Eur J Oral Sci 1996; 104: 221–228
Printed in Denmark . All rights reserved


EUROPEAN JOURNAL OF
ORAL SCIENCES
ISSN 0909-8836

# Lessening dental erosive potential by product modification

**Trevor H Grenby**
Department of Oral Medicine & Pathology,
U M D S, Guy's Hospital, London SE1 9RT, UK

*Grenby TH: Lessening dental erosive potential by product modification. Eur J Oral Sci 1996; 104: 221–228.* © Munksgaard, 1996.

Current interest in dental erosion has led to increasing attention to ways in which potentially erosive products might be modified. Information on how this could be achieved has been hard to gather, and has focused chiefly on possibilities in reformulating soft drinks. The bulk of the work published on this relates to calcium and phosphate supplementation, ranging from early experimentation on saturation of a demineralising medium with tricalcium phosphate, through tests of more soluble phosphates and other calcium salts providing various levels of $Ca^{2+}$ and $PO_4^{3-}$, to a calcium citrate malate additive specially formulated to curb erosion by soft drinks. Opinions on the effectiveness of citrate, the practicability of reducing the acidity levels of soft drinks, and the possible applications of fluoride, bicarbonates and certain constituents of milk products are also included. Finally, an attempt has been made to summarize some of the advantages and shortcomings of the different methods, but it is clear that much further work will be needed before firm guidelines on the best routes to product improvement can be laid down.

Key words: demineralization inhibition; erosion protection; product modification; reformulation

Dr T. H. Grenby, Dept. of Oral Medicine & Pathology, UMDS, Guy's Hospital, London SE1 9RT, UK,
Telefax: +44–1719554455,
E-mail: t.grenby@umds.ac.uk

Anxiety over the causes of dental erosion focuses, rightly or wrongly, on the intake of foods and drinks acidic enough to attack dental hard tissues, but it has been pointed out that certain vegetables, vinegar, dressings, yogurts, ices, acidic medications, and oral hygiene products may also be implicated. It was asserted in 1958 (1), and many times since, that fruit drinks cause erosion, and that changing their form into sweets or frozen lollies will not reduce the erosive potential of such products. Many acidic foods such as fruit are natural in origin and cannot be modified to curb erosion. Certain manufactured foods offer the opportunity for modification, but the characteristics of these products (e.g. flavour and stability) are often dependent on the acids added or formed during manufacture, so that their removal would be impracticable. Oral hygiene products such as mouthrinses and toothpastes also have the potential to be modified, but are usually only mildly acidic and probably of little concern in erosion (see Comments section).

One way in which the effects of acidic foods and drinks may be combated is by modifying their composition so as to reduce their demineralizing action. It is not known whether many manufacturers of the foods and drinks under scrutiny have explored this avenue of product re-formulation. If changes in formulations have been made, they are more likely to have been for the purpose of reducing the potential effects of the products on caries than for attempting to curb erosion, which has not until recently begun to receive detailed attention as a major cause of dental damage.

Out of a dozen manufacturing companies approached for information on product modification, only one was able to offer any help, making it difficult to prepare a review on this subject. The limited data that are available concentrate on soft drinks and do not include oral hygiene products such as mouthrinses, medications and chewable vitamin tablets containing ascorbic acid and sometimes flavoured with citric acid. Consideration of options for re-formulation that have been put forward will therefore be confined to possible ways of modifying the erosive potential of acidic foods and drinks.

## Acidic sweets and ice lollies

See for example the sections on lolly melts, ice lollies and bicarbonate below.

### Fruit juices and nectars

Fruit juices and blends are marketed in various ways and under various sets of regulations according to their composition, governed in the EU by a Directive that limits the use of additives and offers little scope for reducing erosive potential, but does not automatically prohibit the use of specific anti-erosion technology. A careful scrutiny of the literature published on erosion by fruit juices and its prevention and control over the last 30 yr, has revealed not one single reference to any modification of a pure juice with the specific, stated purpose of curbing erosion. As the minimum acidity content of many nectars is also specified in the EU Directive, it is hardly surprising that there is no literature on product modification.

