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SUPPLEMENT

Functional foods/ingredients on dental erosion

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Introduction

Dental erosion is defined as the loss of tooth substance by a chemical process (acid exposure) that does not involve bacteria [91]. With the decline of the prevalence of caries, considerable attention has been focused on tooth erosion. Dental erosion is a multifactorial condition: the interplay of chemical, biological and behavioural factors, which is crucial and helps to explain why some individuals exhibit more erosion than others. Erosive tooth wear can be caused by intrinsic or extrinsic acid, or the combination of both. There is some evidence that the presence of dental erosion is growing steadily. In the United Kingdom, the prevalence of erosion was shown to have increased from the time of the children's dental health survey in year 1993 compared with 1996/1997 [76]. In another UK study, the progression of erosion was investigated: 1,308 children were examined at the age of 12 and again 2 years later. In this study, 4.9% of the subjects at baseline and 13.1% 2 years later had deep enamel or dentine lesions. Twelve per cent of erosion-free children at 12 years developed the condition over the subsequent 2 years. New or more advanced lesions were seen in 27% of the children over the study period [26]. The progression of erosion seems to be greater in older adults (52–56 years) compared with younger (32–36 years) and has a skewed distribution [66].

Currently, increased tooth erosion has been largely linked to the increased consumption of acidic foods and drinks. To reduce or prevent erosive demineralization, strategies have been performed in the laboratory and clinic that are directed at the modification of the chemical, biological and behavioural factors involved in the aetiology of erosion. As dietary modifications are less patient-dependent, more interest has been paid to the erosion-decreasing potential of foods or beverages by various additives. The objective of this overview is to summarize the effective strategies for dietary modification to prevent dental erosion.

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Diagnosis

To diagnose erosion, dental professionals have to rely on clinical appearance, as there is no device available for its detection. The teeth should be dried thoroughly and be well illuminated to reveal minor surface changes. The appearance of smooth, silky-glazed, sometimes dull, enamel with the absence of perikymata and intact enamel along the gingival margin are typical signs. It has been hypothesized that the preserved enamel band along the oral and facial gingival margin could be due to some plaque remnants, which could act as a diffusion barrier for acids. This phenomenon could also be due to an acid neutralizing effect of the sulcular fluid [67]. The clinical examination should be carried out systematically using a simple but accurate index. This is a difficult task to achieve, as an index with a too fine grading shows a small inter- and intraexaminer reliability [62], and vice verse an index with a too rough grading is not able to assess small changes. The initial features of erosion on the occlusal and incisal surfaces are the same as previously described. Further progression of occlusal erosion leads to rounding of the cusps and restorations rising above the level of the adjacent tooth surfaces. In severe cases, the entire occlusal morphology disappears.

Table 1 Criteria for grading erosive wear (Bartlett et al. 8)

Score	
0	No erosive tooth wear
1	Initial loss of surface texture
2*	Distinct defect, hard tissue loss < 50% of the surface area
3*	Hard tissue loss ≥ 50% of the surface area

* In scores 2 and 3, dentine is often involved

The Basic Erosive Wear Examination (BEWE) provides a simple scoring system that can be used with the diagnostic criteria of all current indices [8]. The most severely affected surface in a sextant is recorded with a four level score (Table 1). The maximum score per subject is 18.

It is sometimes challenging to distinguish between the influences of erosion, attrition and abrasion during a clinical examination. Attrition-affected areas are often flat, have glossy areas with distinct margins and corresponding features at the antagonistic teeth. Facial erosion should be distinguished from wedge-shaped defects that are located at, or apical to, the enamel–cementum junction. The coronal part of wedge-shaped defects ideally has a sharp margin and cuts at a right angle into the enamel surface, whereas the apical part bottoms out to the root surface. Thereby, the depth of the defect exceeds its width.

Risk, preventing and modifying factors

There are many factors involved in the erosive tooth wear process. Figure 1 shows the different predisposing factors and aetiologies of the erosive condition. The interplay of all these factors is crucial and helps to explain why some individuals exhibit more erosion than others do, even if they are exposed to exactly the same acid challenges in their diets.

