHO and FDI have endorsed the effectiveness of fluoride-containing toothpastes and have encouraged their use.

Research indicates that fluoridation is effective in populations with widespread use of fluoridated toothpaste and that frequency of tooth brushing has an association with caries prevention in fluoridated communities. In addition, the caries-preventive effects of fluoride in water and fluoride in toothpaste are additive (McDonagh et al. 2000; Marinho et al. 2003; O'Mullane et al. 2016).

Two issues remain topical: first, the appropriate concentration of fluoridated toothpaste for various age groups in the presence or absence of fluoridation and, second, affordability of toothpaste in less well-developed countries. WHO has strongly promoted locally affordable toothpastes (Petersen 2008), although there is concern that some of these contain no, or little, effective fluoride and are mislabeled.

Fluoride Supplements

Fluoride supplements in the form of fluoride drops or tablets were introduced as an alternative to water fluoridation. In theory, tablets containing 1 mg F would mimic a child's fluoride intake if the child drank a liter of water fluoridated at 1 mg F/L. The first trial of fluoride tablets was published in 1955 (Bibby et al. 1955) and followed by many other reports of effectiveness. Subsequent reviews concluded that fluoride tablets can reduce caries in children (Driscoll et al. 1974; Rozier et al. 2010). Bibby suffered high attrition from his sample, alerting to the problem of long-term adherence to tablet regimens. While the daily use of fluoride tablets requires health behavior compliance that many find difficult, they were the vanguard of additional discretionary fluoride vehicles.

The Rise in Dental Fluorosis

When Driscoll and colleagues returned to the Illinois area made famous by Dean, they found slightly more severe fluorosis among children in fluoridated areas than reported 40 y earlier (Driscoll et al. 1983). Crucially, when they repeated the study 5 y later, there had been an increase in the severity of fluorosis across this short period of time (Driscoll et al. 1986). Fluoride intake across the critical years of tooth development was changing. Leverett (1986) not only confirmed this change but shed light on the probable explanation by comparing fluoridated Rochester with nearby nonfluoridated towns. The substantial increase in nonfluoridated areas pointed to an effect of new and additional sources of fluoride intake in young children: fluoridated drinking water was not the only factor behind the risk of dental fluorosis.

A similar increase in the prevalence and severity of dental fluorosis was found at the beginning of the 1990s in Western Australia (Riordan 1993) and in South Australia (Puzio et al. 1993). The prevalence of dental fluorosis using Dean's index was 34% and 19% in fluoridated and nonfluoridated areas, respectively, well above the benchmarks set by Dean's studies.

Risk Factors for Dental Fluorosis

Fluoride intake is considered a necessary factor in the etiology of fluorosis. However, the presence of fluoride may have an effect only during the tooth development stage. Several authors considered a specific "window" period during enamel development as critical for fluorosis to occur (Evans and Darvell 1995; Aoba and Fejerskov 2002). Other authors suggested that the duration of fluoride exposure during the amelogenesis, rather than specific risk periods, would have more impact on the etiology of dental fluorosis (Bardsen 1999; Den Besten 1999). Levy's epidemiological study showed that a combination of years 1, 2, and 3 were more strongly associated with fluorosis that any of the years separately (Hong et al. 2006). However, there was general agreement that exposure during the postsecretory or early maturation period of enamel development may pose a higher risk for fluorosis.

The studies on the prevalence and severity of dental fluorosis in the 1980s suggested that new fluoride sources in the community were contributing to the increase in dental fluorosis. However, it was not until the 1990s that analyses of multiple putative risk factors for dental fluorosis began to be conducted. Early weaning (and therefore greater likelihood of infant formula feeding), reported toothpaste swallowing, licking toothpaste from the tube, and length of time residing in a fluoridated area were associated with dental fluorosis (Riordan 1993).

This information set the context for directions that have been pursued to reestablish a balance in the prevention of caries and dental fluorosis.

Possible Actions for Reducing Fluoride Intake during the Critical Period for Dental Fluorosis

Infant Formula and Fluoride Tablets

Due to the method of manufacture, infant formula powders used to contain appreciable concentrations of fluoride (Silva and Reynolds 1996). After discussions with industry, the concentration of fluoride was reduced substantially, although the timing of this industry change varied across countries. Recent research shows feeding of infant formula even reconstituted with fluoridated water is not a risk factor for dental fluorosis (Do et al. 2012).

A further early change was the steady reduction in dosage and then cessation of fluoride tablet programs (American Academy of Pediatrics 1995). Again, the pace of change varied across countries, but in many, tablets were no longer recommended for use even in nonfluoridated areas by the end of the 20th century.

Ingestion of Fluoride from Fluoridated Toothpaste

Consideration of fluoride intake following ingestion of toothpaste was stimulated by information on toothpaste ingestion by young children and the finding that such ingestion was a risk factor for dental fluorosis (Osuji et al. 1988).