### Soft drinks

A little more information is available about ways in which soft drinks could be modified. Excluding fruit juices, soft drinks may contain sugars, fruit extracts, flavourings, acids (phosphoric, citric, malic and tartaric acids being the most common) and other permitted additives, including ascorbic acid and citrate salts. They may be concentrated, as in squashes and essences that require dilution before consumption, or they may be ready to drink. They may be still or carbonated. Carbonated drinks contain $CO_2$ ($H_2CO_3$) under pressure along with various flavourings, fruit acids and possibly fruit extracts or juices.

Certain drinks are also produced for special purposes, such as providing high energy value or formulated for sportsmen, children, therapeutic use or calorie-control. These may or may not be carbonated, and can also contain flavourings, acids and essences.

Legislative restrictions limit the use of additives in soft drinks to those that are approved and listed in an EU Directive on additives other than colours and sweeteners, so that it would be possible to make alterations to some of the drinks formulations during manufacture. Least attention appears to have been given to the kind that require dilution before use. Although approaches to re-formulation vary, attempts that have been made can be grouped under five main headings:

#### Buffers and buffering systems

A commonly held idea is that inhibitors of erosion would operate by a 'buffering action'. By this it is meant that a high enough concentration of calcium or phosphate added to a drink should cut down the amount of dental enamel that it dissolves. On chemical grounds this is simplistic and not entirely correct.

The most commonly used meaning of buffering in solution is a resistance to pH change, applying to acid-base balance, not to levels of $Ca^{2+}$ and $PO_4^{3-}$ or any other solutes. Buffer solutions therefore usually consist of an acid and one of its salts or a base and one of its salts, especially when the acid or base is a weak one. The function of a buffer is thus to resist changes in pH, $[H_3O^+]$ or $[OH^-]$. This means that buffering in this strict sense would have very limited application in the prevention of erosion (but see below for effects of altering acidity). The expected characteristics and acceptability of soft drinks are related to their tangy, acidic flavour and taste perception. It follows that buffering to maintain the pH at a level near neutrality, or safely above the value at which it could be responsible for any erosion, would affect and diminish these characteristics, and is unlikely to be a practicable way to re-formulate soft drinks.

#### Addition of calcium and/or phosphate supplements to the drinks

The influence of calcium and phosphate added to the drinks is often incorrectly referred to as buffering. The principle that operates is dependent on the Law of Mass Action, which, in the form that applies to solutions, states that "the rate of a chemical reaction (i.e. the dissolution of enamel mineral in this case) is proportional to the concentration of the reacting substances (calcium and/or phosphate) present at any given time". Thus in the case of dental caries or erosion the initial presence of reaction products ($Ca^{2+}$ and $PO_4^{3-}$, $HPO_4^{2-}$, $H_2PO_4^-$, depending on pH) tends to decrease the extent and rate of enamel demineralization. This is the scientific basis for adding calcium and phosphate to acidic drinks to help inhibit erosion, but of course the effectiveness of product modification in this way will depend on many factors, including concentrations and solubility of the Ca and $PO_4$ additives, complex formation, position of the equilibrium point, pH and temperature. Some of the problems encountered in product re-formulation with calcium and phosphate salts are referred to under Comments (below).

The literature on this is reviewed below, with studies *in vitro* first, followed by studies in laboratory animals. In examining the modification of soft drink formulations, it became apparent that the main objective of most of the work was to reduce their cariogenicity, with any influence on erosion subsidiary and of lesser account.

*Saturation of the medium.* In early studies it was observed that the addition of calcium and phosphate ions to acid solutions changed the appearance of acid attack on human enamel and became more protective as their concentrations were increased (2). HARDWICK also drew attention to the demineralisation of enamel by lactic and other acids and the state and possible role of phosphates (3). HILLS & SULLIVAN reported that saturation of the demineralizing medium with calcium and phosphate prevented enamel dissolving at pH 7.0 to 4.0, with partial saturation providing protection only at pH 7.0 to 6.0, but exact details of the calcium phosphate used were lacking (4).

*Tricalcium phosphate as an additive.* Although primarily concerned with potentially erosive tablets containing citric or malic acids, HAY *et al.* (5) exposed extracted human teeth to solutions of acidic ice lollies, acid drops and grapefruit squash, and tested $Ca_3(PO_4)$ as an additive. The drinks + solutions of 2, 4 and 6% calcium phosphate were shaken for 1.5 h before dilution and pH adjustment to match the measured intra-oral pH, but the acidity level was not altered on drinking. Based on figures for phosphate dissolving from the teeth, erosion (µg/tooth) was reduced to insignificant levels and in some cases was eliminated by the additive. It was also found that dentin can be protected against citric and malic acids in a similar way. The optimum Ca:P ratio was said to be approximately that for tri-calcium phosphate, achieved by adding it at 2 – 2.5% to the acidic agents (i.e. providing 600 µg/ml Ca and 300 µg/ml P).

