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Systematic Review

Associations between dietary added sugar intake and micronutrient intake: a systematic review

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There is increasing concern that high intakes of added sugars might compromise intakes of micronutrients. The objectives of this systematic review were (1) to determine whether dietary added sugar intake was associated with micronutrient intakes, and if so, whether there was evidence of micronutrient dilution as a result of higher dietary added sugar intake and (2) if micronutrient dilution was present, to determine whether there was sufficiently robust evidence to support a threshold effect above which there was a significant decline in micronutrient intake or status relative to the recommended intakes. A systematic computerised literature search was undertaken, limited to studies written in English published from 1980 onwards and further studies identified through hand searching papers. Fifteen studies that assessed associations between intakes of added sugars or non-milk extrinsic sugars and micronutrients were included. Overall, there are insufficient data and inconsistency between studies in relationships between added sugars and micronutrient intakes, with no clear evidence of micronutrient dilution or a threshold for a quantitative amount of added sugar intake for any of the micronutrients investigated. The current evidence base is considerably constrained by methodological issues. Further research is required to determine which food products high in added sugars might adversely affect micronutrient intakes by displacing other food items from the diet. Analyses should take into account the magnitude of any observed associations to determine their true biological significance.

Added sugars: Non-milk extrinsic sugars: Nutrient density: Micronutrient intake

In addition to increasing the risk of dental caries (Ruxton *et al.* 1999), it has been suggested that high intakes of added sugars may adversely compromise micronutrient intake and status in the general population. Although guidelines on added sugar intake in relation to preventing dental caries have been established (World Health Organization, 2003), guidelines in relation to limiting micronutrient dilution are less clear and more controversial (Ruxton *et al.* 1999; Murphy & Johnson, 2003). However, it is unclear whether the current literature provides a sufficiently robust evidence base to support or refute this on the grounds of micronutrient dilution.

The definitions used to determine sugar consumption are critically important in assessing the associations between intakes of sugar and micronutrients. In the USA, added sugars are defined as sugars, sweeteners and syrups that are eaten as such or used as ingredients in processed and prepared foods, excluding sugars present in milk and fruit (Institute of Medicine of the National Academies, 2002). In the UK the categorisation of non-milk extrinsic sugars (NMES) is favoured. NMES are defined as all sugars that are not naturally present in milk and milk products and are broadly synonymous with the term free sugars. NMES is similar to, but not identical to, added sugars since the former categorisation incorporates sugars that are found in fruit juices and 50 % of the sugars in cooked and processed fruit (Kelly *et al.* 2005).

In 2000 the Dietary Guidelines Advisory Committee recommended that people should 'choose beverages and foods that moderate your intake of sugars' (US Department of Agriculture, 2000). The guidelines from the WHO in 1990 have been reiterated by the new Joint WHO/FAO Expert Consultation on Diet, Nutrition, and Prevention of Chronic Disease who have recommended that intake of free sugars be no more than 10 % of total energy consumed (World Health Organization, 1990, 2003). The American Institute of Medicine in the 2002 Dietary Reference Intakes concluded that there was insufficient evidence to set an upper intake level for added sugars since there was no specific adverse health outcome associated with 'excessive' intake (Institute of Medicine of the National Academies, 2002). However, they suggested a maximal intake level of 25 % of energy intake from added sugars because of the growing concerns about inadequate intakes of micronutrients, but with the caveat that this should not be interpreted as a recommended intake level.

Abbreviations: AI, adequate intake; NMES, non-milk extrinisic sugars; RDA, recommended daily allowance; RNI, reference nutrient intake.

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It is evident from dietary data that, on the whole, populations have intakes of sugar that are consistently higher than those recommended (Munoz *et al.* 1997; Krebs-Smith, 2001). Data from the US Continuing Survey of Food Intakes by Individuals (1994-6 and 1998) show that the average consumption of added sugar intakes (expressed as % energy) were 15 % in 2–3 year olds and 17 % in 4–5 year olds (Kranz *et al.* 2005) with similar intake levels being reported by national dietary surveys in European countries (Gibson, 1997*b*; Øverby *et al.* 2004). The consequences of this intake level on the quality of the diet are unclear.

The aims of this systematic review were therefore (i) to determine whether dietary added sugar intake is associated with micronutrient intakes, and if so, the magnitude and the direction of the associations; (ii) to assess gender and/or age group differences in any of these observed associations; (iii) to assess whether there is evidence of micronutrient dilution as a result of higher dietary added sugar intake; (iv) if micronutrient dilution is present, to evaluate if the evidence is sufficiently robust to support a threshold effect, above which there is a significant decline in micronutrient intake relative to the recommended intakes. Methodological issues which might limit the current evidence base or affect the interpretation of the evidence are also considered.

Methods

Micronutrient inclusion criteria

The inclusion criteria were made a priori based on the likelihood that added sugar intakes could impact on micronutrient intakes. Only those minerals and vitamins sourced from a few major foods and/or in which deficiencies or sub-optimal status are more likely to occur were included (minerals Ca, Fe, Mg, and Zn; vitamins A, B_1 (thiamin), B_2 (riboflavin), B_6 (pyridoxine), folate, vitamin C (ascorbic acid) and E). Micronutrients with ubiquitous sources were excluded since added sugar intake is unlikely to displace them from the diet (minerals Na and P; vitamins B_3 (pantothenic acid), B_{12}, niacin, D and K).

Literature search strategy

A systematic computerised literature search of published studies from 1980 onwards was undertaken in July 2005. The search was conducted in EmBASE, Ovid Medline and ScienceDirect. Identification of further studies was made through hand searching original articles and reviews on the subject found by the electronic search. Articles were included if they were observational studies conducted in healthy individuals and published in English from 1980.

