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Dietary carbohydrates, glycaemic load, food groups and newly detected type 2 diabetes among urban Asian Indian population in Chennai, India (Chennai Urban Rural Epidemiology Study 59)

Viswanathan Mohan*, Ganesan Radhika, Rangaswamy Mohan Sathya, Selvi Ramjothi Tamil, Anbazhagan Ganesan and Vasudevan Sudha

Madras Diabetes Research Foundation and Dr Mohan's Diabetes Specialities Centre, WHO Collaborating Centre for Non-Communicable Diseases, Gopalapuram, Chennai, India

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The aim of the study was to examine the association of dietary carbohydrates and glycaemic load with the risk of type 2 diabetes among an urban adult Asian Indian population. Adult subjects aged >20 years (*n* 1843) were randomly selected from the Chennai Urban Rural Epidemiology Study, in Chennai city in southern India. Dietary carbohydrates, glycaemic load and food groups were assessed using FFQ. Oral glucose tolerance tests were performed using 75 g glucose in all subjects. Diagnosis of diabetes was based on WHO Consulting Group criteria. OR for newly detected diabetes were calculated for carbohydrates, glycaemic load and specific food groups comparing subjects in the highest with those in the lowest quartiles, after adjustment for potential confounders such as age, sex, BMI, family history of diabetes, physical activity, current smoking, alcohol consumption and relevant dietary factors. We identified 156 (8·5 %) newly diagnosed cases of type 2 diabetes. Refined grain intake was positively associated with the risk of type 2 diabetes (OR 5·31 (95 % CI 2·98, 9·45); $P<0·001$). In the multivariate model, after adjustment for potential confounders, total carbohydrate (OR 4·98 (95 % CI 2·69, 9·19), $P<0·001$), glycaemic load (OR 4·25 (95 % CI 2·33, 7·77); $P<0·001$) and glycaemic index (OR 2·51 (95 % CI 1·42, 4·43); $P=0·006$) were associated with type 2 diabetes. Dietary fibre intake was inversely associated with diabetes (OR 0·31 (95 % CI 0·15, 0·62); $P<0·001$). In urban south Indians, total dietary carbohydrate and glycaemic load are associated with increased, and dietary fibre with decreased, risk of type 2 diabetes.

Carbohydrates: Glycaemic load: Dietary fibre: Refined grains: Type 2 diabetes: Diet: Nutrition: Asian Indians: South Asians

India leads the world with 40·9 million individuals with diabetes and this number is projected to rise to 69·9 millions by the year 2025[1]. Although genetic causes and physical inactivity have been shown, at least in part, to explain the increased susceptibility to insulin resistance and type 2 diabetes in Asian Indians[2,3], very little is known about specific dietary factors in conferring the risk of type 2 diabetes in this ethnic group.

Cereal-based carbohydrates provide the bulk of the energy in Asian Indian diets[4]. In the past, these carbohydrates have been derived from whole grains. However, today, they are replaced with refined carbohydrates, predominantly from rice, due to modern milling technology[5]. It is known that high-carbohydrate diets raise plasma glucose, insulin, TAG and NEFA and thus contribute to insulin resistance[6].

In addition to the quantity, the quality of carbohydrate is also important, particularly its ability to raise glucose levels. Glycaemic index (GI) indicates the glucose-raising effect of a food in comparison with a standard glucose-containing equivalent amount of carbohydrate whereas glycaemic load (GL) is a product of the GI and available carbohydrate content per serving of the food and both have been shown to increase risk of type 2 diabetes in both Western and Asian populations[7–13]. However, some studies report no association between carbohydrates, or GL and diabetes risk[14–16].

Studies have been done in the West where carbohydrates usually do not form the bulk of the energy and also among Asian countries, particularly China and Japan, where the diet is high in carbohydrates[7,17]. However, the present study is unique, as it was conducted among Asian Indians who are at much higher risk of diabetes[18] and premature coronary artery disease[19,20] and also habitually consume a high-carbohydrate diet. Thus, we felt it would be of interest to study the relationship between total carbohydrate intake (quantity), GL (quality and quantity of carbohydrates), carbohydrate-rich food groups and type 2 diabetes among an urban Asian Indian population in Chennai, India.