Biological factors

Biological factors such as tooth structure and positioning in relation to soft tissues and the tongue are related to dental erosion development. A very important biological parameter is saliva. The acquired pellicle may protect against erosion by acting as a diffusion barrier or a perm-selective membrane that prevents direct contact between the acids and the tooth surface, thereby reducing the dissolution rate of dental hard tissue. When an acidic solution comes in contact with enamel, it must first diffuse through the acquired pellicle, and only thereafter can it interact with the enamel. The acquired pellicle is an organic film that is free of bacteria and covers oral hard and soft tissues. It is

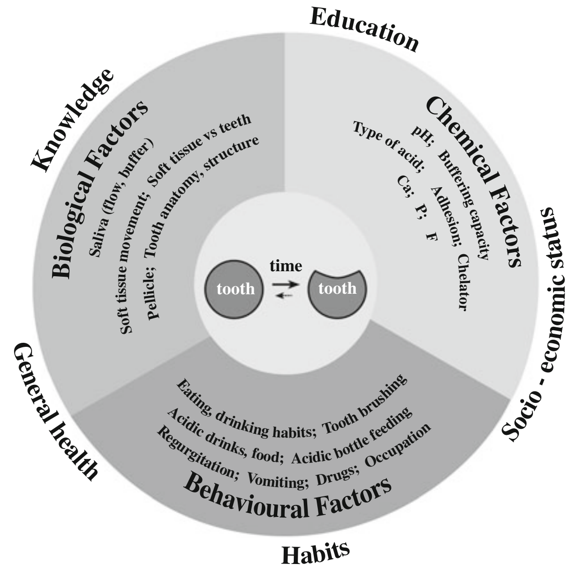

Fig. 1 The different factors influencing dental erosion (modified from Lussi [61])

composed of mucins, glycoproteins and proteins, including several enzymes [36]. On the surface of the enamel, the hydrogen ion component of the acid will start to dissolve the enamel crystal. The prism sheath area is dissolved first, followed by the prism core are, leaving the well-known honeycomb appearance [72]. Thereafter, fresh unionized acid will eventually diffuse into the interprismatic areas of the enamel and further dissolve mineral in the region underneath the surface [27, 30, 67]. This will lead to an outflow of ions (dissolution) and to a subsequent rise in the local pH in the tooth substance immediately below and in the liquid surface layer adjacent to the enamel surface [67]. The events in the dentine are the same in principle, but are even more complex.

Studies have shown that erosion may be associated with low salivary flow or/and low buffering capacity [49, 66, 93]. Dry mouth condition is usually related to ageing [24, 74, 84], even though some other studies have not found this correlation [9, 40]. It is well established that patients taking medications can also present with decreased saliva output [101], as well as those who have received radiation therapy for neck and head cancer [25]. It has been shown that sour foodstuffs have a strong influence on the anticipatory salivary flow [17, 58], which can be significantly increased when compared to the normal unstimulated flow rate [28]. Hypersalivation also occurs in advance of vomiting as a response from the 'vomiting centre' of the brain [59], as seen in individuals suffering from anorexia to bulimia nervosa, rumination or chronic alcoholism [68, 94]. The influence of saliva on the remineralization/rehardening of erosive damaged dental hard tissue is a controversial issue. It seems that in vitro, some rehardening could be expected if a supersaturated solution or saliva with no protein added are used. However, in situ or in vivo, this is the case only to a very small extent and requires several hours if not days [66]. Clinically, after acid intake, the salivary stimulation strategies, for example chewing sugar-free gum or lozenges, are suggested. The stimulated saliva may partially or completely dilute and neutralize the erosive agents from the mouth and consequently play a role in decreasing tooth erosion [37].

Chemical factors

Several studies have shown that the erosive potential of an acidic drink or foodstuff is not exclusively dependent on its pH value, but is also strongly influenced by its mineral content, its titratable acidity (the buffering capacity) and by its calcium chelation properties. Buffering capacity is generally used in chemistry to define a solution's ability to maintain its pH value. The primary determinant of the dissolution rate is its pH value, while buffering capacity has been accepted as a better indicator for the erosive potential of a beverage [29, 79]. Buffering capacity is associated with the undissociated acid in beverages. Undissociated acid is not charged and can diffuse into the hard tissue of the tooth and act as a buffer to maintain the H^+ concentration. Consequently, the driving force for demineralization at the site of dissolution is maintained [30, 34]. Therefore, the greater the buffering capacity of the drink, the longer it will take for saliva to neutralize the acid. However, dilution will also reduce concentrations of Ca and P (if present), which have a protective effect [15, 63, 64].

