

# Diet and the microbial aetiology of dental caries: new paradigms

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The microbial and dietary factors that drive caries have been studied scientifically for 120 years. Frequent and/or excessive sugar (especially sucrose) consumption has been ascribed a central role in caries causation, while *Streptococcus mutans* appeared to play the key role in metabolising sucrose to produce lactic acid, which can demineralise enamel. Many authors described caries as a transmissible infectious disease. However, more recent data have shifted these paradigms. *Streptococcus mutans* does not fulfil Koch's postulates – presence of the organism leading to disease, and absence of the organism precluding disease. Furthermore, molecular microbiological methods have shown that, even with a sugar-rich diet, a much broader spectrum of acidogenic microbes is found in dental plaque. While simple sugars can be cariogenic, cooked starches are also now recognised to be a caries threat, especially because such starches, while not 'sticky in the hand', can be highly retentive in the mouth. Metabolism of starch particles can yield a prolonged acidic challenge, especially at retentive, caries-prone sites. These changes in the paradigms of caries aetiology have important implications for caries control strategies. Preventing the transmission of *S. mutans* will likely be inadequate to prevent caries if a sufficiently carbohydrate-rich diet continues. Similarly, restriction of sucrose intake, although welcome, would be unlikely to be a panacea for caries, especially if frequent starch intake persisted. Instead, approaches to optimise fluoride delivery, to target plaque acidogenicity or acidogenic microbes, to promote plaque alkali generation, to increase salivary flow or replace fermentable carbohydrates with non-fermentable alternatives may be more promising.

**Key words:** Diet, dental plaque, microbiology, dental caries, *S. mutans*, sugar, starch

## INTRODUCTION

There have been numerous reviews on both the microbial aetiology of caries and on the dietary factors associated with caries. This article aims to review the history of the study of how dental caries occurs, and how theories to explain caries have evolved over the last 120 years. In particular, the article focuses on how a broad 'consensus' understanding of caries, from both a dietary and microbiological perspective, which seemed settled only a few years ago has more recently been overturned. The implications of these changes in understanding for strategies appropriate for caries control and prevention are also discussed.

## HISTORICAL BACKGROUND

The theory that microorganisms have a key role in dental caries had been suspected for centuries (van Leeuwenhoek, 1676), and this was further elaborated by Miller in 1890<sup>1</sup>. Miller postulated the chemo-para-

sitic theory of dental caries, with acids produced by the fermentation of sugars by bacteria as the primary factor in dental decay. This remarkable early study remains the bedrock of understanding how dental caries occurs to this day.

For most of the 20th century, debate raged as to the relative roles of particular microbial species in caries aetiology. In 1924, Clarke<sup>2</sup> identified a *Streptococcus*-like bacterium from dental caries lesions which, owing to its somewhat inconsistent cocco-bacillary form under the microscope, he suggested was a mutant *Streptococcus* and consequently proposed the name *Streptococcus mutans*. For many years this finding was under-appreciated, and attention instead focused on lactobacilli isolated from the mouths of those with caries<sup>3</sup>. Further, at this time, dietary deficiencies or inadequate absorption of diet were also considered as potentially significant factors in dental caries, and were purported to account for the lack of specificity of *Lactobacillus* infection leading to dental decay. The lactobacillus paradigm persisted for many years. In

large part this seems to have been because of the ready isolation of lactobacilli following culture in low-pH broths and on low-pH agar, as well as their well-known properties (e.g. in the food industry) as prolific producers of lactic acid.

### CRITICAL ROLE OF BACTERIA AND THE RISE OF *STREPTOCOCCUS MUTANS*

The critical role of microorganisms was confirmed following the Second World War, initially when antibiotics were shown to prevent caries<sup>4</sup>. Later, in a seminal study the development of germ-free (gnotobiotic) animal techniques allowed the conclusive demonstration of the essential role of dental microorganisms in the caries process. Germ-free rats were fed a highly cariogenic diet, developing no caries at all, whereas equivalent conventional animals developed numerous caries lesions<sup>5</sup>. In the 1960s the classic experiments of Keyes and Fitzgerald<sup>6</sup> shone the spotlight once again onto *S. mutans*, which was known to comprise a heterogeneous group with a range of serotypes. Four of these serotypes were subsequently elevated to species in their own right, *S. sobrinus*, *S. rattus*, *S. ferus* and *S. cricetus* – with *S. mutans sensu stricto* limited to the former serotypes c, e and f<sup>7</sup>. Thereafter, this whole group of species have often been referred to collectively as ‘the mutans-streptococci’. Of these species, *S. mutans* and *S. sobrinus* were the only organisms found in moderate numbers or with regular frequency in humans.