Methods and subjects

Participants were recruited from the urban component of the Chennai Urban Rural Epidemiology Study (CURES),

Abbreviations: CURES, Chennai Urban Rural Epidemiology Study; GI, glycaemic index; GL, glycaemic load.

* **Corresponding author:** Dr V. Mohan, fax +9144 2835 0935, email drmohans@vsnl.net

conducted on a representative population of Chennai city (formerly Madras) in southern India, with a population of about 5 million individuals. The methodology of the study has been published elsewhere[21] and our website http://www.drmohansdiabetes.com provides details of the sampling frame. Briefly, Chennai is divided into 155 corporation wards, representing a socio-economically diverse group. In phase I of CURES, 26 001 adults (aged $\geq$ 20 years) from forty-six corporation wards were screened for diabetes using a systematic random sampling technique. Phase 2 of CURES deals with studies on the prevalence of complications of diabetes and both these phases are not discussed further.

In phase 3 of CURES, every tenth participant recruited in phase 1 (*n* 2600) was invited to our centre for detailed biochemical tests. Of these, 2220 participants took part in the dietary assessment study, of whom participants with a self-reported history of diabetes (*n* 114), CVD, hypertension or drug therapy of dyslipidaemia (*n* 42), with missing information on physical activity (*n* 11) and with reported energy intake of $<$2092 kJ or $>$17 573 kJ/d ($<$500 or $>$4200 kcal/d) (*n* 210) were excluded[22]. Thus, a total of 1843 participants were included for the present analysis. The protocol for the study was approved by the Institutional Ethics Committee of the Madras Diabetes Research Foundation and written informed consent was obtained from all study participants.

Ascertainment of outcome

An oral glucose tolerance test was performed after 8–10 h of overnight fasting. Participants were instructed on the day before the test to report between 06.00 and 07.00 hours after abstaining from alcohol and to remain fasting (except for water) after the last meal which was to be consumed before 21:00 hours the previous evening. If the participant did not follow the instructions or in the case of any unexpected illness, appointments were rescheduled and the instructions reinforced again. Blood samples were collected before and 2 h after a glucose load consisting of 75 g glucose in 250 ml water. Blood samples were stored at -70°C until the assays were performed and all biochemical analyses were done on a Hitachi 912 auto-analyser (Hitachi, Mannheim, Germany) utilising kits supplied by Roche Diagnostics (Mannheim, Germany). Diagnosis of diabetes was based on WHO Consulting Group criteria, i.e. fasting plasma glucose $\geq$1260 mg/l (7 mmol/l) or 2 h post-load plasma glucose $\geq$2000 mg/l ($\geq$11·1 mmol/l)[23].

Ascertainment of covariates

Anthropometric measurements including height, weight and waist measurements were measured by the trained research assistants, using standardised techniques as described earlier[21]. Height and weight were measured in light clothing without shoes. The BMI was calculated using the formula: weight (kg)/height (m^2). Waist circumference was measured horizontally midway between the lowest rib margin and the iliac crest at minimal respiration and hip circumference was measured at the widest level over the greatest trochanters. Sociodemographic information, medical history, medications, family history of diabetes, smoking and alcohol consumption were also obtained. Details on physical activity were assessed using a previously validated physical activity questionnaire[3].

Assessment of carbohydrates, glycaemic load and other food groups

Interviews were conducted to collect dietary intakes using a validated meal-based semi-quantitative FFQ containing 222 food items to estimate the usual food intake over the past year. A detailed description of this FFQ and the data on reproducibility and validity have been published elsewhere[24]. The energy-adjusted de-attenuated correlation coefficient for estimates from the questionnaire and the six 24 h recalls were 0·72 for carbohydrates (g), 0·51 for GI, 0·54 for GL, 0·70 for refined cereals (g), 0·65 for pulses (g), 0·60 for tubers (g), 0·71 for sugars (g), 0·28 for fruits and vegetables (g) and 0·68 for dairy products (g). The ability of this FFQ to assess dietary carbohydrates and GL was evident in a study that evaluated the relationship of these two variables to HDL-cholesterol levels and TAG levels among men and women[25].

