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Multi-function toothpastes for better oral health: a behavioural perspective

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Since the mid-20th century, a great deal of research and development has been directed to improve the quality, effectiveness and functionality of toothpastes. This review considers the technological advances and scientific background to the development of dentifrices for a variety of expressed different purposes, from caries reduction through incorporation of fluoride, through periodontal disease prevention by use of anti-microbials to tooth whitening, breath freshening and reducing hypersensitivity and calculus formation.

Key words: Toothpaste, abrasivity, oral hygiene, fluoride, dentifrice

The Oxford English Dictionary dates usage of the term dentifrice to 1558, defining it as "a powder or other preparation for rubbing or cleansing the teeth"[1]. For centuries the main uses of dentifrice related to cleaning the teeth, removal of unsightly enamel stains, and promoting 'fresher breath.' In the modern era, toothpastes have replaced toothpowders. Today, toothpastes represent by far the most commonly manufactured preparation intended to be used, in conjunction with the toothbrush, for affecting "the accumulation, removal, and the metabolic activities of dental plaque"[2].

Since the mid-20th century, a great deal of research and development has been directed to improve the quality, effectiveness and functionality of toothpastes[3]. With respect to toothpaste quality, this has been accomplished largely by refining, substituting and reformulating the vital yet inert toothpaste ingredients. With regard to increasing the effectiveness and functionality of toothpaste, this is being achieved by adding to toothpaste a variety of safe, more biologically active yet compatible ingredients that may interact chemically with tooth structure, reduce demineralisation, interfere with bacterial adhesion to the teeth, provide antibacterial action, prevent the formation of supragingival calculus, promote remineralisation, and reduce dentinal hypersensitivity. Thus not only are toothpastes being designed and targeted for specific user groups, toothpastes are increasingly being formulated to provide multiple cosmetic and therapeutic benefits. In short, the science and technology underlying the design, composition and manufacture of modern toothpastes have become enormously sophisticated. Dentists are therefore faced with the increasing challenge of advising their patients to make evidence-based choices with regard to the most appropriate and effective toothpaste to use for improved oral health and a better quality of life.

The oral health benefits of toothpastes have been increasingly appreciated around the globe. *Table 1* indicates that the 2006 world-wide sales of toothpaste were estimated to be $14.4 billion USD[4]. Since 2000, the international growth of toothpaste sales has been greatest in Europe (particularly Eastern Europe) and Australasia. In contrast, toothpaste sales in the Americas - North, Central and South – have been relatively flat.

Table 1 World Toothpaste Market, US$ mn

Region	2006	2006	% growth
Asia Pacific	3,328	4,208	20.9
Australasia	136	209	53.7
Eastern Europe	628	1,197	90.6
Latin America	1,837	2,125	15.7
Mid. East & Africa	557	729	30.9
North America	2,103	2,267	07.8
Western Europe	2,546	3,702	45.4
World	11,135	14,437	29.7

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If the objective is to bring the benefit of quality toothpaste use to more people, there are two additional and major challenges to be faced. One is to motivate current users of toothpaste to become more informed, more active and effective users of modern dentifrices. Two is to encourage greater acceptance and accessibility to quality toothpastes in those global regions defined as emerging market economies. In the latter respect, the goal is to make the use of good modern toothpastes and toothbrushes as ubiquitous an oral health habit as it has become in the mature economy countries. To effect such behaviour change would require the application of high quality behavioural science and well-grounded motivational methods, both being important keys to achieving success. A precondition, however, is for both users and potential users of dentifrices to be fully informed about what toothpastes are and what benefits they can bring. Such an educational objective requires dental professionals, the intermediaries in this process, to develop more interest and knowledge about modern day oral hygiene technologies, particularly toothpastes.

Toothpaste composition

The basic ingredient categories that make up toothpaste are shown in *Table 2*. For each category of ingredient, *Table 2* also indicates the approximate composition ranges (w/w%) that may be found across different toothpastes[5-7]. Toothpastes are manufactured as three-phase systems, namely:

- The continuous phase comprising humectants, water and dissolved salts
- The dispersed phase comprising an emulsion of surfactants and flavour oils together with binders (gums) to gel the continuous phase
- The solid phase comprising largely the abrasives that are suspended throughout the continuous phase by the gel network formed with the binder system[7].

Selecting different ingredients within categories, and/or varying even slightly the percent contribution made by each ingredient category, will greatly affect the even most basic physical characteristics of the toothpaste.

To illustrate further the science underlying toothpaste composition and the implicit challenges in formulating toothpastes that users would find practical and easy to use, some ingredient options for just two of the above ingredient categories are displayed in *Tables 3 and 4*. A partial list of possible ingredients under the category of organic thickeners (gums) is shown in *Table 3*. One or more of these ingredients combine with the 'continuous phase', i.e., humectants and water, to give the toothpaste its body when squeezed out of the tube. Users do not like toothpastes where liquids have separated from solids, or pastes that are 'runny' and difficult to control on a brush, or pastes that are stringy creating a mess in uncapping and capping the tube. Ensuring the ideal properties of the toothpaste, that is the paste's body or consistency on the brush, as well as the paste's squeezability and flow are but two extremely important properties that help define the toothpaste's rheology, and that are critical to gaining user acceptance for the product. In fact, optimal rheological properties of toothpaste are essential in that they contribute to the decision making and behaviour by users, determining the acceptance and long-term success of a particular toothpaste.

