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Dentifrice Fluoride

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An astute observation by a young dentist in 1901 began the understanding of the role of fluoride ions in tooth decay prevention *(1)* and laid the foundation for one of the most successful public health programs in history. By 1955 academic and industrial researchers had combined their efforts to formulate and commercialize fluoride-containing dentifrice products of demonstrable efficiency. Today, over $3 billion worth of oral care products are sold in North America alone. Meanwhile, researchers continue to discover more clues to the remarkable effectiveness of this novel element.

History

When recently graduated Frederick S. McKay opened his first practice in Colorado Springs, Colorado, he noticed that many of his patients had mottled brown teeth yet were surprisingly free of dental caries (tooth decay). He also found unusually high levels of naturally occurring fluorine in the water supply and surmised a connection between these phenomena.

McKay worked for many years with Grover Kempf of the U.S. Public Health Service and H. V. Churchill of the Aluminum Company of America to test this hypothesis. Later, careful research by H. Trendley Dean of the Dental Hygiene Unit at the National Institutes of Health established that fluoride levels below 1 ppm (part per million) could reduce or prevent caries without the undesirable staining *(2, 3)*.

Using the results of McKay's work, the city of Grand Rapids, Michigan, began an experimental program of fluoridation of its public water supply in 1945. During the following 15 years, the rate of tooth decay among the city's 30,000 schoolchildren was monitored. Tooth decay rates in children born after the onset of the program dropped by 60% *(3)*.

Story of "Crest": The First Fluoride Toothpaste Sanctioned by the ADA

Indiana University researchers in the 1940s had demonstrated that isolated powdered tooth enamel when treated with sodium fluoride is less soluble in acid than untreated enamel *(4)*. Teeth are constantly exposed to acid created by the action of bacteria found in the mouth on sugars present in food. It was hypothesized that fluoride inhibits tooth decay by rendering the outer layer of the tooth less soluble to acid. The effects of different fluorides were tested and one compound appeared markedly more effective than others—stannous fluoride *(4)*. In 1947, Joe Muhler and Grant Van Huysen published results in the *Journal of Dental Research* that demonstrated the effectiveness of stannous fluoride in reducing the solubility of tooth enamel in acid *(5)*. This work stimulated the curiosity of researchers at The Procter & Gamble Company (P&G), which funded further studies *(1, 6)*.

In 1951, after safe levels of tin and fluorine had been established for humans, the Indiana Division of Dental Health launched studies of the efficacy of topical application of stannous fluoride and sodium fluoride to the teeth of children in Bloomington, Indiana. After one year it was clear that stannous fluoride was more effective than sodium fluoride in protecting teeth against cavities.

Dentists carried out parallel work to create a dentifrice that would exhibit the same degree of effectiveness. In 1952, P&G formulated the first test toothpaste containing stannous fluoride, and in 1955 there was enough evidence of its effectiveness for the Food and Drug Administration (FDA) to grant its approval. The resulting product was "Crest", which earned the ADA Council on Dental Therapeutics endorsement in 1960 as "an effective decay preventive dentifrice that can be of significant value when used in a conscientiously applied program of oral hygiene and regular professional care" *(6, 7)*. By 1962, one of every three tubes of toothpaste sold in the United States was a tube of Crest *(6)*.

In a parallel development, work by Ozark-Mahoning Company of Tulsa, Oklahoma (now Ozark Fluorine Specialties), in collaboration with the Colgate-Palmolive Company, led to the adoption of sodium monofluorophosphate in "Colgate MFP™" toothpaste *(8–10)*.

Nearly a half century later, fluoride continues to be the dental profession's main weapon in the battle against tooth decay. Today most municipal water systems add fluoride to their water, and virtually all toothpastes on the market contain fluoride.

What Is Fluoride?

As the 17th most abundant element in the Earth's crust, fluorine, in the form of the fluoride ion, occurs naturally in all water sources, including the oceans. Fluoride used for dental applications is available from two major sources: products containing fluoride in their formulations (topical) and fluorides that are ingested into the body from treated water and other sources (systemic).