From the 1960s onwards, a great range of clinical studies established a clear link between the presence of mutans-streptococci and susceptibility to and incidence of caries<sup>8–11</sup>, not least because a number of excellent selective agar media were developed for *S. mutans*. In the same period, several studies were published connecting changes in the oral microflora to diet (specifically a high and frequent intake of fermentable sugar) and to dental caries<sup>12–16</sup>. As a result of these data, the focus on *S. mutans* became steadily more intense. A number of papers were published that specifically identified *S. mutans* as an ‘odontopathogen’<sup>17</sup> and in some cases the odontopathogen. The particular biochemical characteristics of the mutans-streptococci related to their proposed cariogenic role were put under the microscope. The entire pathway of glucose and sucrose metabolism was of particular interest, ranging from the sugar uptake systems (either high or low affinity) through glycolytic and fermentative pathways to proton-translocating ATPases<sup>18–20</sup>. These studies established that *S. mutans* was obviously adapted for a glycolytic ‘lifestyle’ and had a moderately higher rate of acid production from sugar than other oral streptococci<sup>21</sup>. In particular, however, this study reinforced earlier mixed culture data<sup>22,23</sup>

that suggested *S. mutans* was especially able to continue to generate acid relatively rapidly and continue to grow in moderately acidified environments. The high tolerance of *S. mutans* to environmental acidification was notable, driven by DNA repair mechanisms, a broader tolerance of intracellular acidification, higher activity of H<sup>+</sup>-ATPases at low pH and a range of other mechanisms<sup>24</sup>. In addition, the production of extracellular polysaccharides (EPS)<sup>25,26</sup> was also mooted as an important contributor to *S. mutans* pathogenicity. From these studies, a consensus of *S. mutans* as the ‘arch-villain’ in causation of dental caries arose.

The ecological studies that demonstrated *S. mutans*’ greater ability to survive and flourish in low-pH conditions generated from sugar metabolism<sup>22,23</sup> helped to explain how *S. mutans* is found more commonly than a range of other organisms under conditions where there is a high and/or frequent sugar intake. Furthermore, other factors *in vivo*, such as reduced buffering capacity in xerostomia, would also act to promote *S. mutans* selection in plaque. As the genome of *S. mutans* was elucidated, it became clear how the organism had adapted to its ecological niche, with an exceptionally broad range of genes found for carbohydrate uptake systems, together with a number for acid tolerance mechanisms and glucan binding<sup>27</sup>: all are assumed to contribute to *S. mutans* competitiveness in the oral environment.

### DIET, CARIES AND PLAQUE METABOLISM: SUGARS AND SUCROSE

The most studied components of diet in relation to caries are sugars, and in particular sucrose, which has widely been ascribed a central role in caries aetiology. The Vipeholm caries studies<sup>28</sup> unequivocally connected the quantity and frequency of sucrose intake with caries, together with significant effects on cariogenicity of the physical form of the food containing sucrose. This seminal study is reinforced by earlier studies of the lack of caries in populations less exposed to ‘Western’ diets high in sucrose<sup>3</sup>. Furthermore, the Hopewood House study showed that a cohort of children in an orphanage whose dietary intake of refined carbohydrates was deliberately restricted showed significantly less caries than matched controls in the general population<sup>29</sup>. At a country-wide population level, when dietary sugars were restricted by rationing during World War II, rates of caries in the population fell sharply<sup>30,31</sup>. Because of this focus on sugars, and in particular on sucrose, in parallel with the focus on *S. mutans*, studies concentrated almost exclusively on the role of sucrose in dental caries. Sucrose catabolism, in common with pathways for glucose, fructose and a

number of other monosaccharides and disaccharides, can readily yield acidic end products, especially lactate<sup>32</sup>. Uniquely, however, sucrose can also be metabolised via glucosyl- and fructosyl-transferases (GTFs/FTFs) to form glucans or fructans, respectively<sup>33</sup>. These polymers vary in structure and solubility and have been proposed to serve either as a reserve nutritional source during the 'feast-famine' existence of dental plaque and/or as a key contributor to the physical integrity of plaque, acting as a 'glue' to hold plaque together, as well as altering the diffusion characteristics of plaque<sup>34,35</sup>.