Individuals were asked to estimate the usual frequency (number of times per day/week/month/year or never) and their usual serving size of the given portion size of the various food items. Common household measures such as cups, ladles, spoons, wedges and circles and a visual atlas were shown. Participants were also asked to specify type of cereals usually consumed. Refined grains were defined as foods in which the bran and germ layer are removed, with loss of dietary fibre, vitamins and minerals, leaving the starchy endosperm and included polished white rice, vermicelli, semolina and white flour-based products. To avoid confounding by body size, physical activity and metabolic efficiency and reduce extraneous variation, dietary carbohydrates and GL were adjusted for total energy intake using the residual method[26].

Nutrient intakes were calculated for each participant using an in-house EpiNu India® database developed by our team[24]. Weighted dietary GI for each participant was calculated by summing the products of daily available carbohydrate content per portion for each food item multiplied by the usual serving size and the average frequency per d multiplied by its GI, divided by the total daily carbohydrate intake. Available carbohydrate intake was calculated as total carbohydrate minus total dietary fibre wherever direct measurements were not available.

The GL of the individual food was calculated by multiplying the dietary GI by the total amount of available carbohydrate intake and multiplied by the frequency of consumption and summed to obtain average daily dietary GL. Since there are no national food composition tables containing values of Indian foods for GI, for single foods we used the 2002 international table of GI and GL values[27]; for mixed Indian meals, the GI was derived from the GI of the individual foods as proposed by FAO/WHO in 1998[28]. As there is likelihood of wide variation in the rice varieties, GI testing was done in-house for the common white polished rice variety using standardised international methodology[28], and substituted in the EpiNu database.

Statistical analysis

All analyses were conducted using the SPSS statistical software package (version 12.0; SPSS Inc., Chicago, IL, USA). In separate models, first-order interactions between sex and carbohydrates were entered to determine whether association was similar between men and women. There was no interaction by sex on the association of total carbohydrate and GL and therefore we present results for men and women combined. Subjects were divided into quartiles of total carbohydrate, GL and specific food groups and the mean of each is reported and compared for the descriptive characteristic. One-way ANOVA (continuous variables) and the χ^2 test (for proportions) were used to test differences across quartiles.

To evaluate the relationship of carbohydrates, GL and dietary fibre, logistic regression analysis was carried out to calculate the OR and 95 % CI for diabetes, comparing individuals in the highest with those in the lowest quartile as the reference category with adjustment for age (quintiles), sex (males, females) smoking (current, past and never smokers; smokers – smoked at least one cigarette per d for more than 6 months), alcohol (current, past and never consumers: having ever consumed spirits, wine or beer for more than 6 months), household income in Indian rupees (<2000, 2000–5000, 5000–10 000, >10 000), BMI (continuous), physical activity (strenuous, moderate and sedentary), family history of diabetes (first-degree family history: yes or no), total energy (kJ) and dietary fibre (g/1000 kJ). To assess trend across quartiles, we assigned median intake of each quartile category to individuals with intakes in that category and then included this quartile median variable as a continuous factor in logistic regression models.

Results

The study comprised of 1843 participants (771 men and 1072 women) with a mean age of 39·8 (SD 13·0) years. For men, the median unadjusted total dietary carbohydrate intake was 406 (SD 117) g/d, GI was 69 (SD 3), GL was 277 (SD 86) and dietary fibre was 2·87 (SD 0·7) g/1000 kJ; for women, the corresponding values were 402 (SD 124) g/d, 69 (SD 2), 276 (SD 89) and 2·94 (SD 0·7) g/1000 kJ, respectively.

Table 1 shows the association of energy-adjusted total carbohydrate with baseline characteristics. Individuals in the higher quartiles were older, with greater BMI; a greater proportion of individuals were physically inactive and there were fewer smokers or alcohol consumers, but there were lower intakes of dietary fat and fibre.