Search terms

The following search strategy was used for Medline using common medical subject headings (MESH) terms and adapted for use in other databases. Studies were limited to those written in English from January 1980 to July 2005. The following terms were used: dietary carbohydrates, dietary sucrose (this term was only introduced in 1997), dietary sugar, sugar intake *and* nutrient, vitamins, micronutrients (this term was only introduced in 1996), ascorbic acid, trace elements, thiamin, iron, riboflavin, calcium, folate, magnesium, folic acid, zinc, pyridoxine, tocopherol.

Processing of articles

Initial screening of articles was undertaken on the basis of the abstracts. If it was clear from the abstract that the article did not meet the inclusion criteria for this review it was rejected. The full text was obtained on all remaining articles and was further evaluated for inclusion. All articles were then hand searched for any further relevant publications.

Each study was evaluated on the basis of the study design, sample size, how representative of the general population it was, the method and limitations of the dietary assessment method employed, the way in which the food intake data were analysed, how micronutrient intake was assessed and the methods of statistical analyses employed.

Results

Fifteen studies were identified for inclusion in this review. The details of the studies are given in Table 1. The majority of studies (*n* 10) expressed sugar intake as a percentage of reported energy intake, whilst two studies expressed added sugars as absolute intake and two studies analysed the data by both methods. The effect of these different approaches in assessing associations with micronutrient intakes is discussed in detail in the discussion section.

Minerals

Inconsistent results were observed between intakes of Ca, Fe and Mg with added sugar and NMES intakes (Table 2). With respect to Fe intakes, a gender difference was noted with the majority of studies in men reporting null associations between intakes of Fe with added sugars or NMES (Baghurst *et al.* 1992; Gibson, 1997*a*, 2001; Charlton *et al.* 2005), but in women both inverse (Doyle *et al.* 1989; Bowman, 1999; Charlton *et al.* 2005) and null associations (Baghurst *et al.* 1992; Gibson, 2001) were found. Furthermore, in women non-linear relationships between Fe intake and added sugar intakes were also reported (Gibson, 1997*a*) with women in the lowest or highest category of NMES intake having the lowest Fe intakes and only those reporting average intakes of NMES (13–15·7 % of energy intake) achieving the recommended intakes of Fe.

For Zn, results were more consistent with most studies reporting inverse associations between intakes with NMES and added sugar intakes both in adults (Doyle *et al.* 1989; Baghurst *et al.* 1992; Gibson, 1997*a*; Bowman, 1999; Charlton *et al.* 2005) and children (Gibson, 1997*b*; Lyhne & Ovesen, 1999) but some null associations were also noted (Charlton *et al.* 2005). However, in some populations the proportion of individuals meeting the recommended daily allowance (RDA) for Zn was either low across sugar intake tertiles (Gibson, 1997*b*; Bowman, 1999) or in others, Zn intakes remained above the reference nutrient intake (RNI) for all quintiles of sugar intakes (Gibson, 1997*a*; Lyhne & Ovesen, 1999). Inconsistencies between studies in the proportion of people reaching recommended intakes were also observed for Ca.

Table 1. Summary of studies included in the review

Reference	Study details				Dietary assessment
	Age group (years)	Study (country)	Sample size (*n*)	Year(s) collected	Measurement instrument
Alexy *et al.* 2003*	2–18	Longitudinal cohort study (Germany)	849	1985-2001	3d WDR
Baghurst *et al.* 1992	17+	National dietary survey (Australia)	1848	1988-9	FFQ
Bowman, 1999	2+	CSFII (US)	14 709	1994-6	24 h R
Charlton *et al.* 2005	60+	Convenient sample of black elderly (South Africa)	285		24 h R
Doyle *et al.* 1989		Convenient sample of pregnant women (UK)	419		7d DR
Forshee & Storey, 2001	2–19	CSFII (US)		1994-6	2 × 24 h R
Frary *et al.* 2004	6–17	CSFII (US)	3038	1994-6 and 1998	2 × 24 h R
Gibson, 1997*a*	16–64	Dietary and Nutritional Survey (Great Britain)	2197	1986-7	7d WDR
Gibson, 1997*b*	1·5–4·5	NDNS of pre-school children (Great Britain)	1675	1992-3	4d WDR
Gibson, 2001	65+	NDNS of people aged 65 years and over (Great Britain)	806	1994-5	4d WDR
Kranz *et al.* 2005	2–5	CSFII (US)	5437	1994-5 and 1998	2 × 24 h R
Lewis *et al.* 1992	4+	Nationwide Food Consumption Survey (US)	27 942	1977-8	3d DR
Lyhne & Ovesen, 1999	4–14	Dietary Habits Survey (Denmark)	983	1995	7d DR
Øverby *et al.* 2004	4, 9 and 13	Representative sample of children (Norway)	2206	2000-1	4d DR
Rugg-Gunn *et al.* 1991	11–14	Dietary study of children (UK)	405	1979-81	5 × 3d DR

WDR, weighed dietary record;; R, recall; DR, dietary record based on estimated weights of foods; CSFII, Continuing Survey of Food Intakes by Individuals; NDNS, National Diet and Nutrition Survey.
*Longitudinal study design.

One study examined relationships between mineral intakes and the major food sources of added sugars in children (Frary *et al.* 2004). Significant inverse associations were found between sugar-sweetened beverages and the percentage of the adequate intakes (AI) for Ca and Fe. Inverse associations were also observed between sugars and sweets and sweetened grains and percentage of AI for Fe. Conversely, significant positive associations were found between pre-sweetened cereals and the percentage of AI for Ca and Fe, and further between sweetened dairy products and Ca.