The pH value and the Ca, P and F content of a drink or foodstuff determine the degree of saturation (DS) with respect to the tooth mineral, which is the driving force for dissolution. The DS is defined as the ratio of the mean ionic activity product (Ip) for HAP in solution to its solubility product constant (K_{sp}). When the tooth is in contact with acidic solutions, the following reaction occurs:

Precipitation ↔ Dissolution

$$Ca_{10}(PO_4)_6(OH)_2 \leftrightarrow 10Ca^{2+} + 6PO_4^{3-} + 2OH^-$$

A small amount of tooth mineral dissolves, releasing Ca, P and OH ions. This process continues until the solution is saturated with respect to HAP. At that point, the rate of the mineral dissolution is equal to the rate of the mineral precipitation. This equilibrium constant for this saturated solution and solid formation (precipitate) is called K_{sp}. For a solution saturated with respect to HAP, the K_{sp} is $[Ca]^{10}[PO_4]^6[OH]^2$. Strictly speaking, the values within brackets represent the chemical activities of the component ions rather than their actual concentrations. It is noteworthy that when analysing the erosive potential of drinks or foods the chemical activity of a substance is the characteristic property that indicates the free available ions, although concentration is often used in practice instead. Chemical activity is a term used to describe the thermodynamical 'effective concentration' of a species in a mixture. For extremely dilute solutions, the chemical activity is approximately equal to the concentration. However, because activity is dependent on the temperature, pressure and composition of the mixture, the activity and the concentration are significantly different in most circumstances. For undersaturated and supersaturated solutions, the system is not at equilibrium, and Ip that has the same expression as K_{sp} is used. If $Ip = K_{sp}$, then the solution is just saturated with respect to HA. If $Ip > K_{sp}$, the solution is supersaturated with respect to dental hard tissue and will not dissolve it. If $Ip < K_{sp}$, the solution is undersaturated and leads to initial surface demineralization that is followed by a local rise in pH and increased mineral content in the liquid surface layer adjacent to the tooth surface. This layer will then become saturated with respect to the enamel (or dentine) and will not demineralize further [22, 30].

Acids, such as citric acid, exist in water as a mixture of H^+, acid anions (e.g. citrate) and undissociated acid molecules, with the amounts of each determined by the acid dissociation constant and the pH of the solution. The H^+ directly attack the crystal surface. Over and above the effect of the H^+, the citrate anions may complex with Ca when the pH is high enough. Consequently, acids such as citric acid have double actions and may be highly damaging to the tooth surface [30]. Up to 32% of the Ca in saliva can be complexed by citrate at concentrations common in fruit juices, thus reducing the supersaturation of saliva and increasing the driving force for dissolution with respect to tooth minerals [73].

In summary, the two often-cited parameters, the pH and the titratable acidity, do not readily explain the extent of the erosive potential of food and drink. The mineral content is also an important parameter, as is the ability of any of the components to complex calcium and to remove it from the mineral surface.

Behavioural factors

The manner in which dietary acids are introduced into the mouth will affect which teeth are contacted by the erosive challenge and, possibly, the clearance pattern. As lifestyles have changed throughout the decades, the total amount and frequency of consumption of acidic foods and drinks have also increased [16]. Soft drink consumption in the United States increased by 300% in 20 years [16], and serving sizes increased from 185 gr (6.6 oz) in the 1950s to 340 gr (12 oz) in the 1960s and to 570 gr (20 oz) in the late 1990s. Around the year 1995, between 56 and 85% of school children in the USA consumed at least one soft drink daily, with the highest amounts ingested by adolescent men. Of this group, 20% consumed four or more servings daily [32]. In 2007, the worldwide annual consumption of soft drink reached 552 billion litres, the equivalent of just under 83 l per person per year, and this is projected to increase to 95 l per person per year by 2012. However, the figure has already reached an average of 212 l per person per year in the United States in 2009 [81]. Studies in children and adults have shown that this number of servings per day is associated with the presence and the progression of erosion when other risk factors exist [66, 78].