It was not clear whether the authors had fully taken into account the low water solubility of tricalcium phosphate at neutral pH values, but they did comment that protection probably depended on the presence of ionized calcium and phosphate. They proposed the use of other calcium phosphates or mixtures of calcium salts and phosphates, e.g. $CaHPO_4$ + calcium acetate, which would dissolve more rapidly. When added in the correct proportions and amounts specified in the reference at pH 4.0, these were said to give substantially complete protection of both enamel and dentine.

*Supplemented ice lolly melts.* Using similar methods *in vitro*, but extending the work to rats *in vivo*, WAGG *et al.* (6) tested ice lolly melts (i.e. sweetened, acidic solutions of natural or simulated fruit juices) containing two types of supplements, in both of which phosphate was present in the form of $Ca(H_2PO_4)_2$: $2H_2O$, plus either calcium lactate or calcium carbonate, giving Ca and P levels of 625–1,056 and 434–786 µg/ml respectively. These formulations were intended to produce the desirable Ca:P ratio of 1.5. There was no mention of any pH adjustment.

At intermediate levels of Ca and P supplementation, protection from calcium lactate was slightly (but not significantly) better than from calcium carbonate. No significant differences were found between the two types of lolly melts, both of which were effective. Rats receiving the products showed an atypical form of erosion, with only slight damage confined to exposed dentine on the occlusal surfaces of the teeth. It was concluded that both types of protected lollies were significantly less erosive than unmodified ones.

*High-phosphorus lolly supplementation.* The same objective was pursued in some more recent work in which lollies re-formulated with a relatively high-phosphate combination of sodium tetrapyrophosphate, acid calcium phosphate and calcium carbonate were evaluated (7). The Ca/P ratios of the supplements were approximately 0.7, as opposed to 1.24 to 1.44 in earlier studies. Their pH values (unadjusted) were within the limits of 3.50 to 3.75, their Ca contents ranged from 550 to 730 ppm, and their P contents ranged from 625 to 1,000 ppm. Demineralization trials were carried out on intact enamel surfaces, pulverized enamel and hydroxyapatite. Compared with the basic version of the lollies, all five supplemented formulations showed significantly less attack on pulverized dental mineral, as measured by the dissolution of calcium and phosphate under standardized conditions . The lowest and highest levels of supplementation (Ca 430 and 730 ppm; P 625 and 1,000 ppm) did not show any significant differences from the standard level of 550 ppm Ca and 780 ppm P, so under the conditions used the lowest levels were sufficient for optimum protection.

*Modification of acid-containing beverages.* In experiments in laboratory animals, adding 1% $NaH_2PO_4 \cdot H_2O$ to a sucrose-containing powdered soft drink mix and a powdered breakfast orange drink mix reduced both enamel dissolution *in vitro* and erosion in rats *in vivo*, although the main interest was in dental caries, not erosion (8).

*Effects of additives to soft drinks.* REUSSNER *et al.* advanced this work, starting with a thorough literature review and proceeding to describe four separate studies, examining the potential erosiveness of a range of soft drinks and the effects of various additives (9). In their first rat trial, only 0.03% sodium monofluorophosphate showed a significant action (36% reduction) in curbing erosion, probably attributable to the fluoride it provided rather than to its phosphate content, since 0.21% mono-sodium orthophosphate, 0.15% sodium hexametaphosphate, 0.15% sodium trimetaphosphate and 0.13% calcium chloride, added to a grape powdered beverage mix, were all ineffective.

In later experiments using rats, monocalcium phosphate (MCP) at 0.15% or 0.30% curbed erosion effectively when added to a grape powder beverage mix, reconstituted frozen orange juice, and a reconstituted orange-flavoured beverage mix. The MCP increased the beverage total acidity by between 11 and 38% but raised the average pH from 2.5 to 2.8. The authors commented that this compound has good solubility and no taste drawbacks. Another possibility, tricalcium phosphate, is used as an anti-caking agent in powdered beverage mixes, but its usefulness is limited by its relatively low solubility.