Table 1. Baseline characteristics according to quartiles of energy-adjusted dietary carbohydrate*
(Mean values and standard deviations or numbers of participants and percentages)

	Quartiles of carbohydrates (*n* 1843)								
	1 (Lowest) (*n* 460)		2 (*n* 461)		3 (*n* 461)		4 (Highest) (*n* 461)		
Variables	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P*
Median carbohydrate intake (g/d)	294·0		368·9		443·4		587·1		<0·001
Age (years)	37·9	11·7	39·1	13·1	40·8	13·3	41·7	13·8	<0·001
Sex									<0·001
n	260		186		171		154		
% of men	53·3		40·2		36·3		36·6		
BMI (kg/m^2)	22·2	4·2	23·3	4·0	23·2	4·5	25·1	4·9	<0·001
Waist (cm)	80·3	11·2	82·8	10·2	82·9	12·2	88·5	12·3	<0·001
Physical inactivity									<0·001
n	338		339		366		331		
%	69·3		73·2		77·7		78·6		
Current smoking									<0·001
n	101		49		56		45		
%	20·7		10·6		11·9		10·7		
Alcohol intake									<0·001
n	125		71		62		56		
%	25·6		15·3		13·2		13·3		
Family history of diabetes mellitus									0·390
n	117		98		90		92		
%	24·0		21·2		19·1		21·9		
Energy (kJ/d)	12 293	2431	11 133	2782	11 201	2916	12 527	3071	0·191
Carbohydrate (% of energy)	56·9	9·3	64·4	2·1	68·4	1·8	72·8	2·1	<0·001
Protein (% of energy)	12·2	2·1	12·0	1·4	11·2	1·0	10·3	0·9	<0·001
Total fat (% of energy)	25·7	5·3	23·5	2·1	20·4	1·7	16·9	2·0	<0·001
Dietary fibre (g/1000 kJ)	2·84	0·8	3·06	0·6	2·99	0·6	2·75	0·7	0·086
Food groups (g/d)									
Refined grains	320·6	100·6	359·6	116·7	405·6	115·7	516·5	137·1	<0·001
Legumes	57·5	21·7	56·1	19·3	50·2	16·4	47·1	17·5	<0·001
Added sugar	28·6	24·7	24·5	19·1	22·9	21·7	23·5	24·5	<0·001
Fruits and vegetables	298·2	143·6	275·8	122·6	253·3	106·9	233·2	116·7	<0·001
Tubers	155·0	59·3	138·7	51·5	128·7	47·1	117·1	50·5	<0·001
Dairy products	450·3	256·8	369·1	214·1	324·3	186·4	309·8	186·3	<0·001

* Quartiles of energy-adjusted carbohydrate using the residual method.

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Table 2. Baseline characteristics according to quartiles of energy-adjusted glycaemic load intakes*

(Mean values and standard deviations or numbers of participants and percentages)

	Quartiles of glycaemic load (*n* 1843)								
	1 (Lowest) (*n* 460)		2 (*n* 461)		3 (*n* 461)		4 (Highest) (*n* 461)		
Variables	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P*
Median glycaemic load	198·7		252·2		307·2		413·4		<0·001
Age (years)	37·9	11·9	39·8	12·9	40·2	13·2	41·6	13·9	<0·001
Sex									<0·001
n	249		193		166		163		
% of men	52·0		41·2		35·6		37·9		
BMI (kg/m^2)	23·1	4·3	23·6	4·6	23·7	4·6	24·6	4·6	0·008
Waist (cm)	80·7	11·4	83·5	11·6	82·8	11·7	83·9	12·6	0·003
Physical inactivity									<0·001
n	326		355		354		333		
%	68·1		75·9		76·0		78·8		
Current smoking									<0·001
n	99		53		51		48		
%	20·7		11·3		10·9		11·2		
Alcohol intake									<0·001
n	122		70		67		55		
%	25·5		15·0		14·4		12·8		
Family history of diabetes mellitus									0·380
n	112		104		87		94		
%	23·4		22·2		18·7		21·9		
Energy (kJ/d)	12 263	2469	11 183	2686	11 251	2996	12 447	3084	0·299
Carbohydrate (% of energy)	56·9	9·5	64·2	2·3	68·4	1·9	72·7	2·2	<0·001
Protein (% of energy)	12·1	2·1	12·1	1·4	11·2	1·1	10·4	0·9	<0·001
Total fat (% of energy)	25·8	5·3	23·5	2·3	20·5	1·7	16·9	2·0	<0·001
Dietary fibre (g/1000 kJ)	2·92	0·8	3·01	0·6	2·99	0·6	2·75	0·7	0·02
Food groups (g/d)									
Refined grains	313·1	92·2	361·3	116·6	407·6	117·2	517·3	135·8	<0·001
Legumes	59·2	22·7	55·3	17·2	50·3	17·4	46·1	16·5	<0·001
Added sugar	28·5	24·7	25·2	19·7	23·9	22·8	21·8	22·7	<0·001
Fruits and vegetables	312·4	150·8	275·6	113·5	251·1	118·3	220·9	91·7	<0·001
Tubers	156·3	59·9	139·5	51·9	128·9	47·9	115·2	47·1	<0·001
Dairy products	463·7	256·7	386·2	223·3	312·4	171·5	291·6	173·3	<0·001