Topical fluorides strengthen teeth already present in the mouth, making them more decay resistant. Topical fluorides include toothpastes, mouth rinses, and professionally applied fluoride therapies *(9, 11)*. The significant drop in the level of cavities since 1960 is attributed to the widespread public acceptance of fluoride-containing toothpastes. Other sources of self-applied fluoride are mouth rinses available over the counter and by prescription. The ADA recommends the use

Table 1. Typical Components in Fluoride Dentifrices

Type of Component	Component (%) in Dentifrice		
	Brand A	Brand B	Brand C
Therapeutic	(0.40) SnF2	(0.76) Na_2PO_3F	(0.22) NaF
Abrasive	(39) $Ca_2P_2O_7$ (1) $Sn_2P_2O_7$	(41.80) $(NaPO_3)_x$ (5.00) CaHPO4	(40) Ca_2P_2O7
Humectant	(10) Glycerol (20) Sorbitol	(12.80) Glycerol (14.00) Sorbitol	(30) Sorbitol
Water	(25)	(20.10)	(26.10)
Detergent	(4.60)	(1.50) Sodium lauryl sulfate	(1.00) Sodium monoglycerol sulfonate and sodium alkyl sulfate
Miscellaneous	------- -------	(4.00) -------	(2.70) -------

NOTE: Data from ref *14*.

of fluoride rinses, but discourages use by children under age six because they may swallow the rinse.

Dentists and dental hygienists may give patients fluoride treatments as part of routine dental care. The fluorides added to professionally applied gels, foams, and rinses are more concentrated than those in self-applied fluoride sources, and therefore are not needed as frequently.

Fluoride is typically added to a self-applied dentifrice formulation at the level of about 1000 ppm, even in areas where the water supply is fluoridated. Because the fluoride additives are considered active ingredients, the FDA regulates their presence in toothpaste in the United States. Currently, the FDA permits the use of three sources of fluoride: sodium fluoride, stannous fluoride, and sodium monofluorophosphate *(12)*. To be used in dental care products (toothpaste, mouthwash, and professionally applied topical fluoride treatments), the compounds must be made to U.S. Pharmacopoeia standards. Producers of USP-grade fluorides are regularly inspected and reviewed by the FDA *(12, 13)*.

In formulating dental products, the choice of fluoride used—sodium fluoride, stannous fluoride, or sodium monofluorophosphate—is governed by factors of compatibility and cost. Since the fluoride constituent represents only a minor fraction of the weight of the formulation (typically 0.5%), its choice is usually determined by its compatibility with the other ingredients, most often the abrasive and any other active ingredients that may be present *(12, 14)*. Compatibility aside, the efficacy of the fluoride is largely independent of its source. Typical compositions of toothpastes containing the three fluoride sources are given in the Table 1.

Systemic fluorides are those that are ingested into the body and become incorporated into tooth structures as they form. Their action differs from topical fluorides in several ways (Figure 1). Systemic fluorides are deposited throughout the entire enamel layer of the teeth and provide longer-lasting protection than those applied topically. Systemic fluorides can also give topical protection because ingested fluoride is present in saliva, which bathes the teeth, providing a continuous reservoir of fluoride. Fluoride also becomes incorporated into dental plaque and facilitates remineralization. Sources of systemic fluorides include water, dietary fluoride supplements in the forms of tablets, drops, or lozenges, and fluoride present in food and beverages.

Community water fluoridation, which has been around for more than 50 years, adjusts the fluoride content of fluoride-deficient water to the recommended level for optimal dental health. That recommended level is 0.7–1.2 parts fluoride per million parts water. Water fluoridation has been proven to reduce decay in both children and adults. While water fluoridation is an extremely effective and inexpensive means of obtaining the fluoride necessary for optimal tooth decay prevention, not everyone lives in a community with a centralized, public or private water source that can be fluoridated *(2)*. For those individuals, fluoride is available in other forms.