In terms of user behaviour vis-à-vis a specific toothpaste, the product must also meet or exceed the consumers' taste expectations or experience. *Table 4* displays only a few possible sweeteners and flavours commonly used in toothpaste. Although representing only a very small percentage of the total toothpaste formula, flavouring chemicals may profoundly interact with other ingredients used to make toothpaste. For example,

Table 2 Typical Components of Toothpaste

Ingredients	Wt./Wt. %*
Humectants (e.g., Sorbitol, Glycerol)	40-70
Abrasives	10-50
Water	0.0-50
Buffers/salts	0.5-10
Inorganic thickeners	0.0-12
Organic thickeners (gums)	0.4-2.0
Surfactants	0.5-2.5
Flavours & sweeteners	0.8-1.5
Actives (fluoride, triclosan, Zn, Sn, etc.)	0.2-1.5

Table 3 Organic Thickeners (gums)

Sodium carboxymethyl cellulose
Cellulose ethers
Xanthan gum
Carrageenans
Sodium alginate
Carbopols

Table 4 Sweeteners and Flavours

Sweeteners	Flavours (oils)
Sodium saccharin	Mint
Sorbitol	Citrus
Xylitol	Cinnamon
	Many others

some flavourings may interact significantly with the abrasive system used for the toothpaste. Some volatile flavour molecules may interact strongly with some types of surfactants/foaming agents commonly used in the manufacture of toothpastes. Other flavouring agents have been known to affect the materials used to make the toothpaste tube. It is also well known that certain active ingredients used in a toothpaste (e.g., stannous fluoride and zinc citrate) may be perceived as astringent and could affect the overall flavour of a toothpaste, and hence its longer term acceptability to the user, unless this is controlled by an appropriate choice of flavour ingredients. Importantly, in different regions of the world different flavours are preferred, representing yet another consumer preference (and likely behaviour) that toothpaste manufacturers cannot ignore.

A fuller discussion of toothpaste composition, specifically the many ingredients required for a successful formulation, is beyond the scope of this paper. However, that does not imply that the technical functions of the different ingredients are of minor importance for the achievement of personal oral hygiene and optimal oral health. Indeed, it cannot be stressed enough that high quality toothpastes that meet the sensory needs of the user (i.e., in terms of appearance and taste) are prerequisites if the regular, conscientious practice of oral hygiene is expected. In the sections to follow, this theme will serve as a recurring and unifying principle.

Multiple functionalities in modern toothpastes

Historically, toothpastes were designed to provide a limited set of benefits to the user, typically tooth cleaning and breath freshening. In addition, some specialised purpose toothpastes began to appear, for example those to fight smoker stain or to reduce dentinal hypersensitivity. Very importantly, by 1955 Muhler *et al* reported the first clinical trial of a novel stannous fluoride (SnF_2) containing toothpaste that proved clinically effective in reducing tooth decay[8]. The Procter & Gamble company moved rapidly to market this toothpaste under the name of Crest[9]. For the next 25 years, intensive research and development by the major toothpaste companies focused on developing better anti-caries dentifrices. The research and development agenda followed two streams. One was finding and formulating new and more effective fluoride compounds[5]. Two was directed at refining and enhancing the toothpaste abrasive systems to make them more compatible with the preventive action of fluoride while enhancing the tooth cleaning and polishing properties. Those research programmes were ultimately successful and led to the introduction of sodium monofluorophosphate[10], neutral sodium fluoride[11], and amine fluoride toothpastes[12], and later to the incorporation of several superior and compatible abrasive systems for use in fluoridated toothpaste[13,14].

From that point on, fluoridated toothpastes became the public health standard, and subsequent innovations in dentifrice technology were layered over the caries prevention benefit of fluoride toothpastes[15]. In the mid- to late-1980s, clinical trials were undertaken to that evaluated fluoride toothpastes with additional active ingredients offering anti-bacterial and anti-plaque properties. Other fluoride toothpaste trials were run to evaluate additional chemical agents for the prevention of calculus or tartar build-up. The beginnings of efficacious, scientifically proven, multi-function and multi-benefit pastes began to emerge with the early- to mid-1990s.

In response to these developments, the major toothpaste manufacturers have intensified their research and development efforts to build additional functionalities into their toothpastes[15,16]. *Table 5* lists a number of functions/benefits that have relevance to the public and that toothpaste manufacturers are seeking to incorporate within a single toothpaste.

Table 5 Modern Toothpaste Functions

Caries prevention
• Fluoride delivery
• Demineralization (diminish)
• Remineralization (promote)
Bacterial plaque and gingivitis prevention
Calculus prevention
Tooth whitening (extrinsic stain reduction)
Dentin hypersensitivity reduction
Breath freshening

Designing and producing clinically effective, multifunction toothpastes is an extremely complex undertaking. In formulating them a myriad of basic concerns must be satisfied, including safety, optimal rheology, pleasant flavour, packaging, shelf-life and acceptable cost. Beyond that, the ultimate goal is to ensure that the toothpaste ingredients designed to accomplish each specialised function will remain compatible in a combined or final formulation. That requires for each active ingredient in the formulation to retain its specific activity over time and under various storage conditions, and to do so without compromising the other active ingredients to perform in a clinically effective manner. Through the application of modern science and technology, such a goal is being increasingly realised.