*Addition of calcium lactate to a cola drink.* A further trial of a calcium salt was conducted in rats housed in a programmable feeder for 5 wk and receiving either a cola drink or a cola drink supplemented with 5% calcium lactate, the pH of which had been adjusted to match that of the cola by the addition of citric and phophoric acids (10). The drinking fluids were delivered in 17 equal volumes over 24 h. At the end of each 24-h period the volume of fluid left was measured. The difference between the volume delivered and the volume remaining was taken as the volume consumed, but the duration of exposure was not stated. Recording erosion by the method of RESTARSKI (11), supplementation of the cola drink significantly reduced the scores to a level no different from that of a third group which drank only distilled water. The authors did not know whether the fall in erosion was attributable to calcium ions or lactate or both, but they suggested that the effect involved a process of remineralisation, so it was presumed to depend on the presence of $Ca^{2+}$. The calcium lactate was fairly soluble and did not have the taste problems associated with other compounds proposed as additives.

*A calcium citrate malate additive to prevent erosion.* The research on Ca and P supplementation, summarized above, provided the background for formulating a new type of low-erosivity fruit drink in one of the few practical applications of the findings. Starting with the premise that 'erosion normally occurs during consumption of acidic beverages', pH below 5.5, comprising water, sweetener and flavour or juice, ANDON *et al.* made a US Patent claim for calcium citrate malate (CCM) as an additive to prevent enamel erosion (12). The additive was in fact a combination of calcium with citric and malic acids in the form of a soluble complex at a level providing 0.02% to 0.15% of calcium in the drink. Some details of its composition were given in the patent specification, including the preferred calcium: citrate: malate ratio of 4:2:3. The supplement can also contain other ions such as carbonate, hydroxide and phosphate, depending on the calcium source, and the method of making it was described.

Examples of experiments showing the effectiveness of the supplements were quoted, with the erosion of an 'enamel-like disc', measured gravimetrically as percentage weight loss, reduced from 8.25% to figures in the range of 0.05% to 0.75% in the presence of varying concentrations of CCM, and good properties in preserving the hardness of enamel. In groups of rats, erosion was reduced from $4.29 \pm 0.85$ (mean±SD), recorded on a 0–6 grading scale of increasing severity, to $0.95 \pm 0.38$ and $0.71 \pm 0.55$ by the CCM supplement. It was also found to be highly effective in various types of fruit drinks in further rat trials.

#### The addition of citrate to drinks

Another approach has been the supplementation of drinks with citrate. Initially, it appeared that raising the titratable acidity of blackcurrant, orange and cola drinks by citrate would increase erosivity (13), although the main object appeared to be to control cariogenicity (14). Attention had previously been focused on the chelating action of citrate along with its possible role in demineralization (15, 16), and it has been pointed out that the theory that citrate could be beneficial is erroneous because of its strong chelating properties. On the other hand, attention has been drawn to the fact that the chelation properties of citrate should be of little importance at the low pH levels of acidic drinks.

In more recent work, a 10% sucrose solution had less effect in lowering the pH of dental plaque when 0.1, 0.2 or 0.4% disodium hydrogen citrate was added (17), and 0.103% citrate was also effective as a supplement in a blackcurrant drink (18). The comment was made that the stimulation of salivary flow by citrate may lead to quicker clearance of acid after an acidogenic challenge. Although raising the concentration of citrate might increase the erosive potential of the drinks, it was felt that at low concentrations it might help to buffer the acids in fruit-based drinks, by this means reducing their erosiveness.

Thus the usefulness of citrate in curbing erosion is unclear. Citrate inhibits phosphofructokinase and impedes glycolysis in *Streptococcus mutans* and *S. sanguis.* Orange juice, with a relatively high level of 5.66 g citrate/l, was associated with a greater fall in human dental plaque pH after a 10% sucrose solution rinse than other fruit drinks containing lower levels of citrate (13), which may have led POLLARD *et al.* (17) to suggest that controlling the level of citrate in drinks might assist in the development of products that have a reduced inherent acidogenicity and therefore lower erosive potential.