### FREQUENCY OF SUGAR INTAKE AND 'CRITICAL PH'

When considering the effect of frequency of acid challenge on caries, consideration should be given to the chemical characteristics of plaque as well as its microbiological characteristics, and the effect that this can have on demineralisation and remineralisation.

It is sometimes said that when bacterially produced acids are sufficient to reduce plaque pH below the so-called 'critical pH', then the enamel will start to dissolve. However, the picture is rather more complex than this<sup>36</sup>. Whether or not enamel will dissolve depends largely on the 'degree of saturation' with respect to enamel ( $DS_{En}$ ) of the fluid in contact with it and in the case of caries this will be the plaque-fluid (PF).  $DS_{En}$  is dependent upon the calcium and phosphate concentrations (strictly, activities) of the PF and the pH. At resting pH, sufficient calcium and phosphate are present in the PF to both prevent demineralisation and to drive remineralisation. As the pH falls, however, for given calcium and phosphate concentrations, a point will be reached when these concentrations are insufficient to prevent dissolution, and net demineralisation will occur. In principle, if sufficient calcium and phosphate are present then demineralisation will be prevented no matter how acidic the environment. For example, Gao *et al.*<sup>37</sup> showed that enamel resisted dissolution even at pH 2.5 when sufficiently large amounts of calcium and phosphate were added to the demineralising solution.

Plaque-fluid calcium and phosphate concentrations will vary within and between individuals, as will enamel solubility within and between teeth. Therefore, the critical pH is not a fixed value, despite often being cited as such, and in fact a range of values exists<sup>36,38,39</sup>. This is typically between about pH 5.0 and 5.5.

In a sense, fluoride lowers the critical pH in more than one way. During demineralisation events, fluoride reduces the rate of demineralisation of enamel.

However, counter-intuitively, the low pH itself may accelerate the deposition of fluoridated apatites, which are more resistant to subsequent dissolution, with a fuller lesion consolidation than might be seen during remineralisation at pH values closer to neutral, where arrest may occur through extensive remineralisation of the surface of the lesion.

Frequent sucrose challenges may, in effect, decrease the critical pH. Pearce<sup>40</sup> suggested that plaque can act as a 'saturation buffer', releasing calcium into the PF during acidic challenges, and that repeated pH challenges would deplete the calcium reservoir and hence this buffering effect.

In plaque, both calcium and fluoride, associated with bacterial lipoteichoic acid, are likely to be released during acidogenesis<sup>41,42</sup> most likely via protonation of anionic binding sites<sup>42</sup>. Dissolution of calcium fluoride-like minerals, whose incorporated phosphate renders them pH dependent in terms of solubility, may also be involved. However, there is some doubt over whether these deposits form at all, or if they do, whether they are substantive, at oral fluoride concentrations similar to those prevailing during application of fluoride from mass-market toothpastes<sup>43</sup>. Regardless of this, subsequent clinical studies into the effect of frequency of sucrose challenge on plaque composition confirmed the depletion effect for calcium and fluoride<sup>44,45</sup>.

The ability of fluoride to mitigate the effects of frequent sucrose challenges has been demonstrated during *in situ* studies. Duggal *et al.*<sup>46</sup> reported that in subjects who did not use fluoride toothpaste, significant demineralisation of enamel inserts placed intraorally occurred when sucrose-induced caries challenges exceeded three per day, when fluoride toothpaste was used, seven or more challenges were needed before any demineralisation occurred. A similar effect was reported by Cury *et al.*<sup>47</sup>.

A further factor to consider is the effect of frequency of sucrose challenges and hence, acid production, on enamel itself; it has been suggested that protonation of as yet undissolved dental mineral may leave it more vulnerable to dissolution during subsequent challenges<sup>48</sup>. Presumably, more frequent protonation would accentuate this effect.

Overall, these observations correlate with authoritative reviews that conclude that the balance of studies does not demonstrate a relationship between the quantity of sugar, but a moderately significant relationship of frequency of sugar to dental caries<sup>49-51</sup>.

### TARGETED *S. MUTANS* CONTROL STRATEGIES FOR CARIES

The consensus that *S. mutans* was the *sine qua non* for caries led to a search for *S. mutans*-specific

remedies. Caries was referred to as a transmissible infectious disease. Caufield and colleagues<sup>52</sup> demonstrated a ‘window of infectivity’ for *S. mutans* and thus approaches to limit childhood acquisition of the key organism were investigated, for example using chlorhexidine varnishes<sup>53</sup>. Vaccine strategies have been investigated and were reviewed by Russell<sup>54</sup>, although the risk–benefit ratio of this approach remains to be established. Replacement therapy, wherein related species of mutans-streptococci deficient in a particular metabolic pathway are used to displace wild-type mutans-streptococci has also been developed<sup>55</sup>.