The emerging availability of these multi-function toothpastes provides both advantages and challenges for users. From the potential user's perspective the multifunction dentifrice formulation means more concurrent oral health benefits in one package. Such benefits are available, however, only from a thorough tooth cleaning session, preferably twice a day. Obviously, the user's daily decisions and behaviours are critical in this regard. While multiple oral health benefits may be a plus for many, the multi-function toothpastes are likely to be marketed as 'premium products', and may therefore demand a higher price. Many potential users will turn to their dental professional and may ask three simple questions:

- Do these new multi-function toothpastes really work as advertised?
- Are they worth the extra cost?
- Do you use a multi-function paste yourself, and if so, which one?

Dental professionals can answer the third question very easily. However, many dentists are hard-pressed to answer the first two questions that focus on the efficacy and value of the newer, multifunction toothpastes. What follows is a series of brief descriptions pertaining to the several oral health benefits one might expect from appropriate use of contemporary multi-function toothpastes.

Caries prevention with fluoridated toothpastes

It has been well known for over half a century that in properly formulated toothpastes fluoride is the key active ingredient for the prevention of dental caries[3,9,15,17]. Fluoridated toothpastes are now widely available around the world, and in some countries represent over 90% or more of toothpastes sold[18]. Indeed, properly formulated fluoridated toothpastes are the base or standard from which more specialised or multi-function toothpastes are developed. Recently Marinho *et al* and Twetman *et al* conducted and published excellent systematic reviews of caries clinical trials[17,19]. Their analyses, using the Cochran approach, were based on the most stringent scientific criteria that can be applied for extracting evidence from the vast literature on this subject. After a careful consideration of quality-weighted evidence, the authors concluded that fluoridated toothpastes continue to be effective in caries prevention, particularly for children, and can be expected to achieve a 25% caries increment reduction (mean prevented fraction) versus non-fluoridated toothpastes. Twetman *et al.*[17] go on to state that "toothbrushing with fluoride toothpaste needs continuous promotion and reinforcement in all age groups."

Essentially the same point was made at a recent meeting of three eminent organisations involved in public dental health and research. In November 2006 the Global Fluoride Consultation, jointly organised by the FDI, IADR and WHO, brought together dental researchers from academia and industry[20]. The statement issued after three days of deliberation concluded that, "Taking account of the scientific evidence, as well as several WHO World Health Assembly Resolutions and other technical reports, the experts reaffirmed the efficiency, cost effectiveness, and safety of the daily use of optimal fluoride."

While a great deal is known and much clinical experience has been accumulated about fluoridated toothpastes, there remain key points that require ongoing attention by dental professionals and the public alike. First, as shown in *Table 6*, there are four fluoride agents used in dentifrices to deliver the fluoride ion[9]. These agents together with their approximate w/w% concentrations are 0.66% amine fluoride (NH_4F), 0.245% sodium fluoride (NaF), 0.76% sodium monofluorophosphate (Na_2FPO_3), and 0.454% stannous fluoride (SnF_2). Although these percentage composition figures necessarily vary, they all make available 1,000-1,250ppm fluoride ion to the dentifrice. High quality products can be made with all four of these fluoride sources, although the dentifrice formulations will vary dramatically to account for the very distinct chemical behaviours associated with each individual fluoride agent.

Table 6 Ionic Fluoride Concentration in Dentifrices with Differing Fluoride Species[a]

Fluoride Species	500 ppmF	1000 ppmF	1500 ppmF
NaF	0.11%	0.22%	0.33%
NaFPO3	0.38%	0.76%	1.14%
SnF2	0.22%	0.45%	0.67%
NH4F	0.33%	0.66%	0.99%

[a] nominal levels; actual levels chosen may be lower to ensure maximum levels do not exceed regulatory limits.

Second is the fluoride ion concentration. Most commonly, toothpastes are formulated with a fluoride ion concentration of between 1,000 and 1,500ppm fluoride ion[9]. In recent years considerable attention has been given to so-called paediatric dentifrices, formulated with a fluoride ion concentration of 500-600ppm F[21]. In contrast, for highly caries susceptible adults and medically compromised patients, dentists are also able to prescribe, generally for 30-day usage, high fluoride concentration toothpastes that may deliver up to 5,000 ppm of fluoride or more[22,23]. Patients undergoing oral cancer therapy or suffering from temporary dry mouth conditions would be candidates for such preparations. Dental professionals recommending fluoride dentifrices for adults should keep in mind that caries prevention effectiveness exhibits a dose-response relationship[17,24].

Third, for the fluoride in dentifrice to be maximally effective requires that the fluoride formula is compatible with the ingredients of the toothpaste. This applies particularly to the paste's abrasive system. For example, for neutral NaF toothpastes, a common abrasive compound such as calcium carbonate would bind free fluoride ion, reducing the effective concentration of active fluoride in, and caries preventive efficacy of, such a toothpaste[25]. Such a fluoride binding process is time and storage condition dependent. On the other hand, calcium carbonate is a perfectly acceptable and effective toothpaste abrasive agent when used in conjunction with Na_2FPO_3 as the toothpaste's fluoride formulation. Other abrasive materials that may be added to tooth paste include precipitated silica, calcium phosphates, aluminium oxide, and pumice. The fluoride ion's compatibility with any of these abrasive materials, whether singly or in combination, must be convincingly established by the toothpaste's manufacturer.