#### Reducing the acidity levels of the drinks

As erosion is a consequence of acid attack, an obvious way of curbing it is by lowering the acid content of the drinks that do the damage. This raises formulation difficulties, however, because the taste perception of the drinks is related to their tangy flavour and acidity. Soft drinks can contain acids from at least two different sources: [a] fruit acids and other acids that provide flavour, and [b] carbonic acid under pressure in sparkling drinks.

[a] Choosing and blending the acids is a specialized skill of drink technologists, but of course fruit juices from different sources vary appreciably in their levels of acidity (see for example 19), so that it might be possible to increase the proportion of potentially less erosive types in drinks formulations at the expense of the more highly erosive ones. Total titratable acidity gives a better guide to potential erosivity than pH. Titratable acidity levels and buffer capacity (calculated using the inverse slope of the tangent through pH 5.5) of a range of fruit juices and soft drinks have been reported (20). In some recent studies on juices, the total titratable acidity levels (equivalence to 0.05M NaOH) were blackcurrant (73) >>raspberry (44) >rosehip, orange and strawberry (all approx. equal at 26–28) >apple (20) (unpublished observations). There is some evidence that this approach has been used to make sure that the acidity of infants' fruit drinks is low, keeping the levels of demineralization significantly lower than those from a selection of adults' fruit drinks (21).

The molecular structures of various demineralizing acids have been investigated, and the importance of multiple charges on the ions, as in polycarboxylic acids, has been demonstrated by chemical procedures and analyses (16). Acidulation of sweets with malic acid, a weak demineralizing agent, was said to exert some protective effect against enamel dissolution in the presence of other acids (22). Various drinks were examined by GROBLER *et al.*, who commented that heavily buffered fruit juices may be more erosive than other soft drinks. Buffering was recorded as mol base/l drink$\times 10^{-3}$, so it may equate with titratable acid (23).

From measurements of hardness and by SEM and profilometric analysis of bovine teeth and tests of the dissolution of hydroxyapatite *in vitro*, it was concluded that citric acid is more erosive than malic acid, and that malic acid should be a better choice as a component of sports drinks than citric or orthophosphoric acids (24).

[b] Little precise information is available on the influence of the carbonation of drinks on their erosive potential, and it is difficult to determine this exactly. As soon as a container of carbonated drink is opened, it begins to lose carbon dioxide and its acidity changes. However, comparing carbonated and still orange drinks, the carbonated version was more acidic (pH 2.61, titratable acid$\equiv$1.76$\pm$0.06 ml 0.05M NaOH/ml of drink, compared with figures of 3.00 and 1.41$\pm$0.01 for the still drink), and given to rats as their drinking fluid, it left them with far less intact enamel (approx. 6% vs. 27%) and far more eroded enamel (73% vs. 38%) than the still drink (19). The implication is that if the composition of drinks could be modified by reducing the degree of carbonation, this might help to limit the risk of erosion, although it has been pointed out that the contribution of carbonation to total titratable acidity is outweighed by the effects of other fruit acids and ingredients such as phosphoric acid.

In another large-scale trial with drinks available *ad libitum* to groups of laboratory rats for a period of 6 wk from weaning, two different types of canned carbonated drinks were compared with pure orange juice for dental erosion measured by digital image analysis. The percentage of intact enamel averaged 97.8 on the water control, 23.0 on the carbonated drinks, and 12.2 on orange juice. The extent of eroded enamel was 0.6 (water), 50.5 (carbonated drinks) and 70.2 (orange juice), but exposed dentin averaged 0 (water), 16.7 (carbonated drinks) and 7.3 (orange juice). The average total titratable acidity figures (% w/v) were 0.39 for the carbonated drinks and 0.90 for the orange juice, which correlated well with the extent of enamel erosion, and showed the erosivity of the orange juice.

#### Fluoride

By far the greatest interest in fluoride has been in its properties as an anti-cariogenic agent. Although there has been controversy over its mechanism of action, it is known to improve the acid resistance of enamel when incorporated into the apatite structure, so it might also assist in strengthening the enamel against erosion. Little attention has been paid to this, but HOLLOWAY *et al.* (1), using the RESTARSKI (11) asessment method in laboratory animals, reported that sodium fluoride at 2 ppm reduced the erosive power of fruit drinks, and LUSSI *et al.* (20) observed that fluoride levels in a range of juices and drinks were statistically correlated with their potential erosiveness *in vitro*, measured by surface hardness and iodide permeability.