Studies in children and adults have shown that the number of servings per day is associated with the presence and the progression of erosion when other risk factors such as swishing drinks are present [66, 78]. High erosion was associated with a method of drinking whereby the drink was kept in the mouth for a longer period of time [53]. Considerable risk of erosion was found with the frequent consumption of citrus fruits (more than twice a day) as well as the daily consumption of soft drink [49]. On the other hand, other studies were not able to find an association between dental erosion and behavioural factors [48], or they found only a weak association [75]. One can only speculate about the reasons. A possible explanation is the mode of questioning (oral vs. written questionnaire), the statistics employed (multivariate vs. univariate) and the population group under study (selected vs. randomly).

Excessive consumption of acidic candies combined with a low salivary buffering capacity or hyposalivation may aggravate erosive lesions [23, 51, 65]. The high intake of herbal teas, widely perceived as a healthy drink, may have an erosive potential exceeding that of orange juice [85].

A healthier lifestyle, paradoxically, can lead to dental health problems in the form of dental erosion, as it often involves a considered healthy diet with more fruits and vegetables. Health-conscious individuals also tend to have better than average oral hygiene. While good oral hygiene is of proven value in the prevention of periodontal disease and dental caries, frequent tooth brushing with abrasive oral hygiene products may enhance erosive tooth wear. At the other end of the spectrum, an unhealthy lifestyle may also be associated with dental erosion [102]. Wine has properties such as low pH and low calcium and phosphate content, which result in erosive potential. Alcoholics may be at particular risk for dental erosion and tooth wear as they often suffer from regurgitation.

The role of fluoride, calcium and phosphate in the prevention of erosion

Efforts have been taken to modify drinks or beverages with fluoride due to the previous findings that fluoride successfully inhibits tooth caries [71, 96]. Fluoride supplementation was found to reduce the erosive potential of a series of beverages, for example soft drinks and sports drinks [31, 35, 95]. It was also demonstrated that fluoride levels in beverages were statistically correlated with their potential erosive capability when no other aggressive factors were present [63]. However, the fluoride concentrations to be used to reduce tooth erosion have a risk of toxicity. Hence, the widespread use of fluoride is limited.

The modification of drinks and foods with calcium and phosphate compounds is a feasible and promising strategy against tooth erosion, especially with calcium, because of the increasing demand for a higher intake of this salt to satisfy the nutritional needs and to prevent osteoporosis [38]. The addition of calcium and/or phosphate to a beverage will increase its degree of saturation with respect to tooth mineral. Additionally, calcium can bind to citrate and prevent citrate from chelating calcium from enamel [30].

One of the earliest studies to report that the addition of calcium ions to acid solutions had an effect on the appearance of acid attack on human enamel was in 1953 by Besic [10]. Afterwards, many in vitro [6, 39, 50, 90] and in situ [45, 99] studies were performed and proved that calcium and/or phosphate additives increased the acid resistance of teeth. In a study by Hooper et al. [43], the erosive potential of sports drinks was reduced due to the addition of a calcium compound. A significant variation in the carbohydrate composition did not influence this outcome. In fact, many calcium-fortified beverages, such as pure juices and other drinks, have been introduced into European and United States markets. The addition of calcium into these commercial beverages was originally aimed to increase dietary calcium intakes for bone accretion and osteoporosis prevention [21, 38]. These commercially applied calcium concentrations were proven to cause less enamel demineralization [21, 38]. A recent study by Jensdottir et al. [52] demonstrated that after adding 15 mM calcium the erosive potential of an acidic candy was also significantly reduced.

In theory, a range of different calcium salts can be used to supply calcium ions, such as calcium gluconate, calcium lactate, calcium malate, calcium chloride and calcium citrate [4, 38, 50]. The challenge for beverage manufacturers is to select an appropriate calcium source that can provide a high ionic calcium concentration and decrease the erosive potential of a specific beverage without altering the taste. The first successfully modified 'tooth-friendly' soft drink was a blackcurrant drink with a low pH value calcium fortification. It has been shown to reduce the erosive demineralization compared with conventional blackcurrant drinks and orange juice during a period of 20 days [45, 46, 99].