A fourth consideration in recommending fluoride toothpastes is to factor in the age of the user. For some time it has been known that children under six years of age frequently have an immaturely developed swallowing reflex, which makes it difficult to expectorate the dentifrice in the mouth after brushing is completed[26-29]. The tendency is for very young children to swallow a significant portion of the toothpaste in the mouth. This, together with fluoride ingested from other dietary components, has been associated with increased risk of very mild or mild enamel fluorosis. For some time dental associations, public health agencies and the toothpaste manufacturers have cooperated in recommending that children under six years of age use only a 'pea-sized' amount of tooth paste on the brush to reduce toothpaste ingestion. As indicated above, some manufacturers have gone further and have introduced 'children's or paediatric' dentifrices containing lower concentrations of fluoride, i.e., 400-600ppm F.

In summary, the evidence accumulated over more than 50 years of scientific research into the anti-caries benefit of fluoride toothpaste, unequivocally shows that regular tooth brushing, preferably at least twice per day, with a properly formulated fluoride toothpaste will reduce dental caries incidence and thus convey an essential oral health benefit.

Chemotherapeutic prevention of bacterial biofilm and gingivitis

Populated with acidogenic and aciduric micro-organisms, bacterial biofilm on the teeth (dental plaque) is a key aetiological contributor to three undesirable dental conditions: Dental caries, gingivitis and its sequellae, and calculus formation. Significantly controlling and reducing the dental biofilm would ameliorate all three conditions. Dentifrice is a logical vehicle with which to introduce appropriate antibacterial and effective non-antiseptic agents to intervene against micro-organisms as well as extracellular matrix that form and constitute the harmful biofilm on the teeth. Many agents have been proposed, some of which are shown in *Table 7* adapted from Cummins[30].

The strongest antibacterial agent identified in the table is the bisguanide antiseptic chlorhexidine gluconate, which inhibits bacteria by disrupting their cell wall causing leakage from the bacterial protoplasm. Very promising in early studies, this agent has been tried in various dentifrice, mouthrinse, and dental varnish systems. Though effective when delivered via the first two vehicles, the strong staining action on dental tissues has proven to be a major barrier to chlorhexidine's inclusion in dentifrices intended for daily use[31-34].

In contrast, the divalent metal ion compounds, stannous fluoride and zinc citrate, as well as the non-ionic antiseptic, triclosan, have all found their way into numerous dentifrice formulations, and all three have been effective in the clinical setting with respect to bacterial biofilm control and gingivitis prevention.

Stannous fluoride, the first fluoride source to be incorporate into a successful anti-caries toothpaste, eventually fell out of favour due to its propensity to stain the teeth[35-38]. More recently, however, SnF_2 in a newly stabilised form has returned to toothpastes as both an anti-caries and as an anti-plaque agent. Fresh reports on stannous fluoride's efficacy in preventing plaque and gingivitis are therefore beginning to appear once again[39-41]. These confirm earlier reports of stannous fluoride's antibacterial properties in the oral environment. Although not as widely used, toothpaste formulations incorporating a combination of amine fluoride and stannous fluoride have also demonstrated limited anti-plaque and anti-gingivitis effects.

Zinc citrate has also been effective in reducing biofilm in clinical trials, but in the past its mildly astringent characteristic has presented taste concerns for some users[30,42,43]. More recently, considerably advanced formulations have been developed that have overcome the earlier taste concerns with zinc citrate[44]. Moreover, enhanced zinc citrate containing toothpastes have been formulated to include 0.3% triclosan[45,46]. These formulations have shown good anti-plaque and anti-gingivitis efficacy.

Toothpaste formulated with triclosan and a copolymer of polyvinyl methyl ether and maleic acid (Gantrez) have consistently demonstrated antibacterial efficacy intra-orally[47-50]. The Gantrez product facilitates increased

Table 7 Candidate Antimicrobial Agents to Combat Dental Biofilms

Agent	Clinical Status
Cetyl pyridinium chloride	Poor efficacy
Chlorhexidine	Good efficacy
Zinc citrate	Efficacious
Stannous fluoride	Efficacious
Triclosan	Efficacious
Thiocyanate/peroxide	Low efficacy

substantivity for the triclosan. When incorporated in toothpaste at the 0.3% concentration, triclosan/Gantrez has demonstrated good efficacy both dental plaque prevention and gingivitis reduction.

In summary, toothpastes that have incorporated suitable antiseptic agents (e.g. chlorhexidine or triclosan) or certain divalent cationic metal compounds (e.g. stannous fluoride or zinc citrate), alone or in combination, have demonstrated clinically relevant efficacy in terms of plaque control and gingivitis prevention. Over time these benefits can be expected to contribute to reduced gingival inflammation, decreased gingival bleeding and generally improved gum health[51].