REUSSNER *et al.* (9) noted the inhibition of erosion in rats by sodium monofluorophosphate in one of their four experiments, in which three other phosphates and calcium chloride as additives to a reconstituted powdered beverage were ineffective. The anti-erosive action of 15 ppm fluoride added to a sports drink mixture (94% w/w sucrose, 3% citric acid, 1% Na citrate, 1% NaCl, 1% KCl), diluted to give a sugar content of 6%, pH 3.2 and given to rats *ad libitum*, was reported by Sorvari *et al.* (25).

Fluoride was also tested as an addition to a pure citrus (orange) drink, pH 3.5 (26). Groups of 6 to 9-yr-old children were given the supplemented (1 mg $F^-$ as NaF) and control drinks for 3 yr, although the main object was the suppression of caries, the incremental rate of which fell by about 30%.

Finally, it must be noted that the unrestricted intake of fluoride by this route is a cause for concern (see comments section).

### Bicarbonates

Another idea put forward (27) was for sufferers from erosion to use a bicarbonate mouthrinse to neutralize the acid after consuming fruits, juices and cola etc. For maximum effect this would need to be used as often as possible straight after the ingestion of the acidic fruits and drinks. This is likely to be impracticable and unappealing in many situations. In addition, incorporating sodium bicarbonate in acidic boiled sweets did not bring about any clear improvement when the sweets were tested in solution form for their demineralizing action, and it is not known what effect this re-formulation would have on their taste (28).

### Milk and milk products

After studying drinks and oral pH, Meurman *et al.* (29) noted that yogurt and sour milk are unlikely to have any local effect on teeth, and experiments with milk have shown that its high calcium and phosphate concentrations may counteract enamel dissolution. The inhibitory action of casein and certain peptides has been studied by Reynolds and his co-workers (30–33). More recently, careful separation procedures of dairy products have yielded specific glycoprotein or proteose-peptone fractions that can play a part in protecting hydroxyapatite against demineralization. These too may find future application in certain types of drinks with the purpose of helping to limit erosion.

Rehardening of cola-softened enamel by the action of milk or cheese was observed by Gedalia *et al.* (34, 35), who concluded that the remineralizing/repair was probably brought about by organic and mineral material deposited on the enamel surface or by the uptake of calcium and phosphate.

### Comments

Fruit acids and additives such as phosphoric acid are not all equally erosive, and as would be expected from measurements of their acidity, there is wide variation between different fruit juices. Malic acid was found to be less erosive than citric acid in one set of experiments (24), but with the two acids at exactly the same concentrations, the findings were the reverse in a later study, and among six assorted fruit juices, blackcurrant was potentially the most erosive and apple juice the least. With the expanding use of soft drinks, especially in younger age-groups, there is growing concern within the dental profession over the problem of their potential erosiveness and much interest in the ways in which it can be tackled.

Product modification is one option that has not yet been fully explored. It can be seen clearly from the references collected above that the only area in which there has been major activity is in the addition of compounds or mixtures supplying calcium and phosphate to potentially erosive drinks. These should presumably be in ionized or easily ionizable form if they are to suppress demineralisation of dental enamel according to the principles of the Law of Mass Action, but it has not been ruled out that other mechanisms might also operate, including alterations to the properties of the tooth surface and any surface films, such as integuments, pellicle and dental plaque.

It must not be overlooked that the addition of calcium and phosphate salts to soft drinks has an impact on the flavour as well as the pH, depending on the salt used and the amount, so that additional acid may have to be added in order to restore the pH and retain the flavour characteristics. Orange juice can help mask the presence of calcium to some extent. Calcium-fortified products are on the market in the USA and Germany, but do not appear to have been tested for their erosive potential. If calcium is not well masked, the products tend to develop a chalky taste. The problem is that product re-formulation is no simple matter, and many of the additives proposed could exert adverse effects on other ingredients in the drinks. As the manufacturers point out, detailed tests of flavour acceptability would be needed.

One reason for concentrating on this method of product modification is that supplementation with calcium and phosphate compounds is less likely to raise regulatory obstacles than some of the other substances which have been considered. Fluoride, for example, has received passing attention as an anti-erosive additive (see above), but to avoid any risk of over-consumption, intake levels would need to be carefully monitored and controlled, which would be difficult if it were freely available in soft drinks. A major barrier to its application for this purpose would be the prospect of political and activist campaigns that have helped to curtail its use in products other than oral hygiene preparations.