Phosphate is usually applied in combination with calcium and/or fluoride. The presence of both calcium and phosphorus in the same beverage is assumed to have a tandem effect on erosion prevention and be associated with a lower erosive potential of soft drink or orange juice [4, 50]. With a low level of mineral ions (0.5 mM Ca, 0.5 mM P and 0.037 mM F), some modified soft drink induced less dental loss and only exerted a minimal effect on the taste of the test beverages [4]. When the added Ca (42.9 mM) and P (31.2 mM) saturated an orange juice (pH = 4.0) with respect to apatite, Larsen and Nyvad [57] found no significant enamel erosion caused by this modified soft drink after immersion for 7 days.

Recently, much attention has been directed towards the effect of polymer phosphates, such as pyrophosphate, polyphosphate and tripolyphosphate, on tooth erosion. These polymer phosphates are usually used as preservatives in meat products [19] or in non-alcoholic flavoured drinks [7]. In a study by Barbour et al. [7], these food-approved polymer phosphates were observed to significantly reduce the dissolution rate of hydroxyapatite in a citric acid solution representative of soft drink. A subsequent in situ study found that the modifications of acidic soft drink with polyphosphate alone or combined with calcium or xanthan gum are all effective at reducing enamel erosion compared with the unmodified soft acidic drink [44]. The preventive effect of polymer phosphates might be due to the chemical nature of the polymer that it can be adsorbed onto the enamel surface. Phosphate groups in the polyphosphate may bind to the tooth surface and substitute for phosphate groups in the hydroxyapatite. Consequently, the detachment of ions is prevented and the surface area available for dissolution is reduced [6].

Modification of beverages with calcium or calcium phosphate has been generally accepted as an effective anti-erosion strategy, while the stability of the solution is still problematic and phase transformations may occur. To stabilize calcium and phosphate ions, casein phosphopeptides (CPP) were introduced. CPP, heavily phosphorylated peptides derived from milk casein proteins, contain amino acid sequences and strongly bind calcium ions to form soluble complexes [42, 77]. Therefore, CPP can localize ACP to form CPP-ACP nanocomplexes and provide a reservoir of calcium and phosphate ions to maintain a state of supersaturation in close proximity of dental hard tissues and induce possible remineralization [86]. After a number of in the clinic and laboratory experiments, CPP-ACP have been incorporated into dental care products to inhibit caries [1]. Recent evidence has also shown that CPP-ACP may protect teeth against erosion [80, 83, 89]. However, there are also a number of reports that show no protection of CPP-ACP against erosion [60, 75, 99]. As a functional ingredient, CPP-ACP was added to sports drinks by Reynolds et al. [97] and Ramalingam et al. [87] to raise the Ca-concentration in the drinks. The modified sports drinks reduced enamel demineralization and increased remineralization. Moreover, the incorporation of CPP-ACP did not affect the product's taste [87]. In fact, casein alone has also been supplied in some sport drinks. A recent experimental study by Barbour et al. [7] found that casein protein itself, in the absence of any calcium phosphate particles, might provide significant protection against hydroxyapatite dissolution in acids. The inhibition of hydroxyapatite dissolution by casein was ascribed to the binding of casein to the hydroxyapatite surface.

The role of other ingredients in the prevention of erosion

The erosion-inhibiting potential of other metal ions, such as iron and copper, has also been investigated. An in vitro study by Brookes et al. [11], which originally aimed to investigate the effect of the copper ion on caries, showed that 10 mM $CuSO_4 \cdot 5H_2O$ in 10 mM acetic acid (pH = 3.2) reduced erosive tooth mineral loss by 49%. The mechanism of this might involve the formation of an acid-insoluble copper phosphate layer on the tooth surface [11]. A follow-up study by the same group indicated that 10 mM $FeSO_4 \cdot 7H_2O$ reduced synthetic hydroxyapatite loss by 51% [12]. Using bovine enamel powder, Buzalaf et al. [14] came to the same conclusion and demonstrated a reduction in tooth loss by iron ions in acids. Subsequently, a series study by Kato et al. [54–56] provided insight into the erosion resistance capability of iron in soft drink. It was shown that iron could interfere with the enamel dissolution in acidic drinks, where the prevention ability depended on the concentration of iron and the type of acid in the drinks. The mechanism responsible for the erosion-inhibiting of iron is not completely understood. Several possible explanations were suggested, such as forming an acid-resistant coating of hydrous iron oxide on the tooth surface [98], participating in the remineralization of human enamel and in the nucleation of apatite [5, 88], replacing calcium in apatite [69, 88] and inhibiting demineralization [5]. However, Magalhaes et al. [69] found that the addition of low concentrations of Fe (0.047 mM) in combination with Ca (1 mM), F (1 mM) and P (1 mM) into a soft drink did not reduce the enamel loss compared with the pure beverage. Additionally, the supplemented iron might deteriorate the taste of beverages and affect tooth colour [14, 54, 55].