### NEW METHODS, A BROADER MICROBIAL AETIOLOGY

As recently as 2001, a systematic review<sup>56</sup> appeared to cement the central role of *S. mutans* in dental caries. However, at the same time as the genomic studies described above on *S. mutans*, molecular methods were also being applied to define better the oral microflora in general, as well as that specifically associated with caries. These studies were at least *a priori* less prone to the inherent bias of cultural studies using selective and non-selective agar growth media, where, in part, ‘you will find what you look for’. Molecular microbiology studies identified a broader range of caries-associated bacterial species. Aas *et al.*<sup>57</sup> found species including *Actinomyces*, *Abitrophia*, *Atopobium*, *Bifidobacterium*, *Lactobacillus* and *Veillonella* in association with caries. Interestingly, as well as describing this broader aetiology, they appeared also to endorse the secondary role that non-fermentative species such as *Veillonella* could play in the caries microbial community that had first been suggested from animal<sup>58</sup> and *in vitro* experiments<sup>59</sup> more than 30 years earlier. More recently, in a cross-sectional study, Gross *et al.*<sup>60</sup> found that although *S. mutans* was often found in high numbers in the early stages of caries, it was also found in some healthy subjects, and was not statistically associated with the severity of caries; instead, *Propionibacterium* was associated with caries progression, although its numbers were relatively low. The same group carried out a study in which subjects with and without caries were followed longitudinally<sup>60</sup>. This study again found *S. mutans* in high numbers in many subjects, but some subjects with caries had no *S. mutans*. In these subjects with caries, but no *S. mutans*, elevated levels of *S. salivarius*, *S. parasanguinis* and *S. sobrinus* were found. As with the Aas *et al.* study<sup>57</sup>, *Veillonella* spp. was associated with both caries and especially with total acid-producing bacteria. The presence of *Veillonella* spp., but not of *S. mutans*, was predictive of caries risk<sup>60</sup>.

### RECENT STUDIES ON THE INTERACTION OF DIET, MICROFLORA AND CARIES

Relatively few studies using state-of-the-art molecular biology and more modern taxonomic classification have attempted to connect the key components involved in caries: diet and bacterial microflora. These key factors were examined in relation to severe early childhood caries (SECC) using polymerase chain reaction (PCR) detection of three predetermined target bacteria: *S. mutans*, *S. sobrinus* and *Bifidobacterium* species<sup>61</sup>. The study found a range of dietary factors positively associated with caries, including between-meal juice, solid retentive food, putative cariogenicity of food and frequency of eating. All three bacteria selected were associated with SECC, and the two mutans-streptococci with lesion recurrence. Carriage of *S. mutans* was associated with cariogenic food intake, and the combination of various food factors with the presence of *S. mutans* was also associated with caries. Using more traditional methods, including a novel selective medium for bifidobacteria, Kaur *et al.*<sup>62</sup> found increased numbers of bifidobacteria, lactobacilli, mutans-streptococci and yeasts in saliva in caries-active compared to caries-inactive subjects; both bifidobacteria and yeasts were also highly correlated with ‘caries-associated behaviours’ (i.e. poor oral hygiene, total sugar intake and frequency of sugar intake) and use of these microbiological parameters in a discriminant analysis allowed correct classification of caries status in approximately 90% of cases.

### BEYOND SUCROSE – OTHER CARIOGENIC DIETARY COMPONENTS

While the influence of high sugar (sucrose) diets in higher rates of caries is incontestable, it has been clear for some time that other dietary carbohydrates also have the potential to be cariogenic<sup>63</sup>. Some studies found that starchy foods did not produce drops in pH that were as great as those for sucrose or glucose<sup>64,65</sup>. However, other studies showed that a number of foods that contain high concentrations of starches, particularly when in cooked form such as in potato chips (crisps) and biscuits, were highly retentive in the oral cavity; the degree of retentiveness of starches in the mouth bears almost a counter-intuitive relationship with their ‘stickiness’, as assessed by tactile sensation in the hand<sup>66</sup>. This, and a later study<sup>67</sup> by the same group found that food particles from cooked starches were retained for up to 20 minutes. While caramels and chocolate bars gave rise to large initial concentrations of sucrose, these were rapidly lost, with little or no detectable particles of food remaining after only 3 minutes. In contrast, cookies and crackers yielded sucrose values in the mouth that continued to