Product modification by manipulating the acidity levels is another option, but the practicability of this is a technical matter dependent on the limitations of the re-formulation that can be achieved, changes in taste, and the commercial prospects of the altered products. It is also important to remember that acids in drinks can have a preservative effect, so that any reduction in the level of acidity needs to be properly evaluated over a sufficiently long term.

The addition of citrate is one aspect of this. Many products already contain citrate (see 13). Modified products have been tested, but it is not known how close to being put into production they are, and there is some scepticism over the usefulness of citrate on account of its reputed powerful chelating properties, although these may not be operative at the low pH values of soft drinks.

Other suggestions for minimizing erosion potential include modifications to the packaging and the route of intake. GROBLER *et al.* (23) observed that the use of a straw was the least harmful method of imbibing sugar-containing drinks, and should be recommended. Labelling can also be used to warn against too frequent consumption and misuse of potentially erosive products, and was one idea to emerge from studies of the potential dental effects of infants' fruit drinks (21, 36).

No literature has been found on the re-formulation of medicines, oral hygiene preparations, and the various food products and accompaniments listed in the Introduction, but it has been pointed out that, in any case, oral hygiene products are generally only mildly acidic with pH values in the range of 5 to 7 for mouthwashes and 5.8 to 7.25 for toothpastes. The emphasis has been firmly on ways of modifying the composition of fruit juices and soft drinks. The feeling remains that not all the work done along these lines has been made available for inclusion in a review such as this, which has proved difficult to compile.

## References


1. HOLLOWAY PJ, MELLANBY M, STEWART RJC. Fruit drinks and tooth erosion. *Brit Dent J* 1958; **104**: 305–309.
2. BESIC FC. Carieslike enamel changes by chemical means. *J Dent Res* 1953; **32**: 830–839.
3. HARDWICK JL. Enamel caries: a chemico-physical hypothesis. Phase 1-chemical. *Brit Dent J* 1950; **89**: 1–6.
4. HILLS JE, SULLIVAN HR. Studies of the acid decalcification of human dental enamel – I. *Australian Dental J* 1958; **3**: 6–18.
5. HAY DI, PINSENT BRW, SCHRAM CJ, WAGG BJ. The protective effect of calcium and phosphate ions against acid erosion of dental enamel and dentine. *Brit Dent J* 1962: **112**: 283-287.
6. WAGG BJ, FRIEND JV, SMITH JS. Inhibition of the erosive properties of water ices by the addition of calcium and phosphate. *Brit Dent J* 1965; **119**: 118–123.
7. GRENBY TH, SALDANHA MG. The use of high-phosphorus supplements to inhibit dental enamel demineralisation by ice lollies. *Internat J of Food Sciences & Nutrition* 1995; **46**: 275–281.
8. MCDONALD JL, STOOKEY GK. Laboratory studies cocerning the effect of acid-containing beverages on enamel dissolution and experimental dental caries. *J Dent Res* 1973; **52**: 211–216.
9. REUSSNER GH, COCCODRILLI G, THIESSEN R. Effects of phosphates in acid-containing beverages on tooth erosion. *J Dent Res* 1975; **54**: 365–370.
10. BEIRAGHI S, ATKINS S, ROSEN S, WILSON S, ODOM J, BECK M. Effect of calcium lactate in erosion and S. Mutans in rats when added to Coca-Cola. *Pediatric Dentistry* 1989; **11**: 312–315.
11. RESTARSKI JS, GORTNER RA, MCCAY CM. Effect of acid beverages containing fluorides upon the teeth of rats and puppies. *J Amer Dent Assoc* 1945; **32**: 668–675.
12. ANDON MB, KANERVA RL, ROTRUCK JT, SMITH KT. Method of preventing tooth enamel erosion utilizing an acidic beverage containing calcium. 1992 *U S Patent no. 5,108,761.*
13. DUKE SA, MOLYNEUX K, JACKSON RJ. The effect of citrate in drinks on plaque pH. *Brit Dent J* 1988; **164**: 80–82.
14. GRENBY TH, PHILIPS A, DESAI T, MISTRY M. Laboratory studies of the dental properties of soft drinks. *Brit J Nutrition* 1989; **62**: 451–464.
15. MARTIN JJ, ISENBERG HD, SCHATZ V, TRELAWNY BS, SCHATZ A. Chelation, or metal binding, as a new approach to the problem of dental caries. *Revista Mensual de Ciencias Exactas [Madrid]* 1954; **14**: 311–317.
16. KOULORIDES TA, BUONOCORE MG. Effect of organic ions on solubility of enamel and dentine in acid buffers. *J Dent Res* 1961; **40**: 578–593.
17. POLLARD MA, DUGGAL MS, CURZON MJ. The effect of different concentrations of citrate in drinks on plaque pH. *Caries Res* 1993; **27**: 191–194.
18. DUGGAL MS, TAHMASSEBI JF, POLLARD MA. Effect of addition of 0.103% citrate to a blackcurrant drink on plaque pH in vivo. *Caries Res* 1995; **29**: 75–79.
19. MISTRY M, GRENBY TH. Erosion by soft drinks of rat molar teeth assessed by digital image analysis. *Caries Res* 1993; **27**: 21–25.
20. LUSSI A, JÄGGI T, SCHÄRER S. The influence of different factors on *in vitro* enamel erosion. *Caries Res* 1993; **27**: 387– 393.
21. GRENBY TH, MISTRY M, DESAI T. Potential dental effects of infants' fruit drinks studied in vitro. *Brit J Nutrition* 1990; **64**: 273–283.
22. BIBBY BG, MUNDORFF SA. Enamel demineralisation by snack foods. *J Dent Res* 1975; **54**: 461–470.
23. GROBLER SR, JENKINS GN, KOTZE D. The effects of the composition and method of drinking of soft drinks on plaque pH. *Brit Dent J* 1985; **158**: 293–296.
24. MEURMAN JH, HÄRKÖNEN M, NÄVERI H, KOSKINEN J, TORKKO H, RYTÖMAA I, JÄRVINEN V, TURUNEN R. Experimental sports drinks with minimal dental erosion effect. *Scand J Dent Res* 1990; **98**: 120-128.
25. SORVARI R, KIVIRANTA I, LUOMA H. Erosive effect of a sport drink mixture with and without addition of fluoride and magnesium on the molar teeth of rats. *Scand J Dent Res* 1988; **96**: 226–231.