Micronutrient status was only examined in older populations for Fe, with no associations observed between added sugars or NMES and serum ferritin levels, in men or women (Gibson, 2001; Charlton *et al.* 2005).

Vitamins

Inconsistent results were found for vitamins A, B_1, B_2, B_6, folate, C and E with both null and inverse associations reported with added sugar intake, and in the case of vitamin B_2 and C, positive associations were also reported (Tables 3 and 4). However, mean intake levels of vitamin A, B_1, B_2, B_6 and C tended to reach or exceed recommended levels across the range of added sugar intakes (Baghurst *et al.* 1992; Lewis *et al.* 1992; Gibson, 1993, 1997*b*; Bowman, 1999; Lyhne & Ovesen, 1999; Alexy *et al.* 2002; Øverby *et al.* 2004). For vitamin E, in UK adults reported average intakes were all in excess of the RNI (Gibson, 1997*a*), but other studies reported insufficient or marginal vitamin E intakes (relative to the RDA) irrespective of added sugar intake (Bowman, 1999; Lyhne & Ovesen, 1999; Øverby *et al.* 2004; Charlton *et al.* 2005). For folate, overall intakes were low in women and children irrespective of added sugar intake (Baghurst *et al.* 1992; Gibson, 2001; Alexy *et al.* 2003; Frary *et al.* 2004; Charlton *et al.* 2005). This may in part explain the distinct gender differences observed in folate and added sugars or NMES associations, with more studies in women reporting significantly lower folate intakes with high sugar intakes (Doyle *et al.* 1989; Baghurst *et al.* 1992; Bowman, 1999; Charlton *et al.* 2005), and one a null association (Gibson, 2001), compared with studies in men (Baghurst *et al.* 1992; Bowman, 1999; Gibson, 1997*a*, 2001; Charlton *et al.* 2005).

There was a distinct variability between studies in quantifying the actual effect of inverse relationships. For example in children inverse associations between intakes of added sugars and vitamin B_1 were observed. In one study it equated to only a 3 % decrease in vitamin B_1 intake between those children consuming less than 8 % energy as added sugars and those consuming more than 16·6 % (Alexy *et al.* 2003). In the second study a larger difference between the bottom (22 %) and top quartile (31 %) of added sugar intake was found, with those in the top quartile not meeting recommended intakes for B_1 (Øverby *et al.* 2004).

As observed with Fe, non-linear relationships between intakes of added sugars and vitamins were found. For example, women who were moderate consumers of added sugars and NMES were found to have higher vitamin E intakes than those in the highest and lowest categories of sugar intakes (Gibson, 1997*a*). Different results were found with added sugars and NMES, with positive associations between

Table 2. Summary of studies assessing associations between sugar intake and mineral intakes

Reference	Population		Minerals		Sugar intakes		Association	
	Age (yr)	Gender	Evaluated	Expressed as	Definition used	Expressed as	Direction	*P*
Alexy *et al.* 2003	2–18	M+F	Ca, Fe	%RV	AS	%EI	inverse	< 0·01
Baghurst *et al.* 1992	17 +	M	Ca	absol	AS	%EI	positive	< 0·05
	17 +	F	Ca, Fe	absol	AS	%EI		NS
	17 +	M	Fe	absol	AS	%EI		NS
	17 +	M	Mg, Zn	absol	AS	%EI	inverse	< 0·001
	17 +	F	Mg, Zn	absol	AS	%EI	inverse	< 0·001
Bowman, 1999	2 +	M + F	Ca, Fe, Mg, Zn	absol	AS	%EI	inverse	< 0·0125
Charlton *et al.* 2005	60 +	M	Ca, Fe, Mg, Zn	absol	AS	g/d		NS
	60 +	M	Ca, Fe, Mg, Zn	absol	AS	% EI		NS
	60 +	F	Ca	absol	AS	g/day		NS
	60 +	F	Ca, Fe, Mg, Zn	absol	AS	% EI	inverse	< 0·001
	60 +	F	Fe, Mg, Zn	absol	AS	g/d	positive	< 0·05
Doyle *et al.* 1989		F	Ca, Fe, Mg, Zn	/1000 kcal	AS	g/d	inverse	< 0·001
Forshee & Storey, 2001	2 +	M + F	Ca	%RDA	AS	g/d	inverse	< 0·01
	6–11	M + F	Ca	%RDA	AS	g/d		NS
	12–19	M + F	Ca	%RDA	AS	g/d		NS
	2 +	M + F	Fe	%RDA	AS	g/d	positive	< 0·01
	6–11	M + F	Fe	%RDA	AS	g/d	positive	< 0·01
	12–19	M + F	Fe	%RDA	AS	g/d	positive	< 0·01
Frary *et al.* 2004	6–17	M + F	Ca, Fe	%AI	foods	g/d	see text	
Gibson, 1997*a*	16–64	M	Ca, Fe	absol	NMES/AS	%EI		NS
	16–64	F	Ca, Fe	absol	NMES/AS	%EI		NS
	16–64	M	Zn	absol	NMES/AS	%EI	inverse	< 0·01
	16–64	F	Zn	absol	NMES/AS	%EI	inverse	< 0·0001
Gibson, 1997*b*	1·5–4·5	M	Ca, Fe, Zn	absol	NMES	%EI	inverse	< 0·01
	1·5–4·5	F	Ca, Zn	absol	NMES	%EI	inverse	< 0·001
	1·5–4·5	F	Fe	absol	NMES	%EI		NS
Gibson, 2001	65 +	M	Ca, Fe	absol	NMES	%EI		NS
	65 +	F	Ca	absol	NMES	%EI	positive	< 0·001
	65 +	F	Fe	absol	NMES	%EI		NS
Kranz *et al.* 2005	2–3	M + F	Ca, Fe	absol	AS	%EI	inverse	< 0·001
	4–5	M + F	Ca, Fe	absol	AS	%EI	inverse	< 0·001
Lewis *et al.* 1992	4–51 +	M + F	Ca, Fe, Mg	%RDA	AS	g/kg	positive	NA
	4–51 +	M + F	Ca, Fe, Mg	%RDA	AS	%EI	inverse	NA
Lyhne & Ovesen, 1999	4–14	M + F	Ca, Fe, Mg, Zn	mg/10 MJ	AS	%EI	inverse	< 0·001
Øverby *et al.* 2004	4	M + F	Ca, Fe	absol	AS	%EI	inverse	< 0·001
	9	M + F	Ca, Fe	absol	AS	%EI	inverse	< 0·001
	13	M + F	Ca, Fe	absol	AS	%EI	inverse	< 0·001
Rugg-Gunn *et al.* 1991	11–14	M	Ca, Fe	absol	AS	%EI		NS
	11–14	M	Ca, Fe	%RNI	AS	%EI		NS
	11–14	F	Ca, Fe	absol	AS	%EI		NS
	11–14	F	Ca, Fe	%RNI	AS	%EI		NS