rise for up to 15 minutes. Similar profiles were seen for organic acids produced in the food particles by microbial degradation. Similarly, a study by Linke and Birkenfeld<sup>68</sup> found the overall challenge from cooked starch products to be greater than for more obviously sugar-rich candy bars. A broader review of the earlier literature on starch and caries was provided by Lingström *et al*<sup>69</sup>. More recently, dietary survey-based prospective longitudinal studies on incidence of caries showed that processed or cooked starches were associated with greater new caries risk<sup>70,71</sup>. In the latter of these studies, the authors separated consumption of potential caries-risk foods when consumed as snacks as opposed to as part of a meal. Snack consumption of cooked starches was the sole foodstuff that showed significant association with caries; regular soda pop consumption was also associated with caries while toothbrushing was protective<sup>71</sup>.

### COMPONENTS WITH ANTI-CARIES POTENTIAL

Fluoride, supplied either via drinking water<sup>72</sup> and more widely via toothpastes and other oral health-care products, has widely been credited as the key factor in reducing rates of dental caries<sup>73-75</sup>. Moreover, studies, such as Chankanka *et al.*<sup>71</sup>, which showed a beneficial effect of toothbrushing on the risk of caries may reflect increased frequency of fluoride delivery. Such an effect of fluoride, as opposed to toothbrushing *per se* is supported by the study of Koch & Lindhe<sup>76</sup>. This reduction in caries has most often been attributed to the effects of caries on tooth enamel<sup>77</sup>. However, fluoride does have both direct and indirect effects on oral bacteria. Fluoride is not present in sufficient quantities in plaque fluid, typically only as high as approximately 1 mM (19 ppm F), to exert overt antimicrobial effects such as bacterial kill or growth inhibition. However, these average values should be treated with some caution. Plaque fluoride concentrations following application from toothpastes and mouth-rinses are reported in diverse formats. Researchers report data for whole plaque either wet<sup>78</sup> or dried<sup>79</sup>, or as PF concentrations<sup>80</sup>. In some cases the plaque is acidified before analysis, either by direct addition of mineral acid<sup>81</sup> or by exposure to sucrose<sup>82</sup>, to estimate how much fluoride might be released during a cariogenic, or at least an acidic challenge. However, while the reported value is almost invariably an average, fluoride concentration gradients exist in plaque<sup>83</sup> and for any given average, higher (as well as lower) concentrations will exist. Whether or not these are sufficiently high to exert an antimicrobial influence in the clinical setting can only be a matter for speculation, but it raises the possibility that fluoride may have had a hitherto undiscerned effect on caries. A final point to note is that plaque-fluid

fluoride concentrations following application from toothpaste are apparently absent from the literature, except in abstract form<sup>84,85</sup> and more information is needed. However, these concentrations of fluoride can exert significant metabolic effects on various oral bacteria, including *S. mutans*<sup>86,87</sup>. Furthermore, at least *in vitro* these low concentrations of fluoride could have profound effects on the competitiveness of *S. mutans* under conditions of glycolytic acid production<sup>88,89</sup>. The elegant studies of Marquis and colleagues<sup>87,89</sup> describing the metabolic effects of fluoride on oral bacteria, showed that these effects were in large part driven by the weak-acid properties of fluoride, and were especially pronounced at lower pH values. Marquis<sup>89</sup> also pointed out that similar properties were also characteristic of a number of organic acids and food preservatives, which are also widespread in human diets, at least in the developed world. The role of these dietary components in caries has never been investigated, and remains intriguing.

A wide range of non-fermentable, or poorly fermentable, sugars, sugar substitutes and sweeteners have been proposed for many years as a solution to an increasing caries problem associated with humans' sweet tooth habits. In particular, xylitol has been suggested for many years as a potential anti-caries agent. Xylitol is a 5-carbon sugar alcohol found naturally in various plants. It has potential anti-caries activity by virtue of its futile-cycle driven inhibitory effect on *S. mutans* sugar metabolism<sup>90</sup>, while the majority of the oral flora do not metabolise xylitol at all. The effects of xylitol on caries have recently been discussed, relating both to inclusion in chewing gums<sup>91</sup> and more generally<sup>92</sup>. Clinical benefits have been seen in some studies, although these may be restricted to those consuming higher quantities of xylitol or in higher risk individuals<sup>93,94</sup>. Further, the unequivocal demonstration of a more general benefit remains elusive<sup>95</sup>.