Preventing and controlling calculus formation

Theoretically, successful intervention against harmful organisms in the biofilm and reduction of dental plaque should reduce supra-gingival calculus formation and build-up. But in spite of the successful inclusion of antibacterials in modern dentifrices, such a tidy outcome has not been observed. This led toothpaste manufacturers to experiment with agents that interfered with mineral nucleation and growth, on both the salivary pellicle as well as in plaque fluids already supersaturated with respect to calcium and phosphates. *Table 8* displays several agents that are well known as crystal growth inhibitors, including pyrophosphates, diphosphonates hexametaphosphates, zinc citrate, zinc chloride and Gantrez acid, among others[52,53]. All of these agents have found their way into modern dentifrices, and in clinical trials conducted to date have consistently exhibited clinically relevant reductions in calculus formation. Calculus reduction percentages obtained in these studies ranged from 5-50%[53].

Table 8 Agents for Calculus Inhibition

Pyrophosphates
Diphosphonates
Polyphosphates
Hexametaphosphate
Zinc citrate
Zinc chloride
Gantrez acid

White makes the interesting point that in the 1970s there was considerable concern that agents interfering with mineral nucleation to prevent calculus formation might also be expected to diminish remineralisation of early caries lesions, as per the demineralisation-remineralisation model then emerging to explain the dynamics of caries initiation and prevention. Careful attention to this issue indicated that the daily renewal of fluoride from the dentifrice to the plaque fluid on the enamel surface "reversed the negative effects of inhibitors on remineralization"[54]. In a series of more detailed studies, Featherstone and colleagues confirmed that at the levels demonstrated to reduce calculus formation, the introduction of mineralisation inhibitors into fluoridated toothpastes presented no adverse effect on the anticaries properties of the fluoride dentifrices[55].

Tooth whitening by prevention and reduction of extrinsic stains

In many regions of the world the public has become more interested in the cosmetic benefits derived from a healthy natural dentition. This is most readily apparent from the increased demand for orthodontic care and for products/treatments that whiten teeth. Dentifrices can be formulated to provide a measure of tooth whitening through their potential for preventing extrinsic stain formation or by effecting the removal of existing extrinsic stain from tooth enamel. Extrinsic stains on enamel are generally the result from adsorption of chromagens to the salivary pellicle film existing on the teeth[56-58]. Chromagens most typically come from dietary products such as tea or red wine, from preparations containing certain metallic salts, and also from tobacco use.

In recommending a stain removing/whitening dentifrice to patients, dentists should first ensure that they have a good understanding as to the source of the staining[59]. Once the aetiology is properly understood, the alternative treatment priorities should be considered. Is the patient brushing their teeth with recommended frequency? Is the correct technique being employed? Is there a possibility that enamel or dentine erosion and attrition may play a role? Is dentinal sensitivity a problem? Can the aetiological or predisposing factor(s) be modified? In general, focusing on improved tooth brushing habits and combining that with a modern whitening dentifrice is a conservative and tooth-friendly first option in seeking to control and diminish dental stain extent and intensity.

Table 9 shows three groups of agents that may be formulated into dentifrices for the purpose of preventing and/or removing extrinsic enamel stains. These three approaches rely on:

- Carefully calibrated mixtures of abrasive agents
- Chemical agents active on the enamel surface and/or pellicle that reduce stain molecule adhesion or desorb already attached stain molecules
- Bleaching products such as low concentrations of stabilised hydrogen peroxide or analogous oxygen emitting agents[57,58,60].

Table 9 Tooth Whitening Agents

Abrasive agents
• Dicalciumphosphate dihydrate
• Calcium pyrophosphate
• Calcium Carbonate
• Hydrated silica
Chemical agents
• Surfactants (e.g., SLS)
• EDTA
• Citrates
• Pyrophosphates
• Polyphosphates (Hexametaphosphate, Tripolyphosphate)
Bleaching Agents
• Hydrogen peroxide
• Carbamide peroxide

In the main, abrasives used in toothpastes represent three broad categories:

- Phosphates, specifically dicalciumphosphate dihydrate and calcium pyrophosphate
- Carbonates, specifically sodium bicarbonate and calcium carbonate
- Hydrated silica[14].

The key parameters in all cases include the hardness of the mineral employed for the abrasive, the particle size range and number in the mixture of abrasive particles employed, and the particle shape, particularly in terms of particle edges. As indicated earlier, abrasive materials that incorporate calcium tend to bind the ionic fluoride in toothpastes. For that reason, in the early fluoride toothpastes calcium pyrophosphate was heat treated to reduce its interaction with fluoride. In the case of toothpastes employing calcium carbonate or chalk-based abrasives, the fluoride formulation was changed to sodium monofluorophosphate, as this form of fluoride was only hydrolysed once the toothpaste was exposed to the saliva and its enzymes in the mouth. Hydrated silica is the most inert of the three abrasive materials, and it has become the most commonly used abrasive. However, hydrated silica is also the most expensive of the three materials, a factor that may be reflected in the ultimate cost of the toothpaste.

Dentifrices relying on abrasive systems for extrinsic stain prevention or removal will generally employ a mixture of abrasive materials to form an abrasive system. An example of such a system is one where a certain quantity of perlite has been added to the main abrasive being used[61,62]. Perlite is a highly processed amorphous mixed glassy silicate that is milled to produce fine plate-like particles that combine superior stain removal and polishing properties, in conjunction with relatively low abrasivity. Whether added to toothpaste with a silica-based abrasive system or one based upon calcium carbonate, perlite abrasive enhancement appears to have achieved clinically superior extrinsic stain removal[62].