26. Gedalia I, Galon H, Rennert A, Biderco I, Mohr I. Effect of fluoridated citrus beverage on dental caries and on fluoride concentration in the surface enamel of children's teeth. *Caries Res* 1981; **15**: 103–108.
27. Graehn G. [Acid erosion of tooth surface. 3. Prevention and therapy]. *Deutsche Stomatologie* 1991; **41**: 505–507.
28. Grenby TH, Saldanha MG. Comparison of Lycasin versus sucrose sweets in demineralization studies of human enamel and hydroxyapatite. *Caries Res* 1988; **22**: 269–275.
29. Meurman JH, Rytömaa I, Kari K, Laakso T, Murtomaa H. Salivary pH and glucose after consuming various beverages, including sugar-containing drinks. *Caries Res* 1987; **21**: 353–359.
30. Reynold EC. The prevention of sub-surface demineralization of bovine enamel and change in plaque composition by casein in an intra-oral model. *J Dent Res* 1987; **66**: 1120–1127.
31. Reynolds EC, Black CL. Reduction of chocolate's cariogenicity by supplementation with sodium caseinate. *Caries Res* 1987; **25**: 445–451.
32. Reynolds EC, Black CL. Cariogenicity of a confection supplemented with sodium caseinate at a palatable level. *Caries Res* 1989; **32**: 368–370.
33. Reynolds EC, Riley PF, Storey E. Phosphoprotein inhibition of hydroxyapatite dissolution. *Calcif Tiss Int* 1982; **34**: S52–56.
34. Gedalia I, Dakuar A, Shapira L, Lewinstein I, Goultschin J, Rahamim E. Enamel softening with Coca-Cola and rehardening with milk or saliva. *Amer J of Dentistry* 1991; **4**: 120–122.
35. Gedalia I, Ionat-Bendat D, Ben-Mosheh S, Shapira L. Tooth enamel softening with a cola type drink and rehardening with hard cheese or stimulated saliva in situ. *J Oral Rehabilitation* 1991; **18**: 501–506.
36. Grenby TH. Soft drinks, infants' fruit drinks and dental health. *Brit Dent J* 1990; **169**: 228.