M, male; F, female; NMES, non-milk extrinsic sugar; AS, added sugars; %EI, percentage of energy intake; absol, absolute intake values; %RNI, percentage of subjects achieving reference nutrient intakes; %RV, percentage of reference value; %RDA, percentage of recommended daily allowance; NA, no statistical values available.

vitamin C and NMES observed (Gibson, 1997*a*), but in the same study inverse associations seen with added sugars (Gibson, 1997*a*). This is probably a result of the inclusion of fruit juice sugars in the NMES calculation, which are not included in the added sugars definition. Only two studies examined vitamin status reporting null associations between vitamin C status (plasma ascorbic acid) and added sugars or NMES (Gibson, 2001; Charlton *et al.* 2005).

Discussion

The overall conclusion to emerge from this systematic review is that for all of the micronutrients investigated, associations between reported intakes of added sugars and these micronutrients are inconsistent, both across and within age groups, and between men and women. As a result there is currently insufficient data to draw firm conclusions.

Broadly similar conclusions were also reached by The Institute of Medicine after a comprehensive review of the data from the National Health and Nutrition Examination Survey III (Institute of Medicine of the National Academies, 2002) with no consistent trends found between age and gender groups.

Many papers included in this review stopped short of quantifying the actual effect of any significant observed associations. An analysis of the Continuing Survey of Food Intakes by Individuals (1994-6) in 2–19 year olds demonstrated that, although there were some significant inverse correlations between added sugar intake and micronutrient levels, when expressed in terms of unit change, the effects were very small and of no public health significance (Forshee & Storey, 2001).

From a public health point of view, the impact of added sugar intakes on micronutrient intakes needs to be evaluated in the context of the prevalence of intakes of the latter below those recommended. However, in the dietary surveys included in this

Table 3. Summary of studies assessing associations between sugar intake and vitamins A, C and E intakes

	Population		Vitamins		Sugar intakes		Association	
Reference	Age (yr)	Gender	Evaluated	Expressed as	Definition used	Expressed as	Direction	*P*
Alexy *et al.* 2003	2–18	M+F	A, C	%RV	AS	%EI	inverse	< 0·0001
Baghurst *et al.* 1992	17 +	M	A, C	absol	AS	%EI		NS
	17 +	F	A, C	absol	AS	%EI	inverse	< 0·01
Bowman, 1999	2 +	M + F	A, C, E	absol	AS	%EI	inverse	< 0·0125
Charlton *et al.* 2005	60 +	M	A, C, E	absol	AS	g/d		NS
	60 +	M	A, C, E	absol	AS	% EI		NS
	60 +	F	A, C, E	absol	AS	g/d		NS
	60 +	F	A, E	absol	AS	% EI		NS
	60 +	F	C	absol	AS	% EI	inverse	< 0·05
Doyle *et al.* 1989		F	C, E	/1000 kcal	AS	g/d	inverse	< 0·001
Forshee & Storey, 2001	2 +	M + F	A	%RDA	AS	g/d	inverse	< 0·01
	6–11	M + F	A	%RDA	AS	g/d		NS
	12–19	M + F	A	%RDA	AS	g/d		NS
	2 +	M + F	C	%RDA	AS	g/d		NS
	6–11	M + F	C	%RDA	AS	g/d	positive	< 0·01
	12–19	M + F	C	%RDA	AS	g/d	positive	< 0·05
Gibson, 1997*a*	16–64	M	C	absol	NMES	%EI	positive	< 0·01
	16–64	M	C	absol	AS	%EI	inverse	< 0·01
	16–64	F	C	absol	NMES	%EI	positive	< 0·001
	16–64	F	C	absol	AS	%EI		NS
	16–64	M	E	absol	NMES/AS	%EI		NS
	16–64	F	E	absol	NMES/AS	%EI		NS
Gibson, 1997*b*	1·5–4·5	M	C	absol	NMES	%EI	positive	< 0·001
	1·5–4·5	F	C	absol	NMES	%EI	positive	< 0·001
Gibson, 2001	65 +	M	C	absol	NMES	%EI		NS
	65 +	F	C	absol	NMES	%EI		NS
Kranz *et al.* 2005	2–3	M + F	A	absol	AS	%EI	inverse	< 0·001
	4–5	M + F	A	absol	AS	%EI	inverse	< 0·001
	2–3	M + F	C	absol	AS	%EI		NS
	4–5	M + F	C	absol	AS	%EI		NS
Lewis *et al.* 1992	4–51 +	M + F	A, C	%RDA	AS	g/kg	positive	NA
	4–51 +	M + F	A, C	%RDA	AS	%EI	inverse	NA
Lyhne & Ovesen, 1999	4–14	M + F	A	RE/10 MJ	AS	%EI	inverse	< 0·001
	4–14	M + F	C	mg/10 MJ	AS	%EI		NS
	4–14	M + F	E	α-TE/10 MJ	AS	%EI	inverse	< 0·001
Øverby *et al.* 2004	4	M + F	A	absol	AS	%EI	inverse	< 0·001
	9	M + F	A, E	absol	AS	%EI	inverse	< 0·001
	13	M + F	A, C, E	absol	AS	%EI	inverse	< 0·01
	4	M + F	C, E	absol	AS	%EI		NS
	9	M + F	C	absol	AS	%EI		NS
Rugg-Gunn *et al.* 1991	11–14	M	C	absol	AS	%EI		NS
	11–14	M	C	%RNI	AS	%EI		NS
	11–14	F	C	absol	AS	%EI		NS
	11–14	F	C	%RNI	AS	%EI		NS