Dietary fluoride supplements (tablets, drops, or lozenges) are available only by prescription and are intended for use by children ages six months to 16 years living in nonfluoridated areas. The need to take dietary fluoride

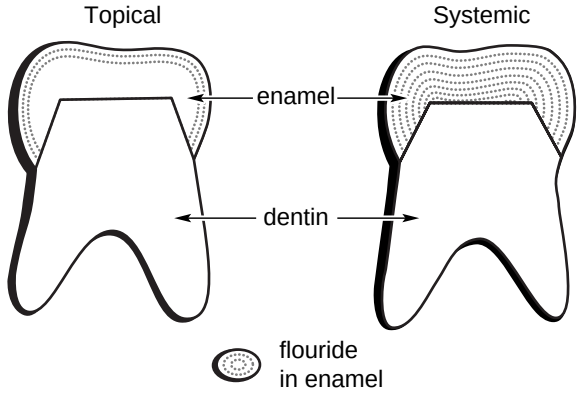

Figure 1. Systemic fluoride is built into the tooth enamel whereas topical fluoride remains largely near the surface *(11)*.

supplements over an extended period of time makes such supplements less cost-effective than water fluoridation; therefore, dietary fluoride supplements are considerably less practical as a widespread alternative to water fluoridation as a public health measure. Fluoride supplements are recommended *only* for children living in nonfluoridated areas.

Fluoridated water may also be present in bottled water, filtered water, and from processed beverages and foods prepared with fluoridated water. It is important to note that the effective prevention of dental decay requires that the proper mix of both forms of fluoride (topical and systemic).

One interesting conjunction of modern dentistry and the role of fluoride ions was summarized in a *Journal* article, The Chemistry of Modern Dental Filling Materials *(15)*. Glass-ionomer cements and the resin modified versions used for dental repair and restoration have been shown to absorb fluoride ions from toothpaste and other fluoride products and release it in clinically useful quantities over periods of months and years. These dental composites seem to act as a type of "storehouse" for the fluoride ion, "taking it up in the presence of high concentrations and releasing it gradually later" *(15)*.

Where Does Fluoride Come From?

The fluoride ion is the only naturally occurring form of the element fluorine. Fluorine is a gas and never occurs in its free state in nature. Fluorine exists only in combination with other elements as a fluoride compound. Fluoride compounds are constituents of minerals in rocks and soil. Water passes over rock formations and dissolves the fluoride compounds that are present, creating fluoride ions, but the concentrations vary widely.

Regardless of the form, commercial fluoride originates as the mineral fluorospar, CaF_2, which is converted by sulfuric acid to hydrogen fluoride (hydrofluoric acid, HF):

$$CaF_2 + H_2SO_4 \rightarrow CaSO_4 + 2HF \quad (1)$$

Sodium fluoride is produced by the neutralization of hydrofluoric acid with sodium hydroxide (eq 2). Stannous fluoride is made by the digestion of tin metal with HF (eq 3), and sodium monofluorophosphate (SMFP) results from the fusion reaction of sodium fluoride with sodium trimetaphosphate at 500 °C (eq 4).

$$NaOH + HF \rightarrow NaF + H_2O \quad (2)$$

$$Sn + 2HF \rightarrow SnF_2 + H_2 \quad (3)$$

$$NaF + NaPO_3 \rightarrow Na_2PO_3F \quad (4)$$

To varying degrees, all three products are soluble in water and release fluoride ions, which can combine with tooth enamel.

How Does Fluoride Work?

Teeth are mineralized tissue. The visible surface of teeth, called enamel, consists of 96–98% hydroxyapatite, $Ca_{10}(PO_4)_6(OH)_2$ (Figure 1). Fluoride is effective in preventing and reversing the early signs of dental caries. Upon exposure to fluoride ion, hydroxyapatite is converted to fluoridated apatite and fluoroapatite:

$$\underset{\text{hydroxyapatite}}{Ca_{10}(PO_4)_6(OH)_2} + F^- \rightarrow \underset{\text{fluoridated apatite}}{Ca_{10}(PO_4)_6(OH)F} + OH^- \quad (5)$$

$$\underset{\text{fluoridated apatite}}{Ca_{10}(PO_4)_6(OH)F} + F^- \rightarrow \underset{\text{fluoroapatite}}{Ca_{10}(PO_4)_6F_2} + OH^- \quad (6)$$