* Quartiles of energy-adjusted glycaemic load using the residual method.

Table 2 shows the association of energy-adjusted GL with baseline characteristics. Subjects in the higher intake of dietary GL tended to be older, exercised less, had a higher BMI and waist circumference but had a lower intake of dietary fat. No association was observed between family history of diabetes and total carbohydrates, or GL intake.

Table 3 shows the association of carbohydrate-specific food groups with type 2 diabetes. Refined grain intake was positively associated with type 2 diabetes in the unadjusted model. The OR for the highest quartile of refined grain, after adjustment for age, sex, BMI, income, physical activity, family history of diabetes, smoking, alcohol and dietary fibre, was 5·31 (95 % CI 2·98, 9·45; $P<0·001$). In multivariate analysis, higher intakes of fruits and vegetables (OR 0·77 (95 % CI 0·48, 1·23); $P<0·001$) and dairy products (OR 0·54 (95 % CI 0·33, 0·86); $P<0·001$) were inversely associated with type 2 diabetes. Added sugar in food preparation, legumes and tubers did not show any association with type 2 diabetes.

We examined the association of dietary carbohydrates with type 2 diabetes (Table 4). Dietary carbohydrates were positively associated with type 2 diabetes in the unadjusted model. The OR for diabetes for the highest quartile of total carbohydrate, after adjustment for age, sex, BMI, income, physical activity, family history of diabetes, smoking, alcohol and dietary fibre, was 4·55 (95 % CI 2·49, 8·29; $P<0·001$). We also observed a positive association between GL and type 2 diabetes (OR 4·25 (95 % CI 2·33, 7·77); $P<0·001$). GI was also positively associated with type 2 diabetes, but the OR of 2·51 (95 % CI 1·42, 4·43; $P=0·006$) was lower than that for GL. The observed association of carbohydrate intake and GL with diabetes remained unchanged even when waist or waist:hip ratio and fruit and vegetable intake were included in the model. Dietary fibre appeared to have a protective effect on type 2 diabetes, as the OR for diabetes was 0·31 (95 % CI 0·15, 0·62; $P<0·001$) after adjustment for the major risk factors including family history of diabetes, smoking, alcohol, physical activity and total carbohydrates.

Fig. 1 shows that the risk (OR) of type 2 diabetes after multivariate adjustment was 2·91 (95 % CI 1·78, 4·77; $P<0·0001$) among subjects with higher GL (>median) but had no family history of diabetes with reference to no family history of diabetes and consuming GL less than the median. However, the highest risk of diabetes was observed among subjects who had a positive family history of diabetes and also consumed a higher GL (OR 3·67 (95 % CI 1·94, 6·97); $P<0·0001$).

Discussion

To our knowledge, this is the first population-based study to examine the association between carbohydrate-specific dietary

Table 3. Risk for newly diagnosed type 2 diabetes according to quartiles of food intake*
(Unadjusted and adjusted odds ratios and 95 % confidence intervals)