M, male; F, female; NMES, non-milk extrinsic sugar; AS, added sugars; %EI, percentage of energy intake; absol, absolute intake values; %RNI, percentage of subjects achieving reference nutrient intakes; %RV, percentage of reference value; %RDA, percentage of recommended daily allowance; NA, no statistical values available; RE, retinol equivalents.

review the proportion of people failing to achieve recommended levels of many micronutrients appears to be consistent across the range of added sugar intakes, and not limited to high consumers of added sugars. Many studies found that estimated average requirements were achieved across the study sample for the micronutrients reviewed here. In children, with the exception of Ca, where reported intakes were below the recommend intakes in the higher added sugars consumers (Lyhne & Ovesen, 1999; Alexy *et al.* 2003; Øverby *et al.* 2004; Kranz *et al.* 2005), intakes of micronutrients appear adequate regardless of the level of added sugar intake (Lewis *et al.* 1992; Gibson, 1997*b*; Bowman, 1999; Lyhne & Ovesen, 1999; Forshee & Storey, 2001). It has been proposed that Ca intakes may be compromised at higher sugar intakes due to the displacement of milk from the diet by sugar-sweetened beverages (Harnack *et al.* 1999).

It should be noted that the achievement of recommended intakes of micronutrients hinges on the cut-offs applied to determine 'inadequate' micronutrient intakes, which vary between countries and studies and make comparisons difficult. Only two studies have examined biochemical indices of micronutrient status, both in elderly populations, and neither found consistent associations with added sugar intake (Charlton *et al.* 2005) or NMES (Gibson, 2001). The inconsistency between the results of the different studies may be in part due to a number of methodological issues discussed as follows.

Definition of sugar

There is large diversity in methodologies and definitions used to evaluate added sugar intake, which impacts on associations

Table 4. Summary of studies assessing associations between sugar intake and B vitamin intakes

	Population		B vitamins		Sugar intakes		Association	
Reference	Age (yr)	Gender	Evaluated	Expressed as	Definition used	Expressed as	Direction	*P*
Alexy *et al.* 2003	2–18	M+F	B1, folate	%RV	AS	%EI	inverse	< 0·05
Baghurst *et al.* 1992	17 +	M	B1, B2	absol	AS	%EI		NS
	17 +	F	B1, B2	absol	AS	%EI		NS
	17 +	M	B6, folate	absol	AS	%EI	inverse	< 0·001
	17 +	F	B6, floate	absol	AS	%EI	inverse	< 0·001
Bowman, 1999	2 +	M + F	B1, B2, B6, folate	absol	AS	% EI	inverse	< 0·0125
Charlton *et al.* 2005	60 +	M	B1, B2, B6, folate	absol	AS	g/d		NS
	60 +	M	B1, B2, B6, folate	absol	AS	% EI		NS
	60 +	F	B1, B6, folate	absol	AS	g/d	positive	< 0·05
	60 +	F	B1, B2, B6, folate	absol	AS	% EI	inverse	< 0·05
	60 +	F	B2	absol	AS	g/d		NS
Doyle *et al.* 1989		F	B1, B6, folate	/1000 kcal	AS	g/d	inverse	< 0·001
Forshee & Storey, 2001	2 +	M + F	folate	%RDA	AS	g/d	inverse	< 0·01
	6–11	M + F	folate	%RDA	AS	g/d	positive	< 0·01
	12–19	M + F	folate	%RDA	AS	g/d		NS
Gibson, 1997*a*	16–64	M	B1, B2, folate	absol	NMES/AS	%EI		NS
	16–64	F	B1, B2, folate	absol	NMES/AS	%EI		NS
Gibson, 1997*b*	1·5–4·5	M	B1, B2, folate	absol	NMES	%EI	inverse	< 0·05
	1·5–4·5	F	B1, B2, folate	absol	NMES	%EI	inverse	< 0·01
Gibson, 2001	65 +	M	B2, folate	absol	NMES	%EI		NS
	65 +	F	B2	absol	NMES	%EI	positive	< 0·001
	65 +	F	folate	absol	NMES	%EI		NS
Kranz *et al.* 2005	2–3	M + F	folate	absol	AS	%EI	inverse	< 0·001
	4–5	M + F	folate	absol	AS	%EI	inverse	< 0·001
Lewis *et al.* 1992	4–51 +	M + F	B1, B2, B6	%RDA	AS	g/kg	positive	NA
	4–51 +	M + F	B1, B2, B6	%RDA	AS	%EI	inverse	NA
Lyhne & Ovesen, 1999	4–14	M + F	B1, B2, B6	mg/10 MJ	AS	%EI	inverse	< 0·001
	4–14	M + F	folate	αg/10 MJ	AS	%EI	inverse	< 0·001
Øverby *et al.* 2004	4y	M + F	B1, B2	absol	AS	%EI	inverse	< 0·001
	9	M + F	B1, B2	absol	AS	%EI	inverse	< 0·001
	13	M + F	B1, B2	absol	AS	%EI	inverse	< 0·001
Rugg-Gunn *et al.* 1991	11–14	M	B1, B2, folate	absol	AS	%EI		NS
	11–14	M	B1, B2	% RNI	AS	%EI		NS
	11–14	F	B1, B2, folate	absol	AS	%EI		NS
	11–14	F	B1, B2	% RNI	AS	%EI		NS