Amaechi et al. [2] found that the supplementation of an orange juice with xylitol (25% w/v) and fluoride (0.5 ppm) had a protective effect on dental erosion in vitro, while xylitol alone did not reduce erosion by orange juice. Xylitol has been approved for use in foods as a non-sugar sweetener for many years and can be found naturally in small quantities in fruits (including berries) and vegetables [33]. It might form complexes with calcium, penetrate into demineralized enamel and interfere with the transport of dissolved ions from the lesion to the demineralizing solution by lowering the diffusion coefficient of the calcium and phosphate ions [70]. More recently, Chunmuang et al. [18] showed that the addition of xylitol (25% w/v) alone or a xylitol (25% w/v)/fluoride (1.0 ppm) combination to orange juice could reduce enamel erosion. The conflicting conclusion was assumed to be due to the different experimental conditions [18].

In a study by Barbour et al. [6], xanthan and carboxymethylcellulose, which are often used in foods and drinks as thickening and gelling agents, were added to citric acid solutions and demonstrated some protection against hydroxyapatite dissolution. The two polymers are presumed to adsorb and form a preventing layer at the hydroxyapatite surface. This layer could inhibit dissolution by reducing diffusion at the hydroxyapatite surface and hence reduce the exchange of hydrogen ions and calcium and phosphate ions between the hydroxyapatite and the solution [6].

Rios et al. [92] found that the light cola drink is less erosive than the regular one. This lower erosive potential is possibly related to the presence of the amino acid phenylalanine. The erosion-preventing action of phenylalanine might be due to two reasons. First, the amino acid could act as a buffer system, increasing the neutralization and buffering the acids from the cola drink. Another possibility is the formation of an amino acid-based layer on dental surfaces. This layer might reduce dental erosion by acting as a diffusion barrier or a perm-selective membrane, thereby preventing the direct contact between the acids and the tooth surface.

Ovalbumin is the main protein found in the white of hens' eggs. It is a complex protein and is used as an additive in many foods [20]. Ovalbumin was observed to adsorb to bovine enamel [82] and inhibit bovine enamel demineralization in vitro [3]. Hemingway et al. [41] added 0.02 and 0.2% w/v ovalbumin to citric acid solutions and found a lower hydroxyapatite dissolution rate under conditions within a range of pH values and calcium concentrations that represent dental erosion by citrus-based soft drink. Therefore, ovalbumin was regarded as a potential additive to reduce tooth erosion by citrus-based drinks. The adsorption of ovalbumin molecules onto the hydroxyapatite surface might be responsible for the protective effect. The adsorbed molecules can form a semi-permeable barrier, hindering the transport of proteins and/or calcium and phosphate ions. In this context, it has to be kept in mind that these strategies need a long enough contact time to the tooth in order to work properly. This contact time may be too short when a beverage is drunk quickly.

The role of the chemical and physical properties of diet in the prevention of erosion

Besides the modification of foods and beverages with a variety of functional ingredients, the optimization of the chemical and physical properties of foods or beverages may be a feasible and promising approach to inhibit tooth erosion and should be given consideration.

It is thought that the erosive potential of citric acid-containing beverages can be also decreased by replacing citric acid with hydrochloric and phosphoric acids, because citric acid is known to exhibit a greater erosive capacity [100]. The greater erosive potential of citric acid might be related to its ability to form chelating complexes. The titratable acidity, or buffering capacity, is a good indicator for the erosive potential of a beverage, even though pH has been used to measure acidity. The high buffering capacity of drinks or beverages resists the ability of saliva to alter pH and maintains the low pH status for a comparatively longer time [29, 79].