In recommending a tooth whitening dentifrice, dental professionals should inform themselves as to the relative dentine abrasivity (RDA) value for the specific toothpaste in question. It is also useful to be aware that most such toothpastes have RDA values of between 90 and 150. These values all fall well below upper RDA limits recommended by ISO standard 11609 (250), the US Food and Drug Administration (200) and the American Dental Association (250). Periodically updated information on toothpaste RDA values can be found at the epinions.com website[63]. Dental professionals also need to be mindful that abrasive-based tooth whitening systems are least effective where toothbrush access or action is most restricted, such as enamel pits and fissures, interdental surfaces, and the enamel areas along the gingival crevices.

Dentifrices relying on the action of chemical agents for stain prevention or removal will usually incorporate selected compounds from a list that includes surfactants, enzyme systems, EDTA and citrates, pyrophosphates, diphosphonates and polyphosphates[64-66]. Some of the most common surfactants include sodium lauryl sulfate and sodium n-lauryl sarcosinate that can act by solubilising and flushing water insoluble stain molecules from the pellicle surface[67]. EDTA and citrates may desorb stain molecules from pellicle and enamel surfaces by chelating calcium from the chromagen harbouring pellicle, which can then be more effectively attacked by surfactants. Among the various phosphates, it has been demonstrated that polyphosphate, especially hexametaphosphate, may be relative more effective in its surface binding chemistry relevant both to the blocking of stain molecule receptor sites and to the desorption of stain molecules from pellicle and enamel surfaces[57,68,69].

Currently only a few dentifrices rely on bleaching ingredients to counteract the stain trapped on the salivary pellicle and enamel surfaces. But those that do employ bleaching technology tend to rely on formulations that incorporate hydrogen peroxide, and occasionally other oxygen generating compounds[70,71]. Several of these formulations rely on dentifrice formulation chemistry that incorporate low amounts of water on a w/w% basis. However, formulations incorporating peroxide stabilisation technologies and dual delivery systems have also been developed. When tested in the field, some peroxide containing toothpastes have been found clinically effective in reducing extrinsic enamel staining[72]. In many countries, however, peroxide containing toothpastes have not been approved as over-the-counter (OTC) products accessible to the general consumer.

The balance between tooth cleaning and tooth abrasion

Nearly 60 years ago Kitchin and Robinson asked the provocative question, 'How abrasive does a toothpaste need to be?'[73]. Their considered response was, "One should use only as much abrasion as necessary to clean one's teeth." A pioneer in this field, Robinson always felt that it was incumbent on dental professionals to help patients by recommending dentifrices based on clinical needs. In this respect, Forward may be consulted for modern-day guidance for dental professionals to consider[74].

Periodically, articles appear that implicitly question whether there is any rationale in using toothpaste to clean the teeth. Almost inevitably a caution is sounded about the abrasive nature of toothpastes[75,76]. While dental professionals should always be aware that toothpastes contain cleaning abrasives, they must also understand that there are tradeoffs to consider.

First, most indexes of toothpaste abrasivity focus on an index based on dentin abrasion, the so-called RDA test[77]. The numbers from that test signify relative placement among toothpastes with respect to abrasive potential, but do not quantify dentine material lost. Moreover, it has been shown that abrasivity rankings of enamel, a material many times harder and abrasion resistant than dentine, can deviate considerable from the RDA rankings[78]. Evaluating toothpastes abrasivity vis-à-vis enamel can certainly be guided by the RDA results, but other considerations identified below will also come into play.

Second, when dentinal or cervical abrasion does occur, the aetiology is most likely to be a combination of toothbrush bristle stiffness, tooth brushing technique, toothpaste abrasivity, and possibly the existence of significant dental erosion[79-81]. The relative contributory weights of these four factors are far from clear.

Third, as shown by Stookey, Burkhard and Schemehorn[82] and by Wulknitz[78], there is a significant distinction between the cleaning effect of a toothpaste and abrasion ascribed to the toothpaste. For example, Wulknitz evaluated 41 European toothpastes, measuring both their RDA and their PCR (pellicle cleaning ratio) and uncovered only a moderate correlation coefficient of 0.66. This finding is congruent with that of Stookey and his colleagues.

Fourth, the link between the *in vitro* RDA test and the dentinal and cervical abrasion as seen *in vivo* has not been well defined. In that regard, the *in situ* tests relying on polished dentine or enamel chips mounted in full or partial dentures are a step in the right direction[79]. Hannig *et al* have commented on analogous disparities relative to the protection offered against abrasion by salivary pellicle[83,84].

Fifth, in the developed countries the chemistry, chemical engineering and quality control of toothpastes has become ever better. Abrasive formulations are now more sophisticated, and tend to emphasise cleaning and polishing functions. The increased use of refined hydrated silicas, and the development of the carbonate/perlite combination as toothpaste abrasives are good examples of increasingly better engineered dentifrices[67,78,85].

Sixth, it is all too frequently overlooked that the users of toothpaste have an enormous choice available to them, as compared to the situation of just a few decades ago. The opportunity to choose a less abrasive dentifrice has been much expanded. For 41 European dentifrices evaluated in 1995, the RDA values ranged from 29 to 194. Of these pastes, 80.5% had an RDA value of under 100. All pastes met the ISO 11609 standard. Among 49 North American toothpastes, the RDA values range between 30.5 and 200[63]. Fully 25 of the dentifrices had RDAs ranging from 35-95, and only two fell into the 175-200 range, an abrasivity level still considered acceptable by ISO, US FDA and the American Dental Association standards.