	Quartiles of food intake (g/d)								
	1 (Lowest) (*n* 460)		2 (*n* 461)		3 (*n* 461)		4 (Highest) (*n* 461)		
Variable	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI	*P* for trend†
Refined grains (g/d)									
Range	130·9–295·6		>295·6–377·06		>377·06–474·8		>474·8–858·6		
Median	245·7		334·7		415·4		584·4		
Newly diagnosed T2DM									<0·001
n	17		28		37		74		
%	3·7		6·1		8·0		16·1		
Unadjusted OR for diabetes	1·00	Reference	1·69	0·90, 3·12	2·27	1·26, 4·10	4·98	2·89, 8·59	<0·001
Adjusted OR for diabetes	1·00	Reference	1·95	1·02, 3·75	2·82	1·51, 5·26	5·31	2·98, 9·45	<0·001
Added sugar (g/d)									
Range	1·0–9·8		9·8–19·5		19·5–33·8		>33·8–233·1		
Median	5·4		14·6		25·5		50·1		
Newly diagnosed T2DM									0·089
n	47		31		32		46		
%	10·2		6·7		6·9		9·9		
Unadjusted OR for diabetes	1·00	Reference	0·63	0·39, 1·02	0·65	0·40, 1·04	0·98	0·63, 1·51	0·087
Adjusted OR	1·00	Reference	0·64	0·39, 1·05	0·72	0·44, 1·19	0·94	0·59, 1·49	0·257
Fruits and vegetables (g/d)									
Range	43·0–180·1		>180·1–241·5		>241·5–326·4		>326·5–1422·1		
Median	143·4		212·8		284·3		395·2		
Newly diagnosed T2DM									<0·001
n	41		38		44		33		
%	8·9		8·2		9·5		7·2		
Unadjusted OR for diabetes	1·00	Reference	0·34	0·18, 0·58	0·85	0·54, 1·29	0·78	0·48, 1·15	<0·001
Adjusted OR for diabetes	1·00	Reference	0·36	0·21, 0·65	0·92	0·59, 1·45	0·77	0·48, 1·23	<0·001
Tubers (g/d)									
Range	13·2–98·5		>98·5–127·8		>127·8–162·4		>162·5–456·4		
Median	80·9		112·9		141·8		195·3		
Newly diagnosed T2DM									0·290
n	45		36		41		34		
%	9·8		7·8		8·9		7·4		
Unadjusted OR for diabetes	1·00	Reference	0·78	0·49, 0·58	0·90	0·58, 1·40	0·73	0·46, 1·17	0·554
Adjusted OR for diabetes	1·00	Reference	1·01	0·61, 1·66	1·28	0·77, 2·14	1·18	0·58, 1·76	0·713
Legumes (g/d)									
Range	3·0–39·9		>39·9–51·3		>51·3–64·3		>64·3–174·8		
Median	32·6		45·5		56·9		73·9		
Newly diagnosed T2DM									0·364
n	44		37		40		35		
%	9·6		8·0		8·7		7·6		
Unadjusted OR	1·00	Reference	0·83	0·52, 1·31	0·89	0·57, 1·41	0·77	0·49, 1·24	0·726
Adjusted OR	1·00	Reference	1·14	0·68, 1·92	0·98	0·58, 1·66	1·26	0·76, 2·08	0·739
Dairy products (g/d)									
Range	1·05–208·91		>209·0–314·8		>315·3–480·0		>480·0–1777·2		
Median	148·5		260·6		387·2		628·8		
Newly diagnosed T2DM									0·011
n	55		37		29		35		
%	12·0		8·0		6·3		7·6		
Unadjusted OR for diabetes	1·00	Reference	0·64	0·41, 0·99	0·49	0·31, 0·79	0·61	0·39, 0·95	<0·001
Adjusted OR for diabetes	1·00	Reference	0·66	0·41, 1·04	0·50	0·30, 0·82	0·54	0·33, 0·86	<0·001

T2DM, type 2 diabetes mellitus.
* The adjusted model was adjusted for age (years in quintiles), sex (males, females), BMI (continuous), family history of diabetes (three categories), cigarette smoking (categorised as non-smokers and habitual smokers), alcohol (never, past and current consumers), physical activity (strenuous, moderate, sedentary) and income in Indian rupees (<2000, 2000–5000, >5000–10 000, >10 000).
† Tests for linear trend were conducted across increasing categories by treating the medians of intake in categories as continuous variables.

factors and risk of type 2 diabetes in an Asian Indian population. After adjustment for several risk factors for diabetes, the findings show a positive association between dietary carbohydrates, GL and refined grains while dietary fibre, fruits and vegetables and dairy products had a negative association.