A number of foods have putative cariostatic properties, including milk and dairy products, apples, cranberries, tea, peanuts and high-fibre foods (reviewed by Moynihan<sup>96</sup>). Traditionally, milk and dairy products have been associated with healthy teeth because of their relatively high calcium content and, presumably, some systemic effect. While this may not be wholly accurate, calcium may still confer a benefit. Although cows' milk has a moderately high lactose content, any cariogenic challenge presented by this lactose seems to be more than offset by the calcium content, along with phosphate, through reductions in undersaturation with respect to enamel during acidogenesis, along with the protective effects of caseins and other milk proteins. Epidemiological studies have demonstrated that associations between milk consumption and caries are at least neutral<sup>97</sup> and in some cases beneficial<sup>98,99</sup>.

Consumption of some types of cheese may be able to tip the 'caries balance' in favour of net remineralisation through their ability to increase salivary flow and pH<sup>100</sup>, elevate plaque calcium concentration<sup>101</sup> and possibly deliver calcium phosphopeptide-amorphous calcium phosphate (CPP-ACP) nano-complexes. There is clinical evidence that CPP-ACP has clinical activity in the remineralisation process<sup>102</sup>. However, the possible benefits of consuming sufficient cheese to confer any caries benefit should be offset against the concomitant increase in consumption of saturated fats.

Flavonoids in apples, cranberries, tea and other products have demonstrated a range of effects, including the ability to reduce bacterial adhesion and antibacterial properties, in experimental studies in animals and in some cases, humans. A recent review considered the evidence that dietary polyphenols decrease the risk of caries<sup>103</sup>. Fibrous foods and peanuts have also demonstrated the ability to stimulate salivary flow, which is itself linked to a caries benefit<sup>96</sup>. The data relating to caries benefits are to some extent equivocal but it is reasonable to say that as well as being, at the least, 'caries neutral', consumption of these foods in place of potentially cariogenic alternatives would lead to better oral health, as well as helping to improve overall health.

For many years, the potential of compounds, such as urea, which could generate alkali in plaque, and thus combat the damaging effects of microbially generated acids was known<sup>104</sup>. It was also recognised some years ago that renal patients with depleted or no kidney function had lower rates of caries<sup>105,106</sup>, concomitant with raised salivary urea concentrations and increased resting salivary pH. On this basis, the use of urea supplementation of either dental products<sup>107</sup> or more recently of chewing gums<sup>108</sup> has been advocated, although, anecdotally, reports of the ammonia odour of such products on use may limit consumer acceptability. Similarly, there is a significant literature on the anti-caries potential of arginine<sup>50</sup>. Indeed, more recent data suggests the arginolytic potential of dental plaque is inversely correlated to experience of caries<sup>109</sup>.

## CONCLUDING OBSERVATIONS

Dental caries is unequivocally a microbial disease, resulting from metabolism of dietary carbohydrates by members of the oral microflora. However, it is disingenuous to describe caries as a transmissible infectious disease, as humans have no choice in acquisition of an oral microflora. In particular, despite three decades of studies focused on *S. mutans* and closely related species, the relationship between the presence of specific bacteria and disease clearly does not meet Koch's key postulates that presence of the organism leads to

disease, and that absence of the organism precludes development of disease. Thus even if approaches targeted to prevent 'transmission' were successful, the available data suggest that a sufficiently carbohydrate-rich diet would still lead to caries. Instead, mutans-streptococci represent the most common manifestation of frequent sugar consumption and consequential microbial plaque acidification. Modern microbiological methods have shown that even in these sugar-rich, regularly acidified circumstances a broader spectrum of microbes is found in plaque. This change in paradigm has implications for caries control strategies. For example, targeted approaches for specific *S. mutans* control may be limited in effect, although more general approaches to target plaque acidogenicity or acidogenic microbes may be more promising. However, the relative importance of diet and specific microflora are not equal. As Zero<sup>110</sup> has pointed out, the lines of evidence linking the cariogenic potential of excessive/frequent carbohydrate intake are much stronger than evidence linking particular species of oral microorganisms, such as mutans-streptococci, with caries. Instead, the widely reported association of these organisms with caries is more in the nature of an indicator of a high-caries-risk diet and/or other predisposing factors (depleted saliva flow or function, presence of dentures, etc.). There is thus probably no alternative to modification of diet to completely remove the risk of caries.

## Conflict of interest

Authors Bradshaw and Lynch are both employees of GlaxoSmithKline Consumer Healthcare.

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