Two policy approaches emerged on how to reduce such ingestion: reducing the fluoride concentration in children's toothpastes (Australia) and a change in toothbrushing behavior to reduce ingestion of toothpaste (commencing toothpaste use either at 18/24/36+ mo, small brush head, smear/rice grain/pea-sized/fingernail-sized amount of toothpaste, parental supervision). Children's toothpaste with fluoride levels of about 400 to 550 ppm were marketed and recommended in Australia.

The combination of these approaches has been found to lead to lower prevalence and severity of dental fluorosis without an apparent change in caries prevention. This was first reported in Western Australia (Riordan 2002) and later in South Australia (Do and Spencer 2007b). The outcomes of these studies pointed to a crucial issue in choice of fluoride vehicle to target to reduce fluorosis. Only if the fluoride vehicle targeted is a risk factor across both fluoridated and nonfluoridated areas will substantial reductions in the prevalence of fluorosis occur across the whole population.

Fluoride Level in Water Supplies

An additional and perhaps alternative approach to reducing the risk of dental fluorosis while maintaining near-maximal prevention of caries is the reduction of the fluoride level in water supplies. In recent years, a number of countries have adopted this approach.

In Malaysia, the concentration of fluoride in drinking water was adjusted downward from 0.7 to 0.5 ppm in 2005 (Ministry of Health of Malaysia 2006). In Singapore, it was reduced from 0.6 ppm to 0.5 ppm in 2008 (Petersen et al. 2012). Ireland and Canada reduced the target concentration from 0.9/1.0 to 0.7 ppm F in 2007 to 2008 (Whelton and O'Mullane 2012). The U.S. Department of Health and Human Services drafted such a recommendation in 2011 and formally adopted the change in 2015 (U.S. Department of Health and Human Services Federal Panel on Community Water Fluoridation 2015). The USPHS now recommends an optimal fluoride concentration of 0.7

Table. Timeline: Evolution of Policies for Global Use of Fluoride.

1931	H. Trendley Dean was assigned to investigate the epidemiology of mottled enamel.
1942	Dean et al. reported on the 21 cities study, which showed how severity of mottling and caries varied with water fluoride concentration and that 1 ppm was likely to be the threshold for minimal mottling and substantially lower caries.
1942	U.S. Public Health Service agreed to plan a trial of water fluoridation.
1945	First water fluoridation trial began with adjustment of the water supply to Grand Rapids to the optimum of 1 ppm. Other cities in the United States and Canada included in trials in 1945 and 1946 as control and test areas.
1950	U.S. Public Health Service endorsed water fluoridation.
1953	Report on 6½ y of water fluoridation: caries experience halved.
1953	Water fluoridation trial began in Europe.
1954	Water fluoridation trial began in New Zealand.
1954	First addition of fluoride to school water supplies in the United States.
1955	Report of first trial of an effective fluoride-containing toothpaste.
1955	Report of first trial of effective use of fluoride tablets.
1955	Fluoridated salt on sale in Switzerland.
1958	First addition of fluoride to milk in Switzerland.
1958	World Health Organization (WHO) report of Expert Committee on Water Fluoridation supportive of water fluoridation as a public health measure.
1962	WHO published a monograph (authored by 29 invited experts) on fluoride and human health.
1962	U.S. Public Health Service recommended that optimum fluoride concentration in water should vary depending on climatic temperature.
1969	WHO reported that water fluoridation programs were under way in more than 30 countries, serving over 120 million people. The Twenty-Second World Health Assembly issued a statement recommending member states to, where practical, introduce water fluoridation.
Early 1970s	Widespread marketing and use of fluoride-containing toothpastes.
1975	Twenty-Eighth World Health Assembly endorsed water fluoridation and other methods of delivering fluoride.
1977	European Commission suggested an upper limit of 1,500 ppmF for toothpastes sold over the counter.
1981	A total of 210 million people worldwide received water fluoridation according to a 1986 WHO report.
1983	First indication of an increase in the prevalence and severity of dental fluorosis in the United States.
1983	Five hundred schools in 13 U.S. states operated school water fluoridation schemes.
1983	Fluoridated salt was available in 23 Swiss cantons and used voluntarily by 70% of the population.
1993	First reports that there could be several risk factors for dental fluorosis.
2007	Sixtieth World Health Assembly issued statement urging member states to consider introducing water fluoridation or other fluoride-based policies, including salt, milk, and affordable fluoride-containing toothpaste.
2007	Canada and Ireland lowered the recommended optimum fluoride concentration in drinking water from 1 to 0.7 ppm.
2009	European Union regulations approved addition of fluoride to foods.
2011	U.S. Public Health Service recommended lowering optimum water fluoride concentrations.
2012	Reported that 370 million people in 27 countries receive fluoridated water.
2013	Reported that over 100 million people use fluoridated salt in Latin America.
2016	Reported that over 1.5 million children receive fluoridated milk in school worldwide.

ppm, which is at the lower end of the previous recommendation of 0.7 to 1.2 ppm F. However, operationally, U.S. water supplies can still operate in the control range of 0.6 to 1.0 mg F/L (U.S. Federal Register 2018).