M, male; F, female; NMES, non-milk extrinsic sugar; AS, added sugars; %EI, percentage of energy intake; absol, absolute intake values; %RNI, percentage of subjects achieving reference nutrient intake; %RV, percentage of reference value; %RDA, percentage of recommended daily allowance; NA, no statistical values available.

with micronutrient intake levels, particularly of some vitamins. Gibson (1997*a*) demonstrated that in the same population different conclusions can be drawn depending on whether NMES or added sugars is used, due to the inclusion of fruit juices in NMES. For example, in adult men vitamin C intakes were significantly positively associated with NMES intakes whilst being significantly inversely associated with added sugar intakes.

The effect of reported energy intake

Opposing conclusions may be drawn from the same dietary data depending on the analytical approach used for adjusting for differences in reported energy intake. Individuals who consume higher amounts of sugar (g/day) tend to have higher total nutrient intakes as a consequence of higher total energy intake (Vanhapelto & Seppanen, 1983; Rugg-Gunn *et al.* 1991; Baghurst *et al.* 1992). To adjust for differences in intakes of foods as a result of body size and energy requirements, added sugar intake is commonly expressed as a percentage of reported total energy intake. This allows comparison between individuals, particularly important in children where there may be a wide variation in energy intakes with age and between genders. However, the patterns of association between added sugar intake and energy intake are inconsistent and often non-linear with some (Kranz *et al.* 2005), but not all studies (Rugg-Gunn *et al.* 1991; Gibson, 1997*a*; Charlton *et al.* 2005), observing that those with higher sugar intakes tended to report consumption of less energy from food. For example, Kranz *et al.* (2005) found that reported energy intake in young children was not linear, such that those with highest sugar consumption (as a percentage of energy intake) had lower energy intakes than those with moderate sugar consumption. Therefore, in such cases expressing energy from sugar intake as a percentage of total energy intake is not appropriate and can result in misleading conclusions.

It is also difficult to interpret results when sugar intake is expressed as a ratio-variable with total energy intake since a change in this ratio can be a result of either a change in total energy intake and/or a change in sugar intake. This relationship between energy intake and added sugar intake is further complicated by the fact that the sugar variable as a component of total energy intake, creates a dependency between the numerator (sugar intake) and the denominator (total energy intake) (Forshee & Storey, 2004). By expressing the data as nutrient densities does not totally remove the effect of energy intake from the analysis. When micronutrient intakes are also expressed as nutrient densities (per unit of energy intake) these issues are not removed, but in fact are amplified (Lyhne & Ovesen, 1999).

Reported energy intake is an important indicator of micronutrient intake and, in general, is significantly positively associated with micronutrient intakes, particularly in young children and older adults (Rugg-Gunn *et al.* 1991; Gibson, 1993; Gibney *et al.* 1995; Linseisen *et al.* 1998). Charlton *et al.* (2005) reported that in elderly subjects more of the variation in daily micronutrient intakes was explained by differences in energy intake than by added sugar intake. For example, for vitamin B_1 intake 60 and 64 % of the variation in women and men respectively was explained by differences in energy intake, whereas in both genders added sugar intake accounted for less than 1 % of the variation in vitamin B_1 intake. Gibson also observed that in British elderly subjects energy intake was a more significant determinant of micronutrient intake than NMES (Gibson, 2001). Thus, in some populations, energy intakes appear to be more predictive of micronutrient intakes than added sugar intake. Micronutrient inadequacy as a result of low energy intakes could well become an increasing problem, not only in the elderly (Charlton *et al.* 1998; Gibson, 2001), but across all age groups as energy requirements are reduced as a result of decreasing energy needs due to physical inactivity. It needs to be stressed that if reported energy intake is used as the denominator in the expression of added sugar intake in analyses, a distinction between added sugars and energy intake with micronutrient intake cannot be made.

A closely related concern is that absolute intakes of micronutrients do not take into account differences in body size and, as a result, expressing the data as nutrient densities raises similar issues to those of adjusting adding sugar for energy intake. To avoid the problems of variability due to body size and differences in micronutrient requirements, some researchers have examined the number of subjects achieving RNI or intakes as a percentage of RNI. However, changes in recommendations over time and differences between countries in their dietary recommendations make comparisons between studies impossible.