Ireland et al. [47] investigated the ability of soft drink to adhere to enamel. Two properties of a variety of drinks, including the contact angle (the angle a droplet of the liquid will make on the surface) and surface tension, were analysed to determine the degree to which a liquid will adhere to a surface. The results showed a ranking of the drinks indicating that the relative stickiness of beverages to enamel might be associated with the tooth erosion. The greater the adherence of an acidic substance is, the longer the contact time with the tooth surface and, therefore, the greater the likelihood of erosion will be. Busscher et al. [13] showed that the displacement of saliva by Cola required 14 mJ/m^2, and the displacement of saliva by Diet Cola required 5 mJ/m^2. However, displacement of Cola film by saliva required 45 mJ/m^2, of Diet Cola by saliva 52 mJ/m^2. It seems to be more difficult to displace a soft drink film by saliva than it is to displace a salivary film by a soft drink [13]. Further research is required to quantify the impact of these factors.

Conclusion

In this paper, the possible risk factors for tooth erosion and their interplay are discussed. Special attention is paid to various modifications of foods or beverages aimed at reducing tooth erosion (Tables 2, 3). Dietary modifications have been developed with varying success, while great efforts are still required to better prevent tooth erosion due to the complicated relationship between diet and erosion. The efficacy of aforementioned supplementation with various functional ingredients depends not only on their type and, but also on a series of factors, such as the pH

Table 2 The concentration range, action mechanism and appraisal of different functional ingredients

Ingredient	Concentration range/ppm	Mode of action	Strength and weakness
Ca	20–1,716	Change the degree of saturation with respect to HA	Nutrition supplementation; taste drawbacks at high concentration
P	15.5–966	Change the degree of saturation with respect to HA	
Fe	70–3360	Form a coating of FeO(OH) on tooth surface, or replace Ca in apatite	Taste drawbacks, tooth staining
Cu	640	Form a coating of Cu_3PO_4 on tooth surface	
Xylitol	2.5×10^5	Form complexes with Ca, interfere with ions transport processes	No toxicity, no taste drawbacks; stomach discomfort and diarrhoea with higher concentrations
Xanthan gum	200	Form a preventing layer on tooth surface	
Carboxymethyl-cellulose	200	Form a preventing layer on tooth surface	
Sodium caseinate	$20–2.0 \times 10^4$	Be adsorbed on tooth surface, stabilize the crystal surface and inhibit ion detachment	No toxicity, no taste drawbacks, need further study
Ovalbumin	$2.0 \times 10^2–2.0 \times 10^3$	Form a semi-permeable barrier on tooth surface	

Table 3 Summary of studies conducted on the protective effects of different functional ingredients against tooth erosion

Author(s)	Year	Ingredient(s)	Solution(s)/candy
Besic	1953	Ca, P	Acetic acid, latic acid
Sorvari et al.	1988	F, Mg	Sports drink
Amaechi et al.	1998	Xylitol, F	Juice
Larsen and Nyvad	1999	Ca, P	Juice
Hughes et al.	1999a, b	Ca	Juice
West et al.	1999	Ca	Juice
Reynolds et al.	1999	CPP-ACP	Sports drink
Brookes et al.	2003	Cu	Acetic acid
Hooper et al.	2004	Ca	Sports drink
Attin et al.	2005	Ca, P, F	Soft drink, juice, sports drink
Jensdottir et al.	2005	Ca, P	Juice
Ramalingam et al.	2005	CPP-ACP	Sports drink
Barbour et al.	2005	Polymer phosphate	Citric acid
Barbour et al.	2005	Carboxymethyl-cellulose	Citric acid
Barbour et al.	2005	Xanthan gum	Citric acid
Buzalaf et al.	2006	Fe	Acetic acid
Jensdottir et al.	2007	Ca	Candy
Hooper et al.	2007	Polyphosphate	Soft drink
Kato et al.	2007a, b, c	Fe	Soft drink
Chunmuang et al.	2007	Xylitol, F	Juice
Barbour et al.	2008	Casein	Citric acid
Hemingway et al.	2008	Ovalbumin	Citric acid
Magalhaes et al.	2009	Ca, F, P, Fe	Soft drink

value, the amount of titratable acidity (or buffering capacity) and the chemical and physical properties of foods or beverages. At the same time, an appealing taste is another important criterion for the successful dietary modification.

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