Reducing dentine hypersensitivity

Dentine or cervical hypersensitivity is a common clinical problem that seems to predominate where exposed dentine has lost the protection of enamel, cementum or a smear layer, leaving open dentinal tubules to be directly exposed to the oral environment[86]. In recent years it is being suggested that the increased use of acidic beverages and juices has promoted softening of enamel and dentine in the cervical areas of the tooth, and that the intensive brushing of the softened or eroded enamel/dentine can lead to significant wear of tooth structure, further contributing to exposed dentine[87].

Although the aetiology and mechanisms of dentinal hypersensitivity have not been fully defined, a consensus currently exists that the 'hydrodynamic theory' of dentinal pain offers the most credible explanation[88]. Dentinal hypersensitivity has been managed by both professional treatment and the use of at-home regimens. For the latter purpose, specific dentifrices designed to combat dentinal or cervical hype sensitivity have existed for several decades[89,90]. These pastes were formulated empirically, offering lower abrasivity and containing a variety of active ingredients. As shown in *Table 10*, these agents had three aims:

- Occluding the dentinal tubules using mineral salts (e.g., strontium chloride, potassium oxalate, stannous fluoride)
- Occluding the tubules using protein precipitants (formaldehyde and glutaraldehyde)
- Desensitising nerve fibres in the dentinal tubules (potassium nitrate)[91,92].

In addition, patients were frequently instructed to use a softer toothbrush and to improve their tooth brushing technique, particularly if they had been using harder toothbrushes and the horizontal scrubbing method.

Table 10 Desensitising Agents for Dentine Hypersensitivity

Dentinal tubules occlusion by minerals
• Strontium chloride
• Potassium oxalate
• Stannous fluoride
Dentinal tubules occlusion by protein precipitation
• Formaldehyde and Glutaraldehyde
Nerve fibre transmission blockage
• Potassium Nitrate

Table 11 Breath Freshening Agents

Essential oils (intense flavourings)
Zinc salts
Sodium bicarbonate (> 20%)
Triclosan

Recognising that maintaining multiple single-purpose dentifrices in the home may represent challenges, some of the newer multifunction toothpastes have been designed to incorporate the reduction of dentinal hypersensitivity as a distinct and additional benefit[93,94]. This is accomplished by formulating a toothpaste with a relatively lower abrasivity (RDA) that will still result in clean and well polished enamel/dentine surfaces. To further enhance efficacy, these multifunction toothpastes are formulated with fluoride and other remineralising agents to enhance caries prevention and to counteract the occurrence of dental erosion, the prevalence of which has been increasingly reported in some countries[95,96]. To successfully create such multi-function toothpastes, the challenge for the manufacturers has been to combine the various ingredients in a manner that assures compatibility, expected activity, and substantivity, while allowing for some of the anticipated vagaries in storage and handling.

Controlling breath malodour with toothpastes

Breath malodour, also known as halitosis, is an oral health concern for many individuals. The pervasiveness of that concern is in part responsible for the widespread use of breath freshening mints, gums, and mouth rinses. The science underlying the causes of oral malodour is quite complex. Certainly the origins of the condition can be linked to the formation of volatile sulphur compounds and other volatile organic acids by certain anaerobic bacteria in the mouth[97-99]. Anaerobic microorganisms that digest protein substances are particularly suspect. It has also been shown that bacteria residing on the posterior portions of the tongue seem to contribute considerably to the breath malodour problem.

Conscientious and regular oral hygiene is basic to the prevention and control of breath malodour. In the dentate mouth, that requires correct tooth brushing and flossing techniques. In addition, it will be useful to brush or gently scrape the posterior third of the tongue to remove desquamated mucosal cells and bacteria residing there.

In recent years dentifrice manufacturers have evaluated methods to incorporate breath freshening technologies into their formulations (*Table 11*). This work appears to be in its early stages. In the main it relies on incorporating one or a combination of the following four constituents in toothpaste: essential oils for stronger flavourings, zinc and stannous salts as antibacterial agents, triclosan as an antibacterial, and higher levels of sodium bicarbonate as part of the abrasive system. When evaluated in clinical trials, most of these four types of breath freshening toothpastes appear to deliver a favourable organoleptic response for up to three hours in comparison to that provided by control toothpastes[100-103]. Considerably more research is needed to provide toothpastes with a superior and longer-lasting breath freshening function.

Herbal and antioxidant enriched toothpastes

The demand for intraoral, over-the-counter dental products that incorporate natural substances, herbs and antioxidants appears to be increasing. As a result dentifrices are beginning to be formulated to incorporate one or more such substances. While still few in number, some of these toothpastes have been evaluated to determine if they provide specific oral health benefits to the user.