It is important to note that there is no optimal approach to adjusting for variations in reported energy intake. Adjusting for energy intake allows comparisons across age groups and takes into account the higher energy needs of larger individuals but, at the same time this adjustment does have its limitations. The nutrient density method (micronutrient intake/energy intake) as discussed earlier does not totally remove the effect of energy intake in the model. The nutrient residual method, derived by the regression of energy intake *v.* added sugars and then entering the residuals from this regression model into analyses examining associations with micronutrient intakes, is another approach. However, this method is susceptible to misspecification since other important variables such as age and gender are significantly related to the omitted energy intake variable. Adding energy intake as a separate covariate appears to be the best method to adjust for energy intake levels, but it could also be argued that the problem of multicollinearity still remains since energy intake is so highly correlated as a covariate with sugar intake (Forshee & Storey, 2004).

Mis-reporting

The well-documented phenomenon of bias in self-reported dietary intake also confounds the problems of evaluating sugar and micronutrient intakes. Mis-reporting, particularly under-reporting, of dietary intake by subjects of all ages is now widely acknowledged (Livingstone & Black, 2003). In some studies it appears to be a particular issue in those categorised as having low intakes of added sugars (Gibson, 1997*a*, 1997*b*). Many studies in this review did not adjust for, or exclude, possible under-reporters or take into account those dieting during the recording period. In adults some studies have identified that sweetened foods and beverages are often under-reported, particularly by overweight individuals (Poppitt *et al.* 1998; Krebs-Smith *et al.* 2000). Individuals reporting low energy intakes have also been found to be less likely to report sweetened beverages, sweetened grain products, sweet spreads, syrups and sweets and/or to report them in smaller portions (Krebs-Smith *et al.* 2000).

It is difficult to identify if foods high in added sugars are more likely to be systematically under-reported, which may underestimate any true associations between added sugars and micronutrients. Where possible, it is important to adopt more than one analytical approach in order to fully evaluate the inconsistency in results between methods with different sources of bias; for example, where information on physical activity is available, to adjust for energy expenditure requirements.

Food sources of added sugars

Any observed associations between added sugar intakes and micronutrient intakes are highly dependent on the foods that are consumed and this could, in part, explain the inconsistencies seen in results between the studies. For example, distinctly different patterns in sugar intake and micronutrient intakes could be observed depending on the primary food groups from which added sugars in the diet are derived. If the primary source of added sugars in the diet is from sugar-sweetened cereals, rather than sugar-sweetened drinks, then a positive effect on micronutrient intakes may be observed if the cereals had been fortified with vitamins and minerals (Frary *et al.* 2004). Added micronutrients in ready-to-eat breakfast cereals, and in high consumers of such cereals, can account for substantial amounts of daily intakes of some vitamins such as B_1, B_2 and folate across the age range in children (Morgan *et al.* 1981; Albertson *et al.* 2003), in adults (Galvin *et al.* 2003) and in the elderly (Morgan & Zabik, 1984). In a US dietary survey, Frary and co-workers examined associations between the five major dietary sources of sugar in children and adolescents and Ca, folate and Fe intakes and found very different patterns depending on the source of the added sugars (Frary *et al.* 2004). For example, Fe intakes were consistently lower in the highest consumers of sugar-sweetened beverages, sweets and sweetened grains but were higher with higher intakes of pre-sweetened cereals.

Full account of food fortification must be made, particularly in the cases of vitamins C, B_1, B_2, B_6 and folate which are most frequently used in food fortification, such as sweetened cereals and breads. A well conducted analysis of nearly 5000 3-d weighed dietary records in 849 children evaluated simultaneously the effect of both added sugar intake and fortified foods on micronutrient density (Alexy *et al.* 2002). It was clear that the effects of fortification on nutrient density far exceeded the effects of added sugar intakes for most micronutrients, with the positive association between vitamin C and fortified food 2–3-fold higher than the observed inverse association with added sugars. Therefore, although higher added sugar consumption may lead to lower nutrient density, the magnitude of this effect may be reversed or at least partially counteracted by food fortification of some commonly consumed sugar-sweetened foods.

Typical food patterns need to be examined to determine the effect of sugar intake on nutrient dilution (Murphy & Johnson, 2003). Since diets are complex, if only the the added sugar component is evaluated in relation to other nutrients, this approach overlooks the interactions between food components and the effect of these interactions on nutrient intakes. For example, if a primary source of added sugar is sweetened cereal products, higher intakes of vitamin D and Ca may be observed due to the consumption of cereal with milk (Morgan *et al.* 1981; Frary *et al.* 2004).

Dietary surveys consistently show that sugar-sweetened drinks are the largest contributor of added sugar intake and in children can contribute more than half of the added sugars derived from the diet (Lyhne & Ovesen, 1999; Guthrie & Morton, 2000; Alexy *et al.* 2003; Øverby *et al.* 2004). This has led to particular concerns about the possible effect of sugar-sweetened drinks on micronutrient dilution and other health outcomes. Some studies have reported that individuals who are high consumers of sugar-sweetened beverages have significantly lower intakes of some micronutrients such as Ca and Mg (Guenther, 1986; Harnack *et al.* 1999; Ballew *et al.* 2000; Mrdjenovic & Levitsky, 2003; Frary *et al.* 2004).

Many studies have reported either a null or a positive association of added sugar intake with vitamin C, particularly in children. This could be due to the consumption of sugar-sweetened beverages which are either fortified with vitamin C and/or vitamin C-containing fruit juices (Ballew *et al.* 2000). In studies where NMES has been used as the measure of sugar intake the positive association seen with vitamin C could reflect intakes of fruit juice, which contribute to the total NMES (Gibson, 1997*b*).