These latter compounds are less acid soluble and serve to protect the tooth from acid formed by the action of bacteria in the mouth on food particles. Acid is formed when the bacteria in plaque digest sugars and carbohydrates from the diet. Repeated acid attacks break down the tooth, which causes cavities. Fluoride also acts to repair, or remineralize, areas in which acid attacks have already begun. The remineralization effect of fluoride is important because it reverses early decay as well as creating a tooth surface that is more resistant to decay.

Fluoride reacts similarly with the hydroxyapatite of dentin, the primary constituent of tooth roots. As roots become exposed with age, they become susceptible to decay and also need protection. Fluoridated water as well as various fluoride products such as toothpaste provide fluoride ions necessary for remineralization.

A Brief History of Toothpaste and Toothbrushes

Toothpaste and toothbrushes have been around for centuries. Toothpaste was used as long ago as 500 B.C.E. in China and India. Modern toothpastes were developed in the 1800s and improvements followed quickly. A dentist called Peabody was the first to add soap to toothpaste in 1824. John Harris added chalk as an additive to toothpaste in the 1850s. In 1873, Colgate mass-produced pleasant smelling toothpaste in a jar. In 1892, Washington Sheffield of Connecticut first put toothpaste into a collapsible tube, called Dr. Sheffield's Creme Dentifrice. By 1896, Colgate Dental Cream was packaged in collapsible tubes. Advancements in synthetic detergents (after World War II) replaced the soap used in toothpaste with emulsifying agents such as sodium lauryl sulfate and sodium ricinoleate.

Toothbrushes, too, have a long history. Early civilizations cleaned their teeth with pig bristles. The ancient Chinese invented natural bristle brushes. French dentists promoted the European use of toothbrushes in the 17th and early 18th centuries. The first mass produced toothbrush was made by William Addis of Clerkenwald, England. The first American to patent a toothbrush was H. N. Wadsworth and companies began to mass-produce toothbrushes in America around 1885. The Florence Manufacturing Company of Massachusetts made an early American toothbrush, the Pro-phy-lactic brush, and was also the first company to sell toothbrushes packaged in boxes.

The first nylon bristle brushes were introduced in 1938. In 1939, the first real electric toothbrush was developed in Switzerland. Squibb first marketed the electrical toothbrush

in the United States in 1960, called the Broxodent. General Electric introduced a rechargeable cordless toothbrush in 1961. Interplak was the first rotary action electrical toothbrush for home use, introduced in 1987.

The Market for Dental Fluoride Today

Most Americans did not brush their teeth until soldiers brought the Army's enforced habit back home from World War II. In slightly more than 50 years, the North American retail market for oral care products exceeded $3 billion *(16)*. Toothpastes, including gels, powders, and polishes, account for over 80% of this quantity. Virtually all of these products incorporate fluoride as an active ingredient. The four principal manufacturers of toothpaste worldwide are Procter & Gamble, Unilever, Colgate-Palmolive, and Beecham. In the U.S. market, Crest and Colgate are the leading brands, followed by Aquafresh, Mentadent, Sensodyne, Close Up, Rembrant, Arm & Hammer, and Ultra Brite. Usage patterns vary widely from country to country and even within the population of a single country. For example, in the United States, about 50% of the population brush twice a day, 10–25% brush more than twice a day, and 30% brush less than twice a day. Americans consume, on the average, 0.9 kg of toothpaste per year *(12)*.

Conclusion

In the past half century, dental care has benefited enormously from the parallel development of fluoride-based dental care products and the widespread adoption of municipal water fluoridation as a public health practice. Whether needed fluoride is obtained through drinking water, supplements, toothpaste, mouthrinses, or fluoride treatments at the dentist office, modern dental health relies on this important and silently effective element.

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