When herb containing toothpaste are subjected to comparative studies with positive controls, it appears that their performance does not appear to generate a measurable, incremental benefit over the positive control[104-106]. In the case of antioxidants added to toothpastes, some preliminary work has been reported on cell cultures *in vitro*. Initial results have been reported as encouraging, but replication and confirmation with larger studies are urgently required[107,108]. Two recently reported clinical studies compared the efficacy of a positive control toothpaste containing 0.3% triclosan with a toothpaste containing both 0.1% vitamin E acetate and 0.5% sunflower oil (with vitamin F)[109]. This formulation was compared to a positive control. Run for a three-week period, the study followed and evaluated a total of 93 subjects. The clinical objectives focused on anti-plaque and anti-gingivitis effects. It was found that after 3 weeks (study 1) and 9 weeks (study 2) both toothpastes had achieved similar and statistically reductions in plaque and gingivitis levels. This demonstrated that the addition of these two vitamins and their carrier products did not interfere with the efficacy in biofilm and gingivitis control. There continues to be considerable interest in oral health products incorporating herbal and antioxidant ingredients, and needed research is underway in several centres.

Good toothpastes and good oral hygiene behaviours

In most parts of the world, countries are experiencing or can expect that an increasing portion of their populations will retain more of their natural dentition for life[110-112]. One might at least speculate that the increased use of ever improving dentifrices has contributed significantly to the promotion of personal oral health. Certainly the reduction of caries, among children, adults and the elderly, is due in significant part to the benefits of fluoridated toothpastes. The anti-plaque, anti-gingivitis and anti-calculus benefits of modern toothpastes also are also likely to be contributing factors to the retention of the natural dentitions.

Beyond that, dentifrices have firmly established themselves as vehicles for effective extrinsic dental stain removal and as tooth whitening formulations. In addition, dentifrices can play a significant role in controlling and reducing dentin hypersensitivity and simultaneously remineralising areas of enamel/dentine erosion. The desire to start each morning with fresher breath is also a daily objective for billions of people around the world, one facilitated in part by toothpaste

The theme of this paper has been to suggest that modern, multi-function toothpastes offer the public more benefits than ever before. This implies that it is in the public's self-interest to continue to embrace high quality dentifrices and toothbrushes, as well as other superior oral hygiene products and practices, to enhance further its oral health and its quality of life. Indeed, there should be little surprise that persons increasingly gravitate to the modern dentifrices available today. The major driver for this is that many of the above-noted benefits can be gained concurrently by the thoughtful and conscientious use of top quality multi-function toothpastes and well-matched toothbrushes.

One may speculate that more persons are ready for such toothpastes, but they may still be looking for the knowledge that will inform, motivate and guide them on the path to better personal oral hygiene behaviour. How to close this information and motivation gap? A key step might be to reduce the outdated thinking, still expressed by many, that 'most toothpastes are about the same.' This mindset is not supported by science, and it would be a positive step to change it. More dental professionals would do well to become more proactive about their patients' oral hygiene and long-term prevention. But with specific regard to toothpastes, the concern is that too few of today's dental health professionals are fully aware of the science involved: i.e., what are modern dentifrices made of, how do they function, and how do they actually perform when properly used?

Without contradicting the main theme developed above, there are strong reasons for maintaining specialised toothpastes in the marketplace. Reference has already been made to paediatric toothpastes formulated with a fluoride concentration in the 400-600ppm fluoride range. It was also pointed out above that toothpastes containing 5,000ppm of fluoride, or even higher concentrations, may be recommended or prescribed for limited use among high caries risk patients. Such pastes may also play a role where dramatic, short-term intervention is required to remineralise tooth surface areas presenting with signs of enamel erosion.

Turning to the industry side of the equation, by shifting their product lines toward reliable multi-function, multi-benefit toothpastes, the better dentifrice manufacturers generally appear to be moving in the right direction. By packaging several discernable oral care functions into one dentifrice product, industry has made things significantly easier for the consumer by giving him/her a high quality, all-in-one product at a very competitive price. Clearly, the newer multi-function toothpastes cost the buyer considerably less than the aggregate cost of the separate specialty dentifrices they replaced.

The issue of toothpaste cost deserves additional attention because price will determine access to toothpastes, especially in the emerging market economies of the world. The need for fluoridated toothpaste is particularly critical in many EME countries where water fluoridation may be impractical, where salt fluoridation has not yet gained traction, and where the infrastructure for dental public health services may be underdeveloped. Recent work by the non-governmental organisation, Aide Odontologique Internationale, has well described the need for greater attention to dental public health in EME nations. Dental caries prevention programs focused on fluorides, including fluoridated toothpastes, feature prominently in some of the AOI initiatives[113,114].

There is an area where the dentifrice industry could perhaps do more, namely in communicating more about its products to dental professionals and to those consumers who are interested in the science and technology underlying effective toothpastes. As distinct from *in vitro, in situ,* and clinical trial studies with finished products, it is striking just how little of the basic information about toothpastes is provided in the scientific literature pertaining to dentistry, and how little space and time is devoted to this subject in most dental school curricula. Most dental professionals, like consumers, must look on the toothpaste packaging to learn what the products' functions and major specifications are. To the degree it exists, the packaging print is excruciatingly small, and the information is relatively generic and minimal. It is not necessary to reveal legitimate trade secrets, but fuller, basic information about the toothpaste, its main components and capabilities are essential. Otherwise, dental professionals will continue to remain in the shadows when it comes to advising as to what, how and why a particular brand of toothpaste can contribute to personal behaviour change that will improve the toothpaste user's quality of life.

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