There has been a secular trend towards decreasing milk consumption in children over the last 20 years which appears to have occurred concurrently with an increase in sugar-sweetened beverages (Niklas *et al.* 1999). Milk products declined from 422 g/d to 396 g/d between 1989-91 and 1994-5 in US children (Morton & Guthrie, 1998). At the same time, soft-drink consumption increased from 198 g/d to 279 g/d. It has been proposed that sugar-sweetened beverages may be replacing milk in children's diets (Harnack *et al.* 1999; Mrdjenovic & Levitsky, 2003; Frary *et al.* 2004; Nielsen & Popkin, 2004), which is a major concern since milk is the main source of Ca in children's diets and data from dietary surveys suggest that Ca intake is considerably lower than recommended (Krebs-Smith, 2001). One study observed that only children who were non-consumers of sugar-sweetened beverages met the AI for Ca (Frary *et al.* 2004). This could be interpreted to mean that any level of intake of these beverages may be detrimental to Ca intake or, alternatively, that non-consumers may also have a different dietary pattern to consumers of sugar-sweetened beverages. An increase in sugar-sweetened milk drinks, such as chocolate milk, has been reported in some populations (Niklas *et al.* 1999; Johnson *et al.* 2002). Even if sugar-sweetened beverages were restricted in children's diets, it is not known whether children would choose to consume more unsweetened milk or find other alternative beverages. In fact one study in children, although observing a secular decrease in consumption of dairy products, reported no association between added sugar intake and intake of dairy products (Alexy *et al.* 2003).

Sugar-sweetened beverages have also been positively associated with saturated fat intake (Frary *et al.* 2004), probably because they are commonly consumed along with foods such as chips, hot dogs, sweets and pastries. A high intake of sugar-sweetened beverages is also associated with reduced fruit consumption (Cullen *et al.* 2002; Frary *et al.* 2004). In general, energy dense micronutrient-poor foods, which include foods high in fat, sweeteners, desserts and/or salty snacks, have been associated with a decreased likelihood of meeting the RDA for a number of micronutrients (Kant, 2000). In this latter study, 27 % of energy intake was provided in the form of 'energy dense nutrient poor foods'. A third of these 'energy dense nutrient poor foods' contained sweeteners, suggesting that micronutrient dilution may be as much linked to other energy dense foods as those high in added sugars.

It needs to be emphasised that since components of the diet are systematically related to each other and moreover, proportional when expressed as a percentage of energy intake, each of the components is likely to be related to micronutrient intake. Thus it is not clear whether the effect of the other components of the diet, such as dietary fat intake, bias the estimated effect of added sugars when they are excluded from the statistical model and thus uncontrolled for. This specification error is not usually taken into account in analyses between added sugars and micronutrient intakes. However, Forshee & Storey (2001) examined the effect of added sugars relative to proportional changes in other macronutrients on micronutrient levels by controlling for the effects of other carbohydrate sources, fat, protein and alcohol and reported that in many cases the associations between the other components and micronutrient levels were stronger than those observed with added sugars.

Nearly all studies in this review observed an inverse association between added sugar intake and dietary fat intake and this association appears to be consistent across age groups (Rugg-Gunn *et al.* 1991; Baghurst *et al.* 1992; Gibson, 1997*b*; Alexy *et al.* 2003; Kranz *et al.* 2005). This fat/sugar 'see saw' phenomenon may, in part, explain the observed inverse associations between added sugars and fat soluble vitamin intakes. This is supported by the findings of Forshee & Storey (2001) who found that a gram of fat had a fourfold greater association with vitamin A intake than a gram of added sugars.

Is there a threshold for sugar intake and micronutrient intake?

Given the inconsistency between study results, no threshold effect for any micronutrient could be determined due to differences in cut-offs to define categories of added sugar intake, ways of expressing sugar intake and methods of analyses. As described above, studies that have examined either the absolute micronutrient intake or the percentage of people achieving the RDA for micronutrients across categories of sugar intake have in fact often found non-linear relationships, such that higher levels of intake or percentage of people achieving the RDA are observed in the moderate added sugar intake categories compared with low and high categories of intakes (Gibson, 1997*a*, 2001). It is not clear why this is the case but non-linear trends in reported energy intake (lower energy intakes in the lowest and highest sugar intake categories) as a result of differential mis-reporting may contribute to this observation.

More studies have been conducted in children than in adults, with different associations between added sugars and micronutrients observed in different age groups. Added sugar intake as a percentage of energy intake tends to increase with age among young people (Øverby *et al.* 2004), whereas the inverse is observed in micronutrient intakes, with lower intakes of some nutrients such as folate, vitamin C and Ca with increasing age (Forshee & Storey, 2001).

Conclusions

The overall conclusion of this review is that no clear or consistent indications of micronutrient dilution or concentration for a quantitative amount of added sugar intake are apparent from the current data available. At the same time, it should be noted that the current evidence base does not support any advantages in terms of micronutrient intake for the highest consumers of added sugars.

Further research is required to determine whether specific food products that are high in added sugars are likely to negatively impact on intakes of micronutrients and which other food items they may be displacing from the diet. This may then lead to public health recommendations on added sugar intake based on food choices and dietary patterns which are easier for consumers to understand, in addition to threshold guidelines based on calculated intakes of added sugars or NMES, which may be used for public health monitoring purposes.

To facilitate this, and to make the interpretation of study results more meaningful, analyses should quantify the magnitude, as well as the direction, of any observed significant associations between intakes of added sugars and micronutrients and also evaluate whether other components of the diet may be leading to inadequate micronutrient intakes.

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