Both the logic of reducing an exposure across life to tackle an exposure during a critical period in early childhood and the strength of the evidence behind the recommendation have been questioned (Spencer and Do 2016). The ultimate test for this approach will lie with ongoing monitoring of both dental caries and fluorosis levels.

The Relative Importance of Dental Fluorosis

Fluorosis indices record the full spectrum of dental fluorosis from a few specks or fine white lines to the most severe form. Interpretation of the relevance of different grades of dental fluorosis has been the subject of study. It is acknowledged, as it was by Dean, that some fluorosis at the lower levels is to be expected alongside the beneficial use of fluoride for oral health. Central to the acceptability of the level of fluorosis in a fluoridated population are 2 issues that have been recently quantified: first, that questionable, very mild, and mild dental fluorosis is aesthetically acceptable to the general public and, second, that severity of dental fluorosis diminishes with age.

The relevant research has been extensively reviewed (Chankanka et al. 2010). It was reported that TF 1 and 2 (Thylstrup-Fejerkov index scores, equivalent to questionable/very mild fluorosis) are rated as better for oral health–related quality of life (OHRQoL) than no fluorosis (Do and Spencer 2007a). A TF score of 3 (equivalent to very mild/mild fluorosis) was no different in a rating of OHRQoL than no fluorosis. This interpretation of the impact of fluorosis is supported by recent work in the United States (Onoriobe et al. 2014). They found that there was no statistical or "minimum important difference" across categories of dental fluorosis scored with Dean's scale in child and parent perceptions.

In a recent study of the natural history of dental fluorosis in young adolescents over a 6-y follow-up period, reductions in the severity of dental fluorosis with time were recorded (Do et al. 2016). This is relevant as Dean's studies, and most subsequent studies, have been carried out in 12-y-olds whose permanent incisor teeth have only recently erupted.

Refining Fluoride Policy for Oral Health

The above information indicates that much has been learned during recent years, allowing policies for caries prevention through the use of fluoride to be refined. The relevant issues are as follows:

- There are several ways of delivering fluoride for caries prevention and that concurrent use of fluoridation and fluoridated toothpaste brings additional benefit.
- While in the days of Dean's studies, water was almost the only source of ingested fluoride, there are now many sources, and these need to be considered when deciding policy.
- The multiplication of fluoride sources has led to a rise in dental fluorosis, but this can be controlled by policy decisions.
- To avoid aesthetically unattractive levels of fluorosis, policy must focus on ensuring the appropriate use of fluorides for children up to age 3 y. Such policies should avoid compromising the availability of effective fluoride for all people throughout the life course into old age.
- The impact of dental fluorosis is less than originally thought, with very mild and mild dental fluorosis being of little aesthetic importance in many communities studied.
- Assessment of the impact of dental caries and fluorosis should be conducted concurrently using community preference metrics relevant to both, like OHRQoL.
- Dental caries is a disease of medical, social, and economic importance, while dental fluorosis, greater than mild severity, is of aesthetic importance only.
- The appropriate use of fluoride results in considerable lifelong benefit to oral health.
- Different fluoride-based programs can be targeted to reduce health and social inequalities.
- Many fluoride-based programs are cost-effective and readily implemented, and they are underused worldwide, despite the high prevalence and impact of dental caries.
- While the appropriate use of fluoride has transformed oral health, dental caries will remain a significant health burden until sugar consumption is reduced in most countries: these are conjoint strategies, not alternatives.

The last 80 y of research informing policy on the use of fluorides at a population level (Table) has seen no change in the fundamental purpose of that policy: to achieve near-maximal prevention of caries without the creation of a prevalence and severity of dental fluorosis that causes concern.

What has changed is the environment in which research and policy is trying to find that balanced position. The number of sources of exposure and intake of fluoride has expanded from simply naturally occurring fluoride in water, foods, and air to 3 forms of adjusted fluoride exposure from water, salt, and milk and finally to a plethora of fluoride sources that are discretionary or delivered to individuals by hand to mouth in the home or dental surgeries. This has greatly increased the complexity of policy around the use of fluorides.

The WHO has had an important role in informing governments and health officials around the world of the great benefits of the appropriate use of fluoride. Many countries have clear policies on fluoride use, but many do not. The challenge for the future is to maximize the potential benefit of fluoride, which research during the past 70 y has been shown to be considerable.

Author Contributions

H.P. Whelton, A.J. Spencer, L.G. Do, A.J. Rugg-Gunn, contributed to conception and design, drafted the manuscript. All authors gave final approval and agree to be accountable for all aspects of the work.

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