In traditional Asian Indian diets, before the advent of mechanical milling, hand pounding of rice was in practice and hence there was better retention of the bran and germ. While modernisation and the growth of rice mills (seven modern rubber-roll sheller mills in 1963 in India compared with 35 088 in 1999) have led to an increased total rice yield, unfortunately the coarse grain has been replaced by a highly refined rice grain with starchy endosperm[5,29]. In the present study, refined grain was positively associated with

Table 4. Risk for newly diagnosed type 2 diabetes according to carbohydrate, glycaemic load and dietary fibre*
(Unadjusted and adjusted odds ratios and 95 % confidence intervals)

	Quartiles								
	1 (Lowest) (*n* 460)		2 (*n* 461)		3 (*n* 461)		4 (Highest) (*n* 461)		
Variable	OR	95 % CI	OR	95 % CI	OR	95 % CI	OR	95 % CI	*P* for trend†
Carbohydrates (g/d)‡									
Range	153·5–333·7		>333·7–403·4		>403·4–498·4		>498·4–763·2		
Median	294·0		368·9		443·4		587·1		
Newly diagnosed T2DM									<0·001
n	20		36		44		56		
%	4·1		7·8		9·1		13·2		
Unadjusted OR for diabetes	1·00	Reference	1·97	1·13, 3·46	2·41	1·39, 4·16	3·59	2·12, 6·09	<0·001
Adjusted OR for diabetes	1·00	Reference	3·05	1·62, 5·77	3·53	1·89, 6·56	4·55	2·49, 8·29	<0·001
Glycaemic index‡									
Range	57·8–67·1		>67·1–68·9		>68·9–70·3		>70·3–73·9		
Median	65·4		68·0		69·5		71·3		
Newly diagnosed T2DM									<0·001
n	25		33		48		50		
%	5·2		7·4		11·1		10·4		
Unadjusted OR for diabetes	1·00	Reference	1·91	0·68, 2·08	1·82	1·07, 3·09	2·01	1·19, 3·40	0·020
Adjusted OR for diabetes	1·00	Reference	1·38	0·76, 2·51	2·12	1·20, 3·75	2·51	1·42, 4·43	0·006
Glycaemic load‡									
Range	103·9–226·4		>226·4–276·6		>276·6–344·6		>344·6–540·8		
Median	198·7		252·2		307·2		413·4		
Newly diagnosed T2DM									<0·001
n	17		37		48		54		
%	3·5		7·9		10·3		2·6		
Unadjusted OR for diabetes	1·00	Reference	2·33	1·29, 4·21	3·12	1·77, 5·51	3·91	2·23, 6·85	<0·001
Adjusted OR for diabetes	1·00	Reference	2·69	1·42, 5·09	3·85	2·08, 7·10	4·25	2·33, 7·77	<0·001
Dietary fibre (g/1000 kJ)									
Range	0·9–2·5		>2·5–2·9		>2·9–3·3		>3·3–7·2		
Median	2·1		2·8		3·1		3·7		
Newly diagnosed T2DM									<0·001
n	42		66		37		11		
%	9·1		14·3		8·0		2·4		
Unadjusted OR for diabetes	1·00	Reference	1·66	1·10, 2·51	0·87	0·56, 1·38	0·24	0·13, 0·48	<0·001
Adjusted OR for diabetes	1·00	Reference	1·95	1·24, 3·06	1·19	0·73, 1·95	0·31	0·15, 0·62	<0·001

T2DM, type 2 diabetes mellitus.
* The adjusted model controlled for age (years in quintiles), sex (males, females), BMI (continuous), family history of diabetes (three categories), cigarette smoking (categorised as non-smokers and habitual smokers), alcohol (never, past and current consumers), physical activity (strenuous, moderate, sedentary) and income in Indian rupees (<2000, 2000–5000, >5000–10 000, >10 000). There was additional adjustment for dietary fibre (for the carbohydrate and glycaemic load models) and for carbohydrate (for the fibre model).
† Tests for linear trend were conducted across increasing categories by treating the medians of intake in categories as continuous variables.
‡ Energy adjusted using the residual method.

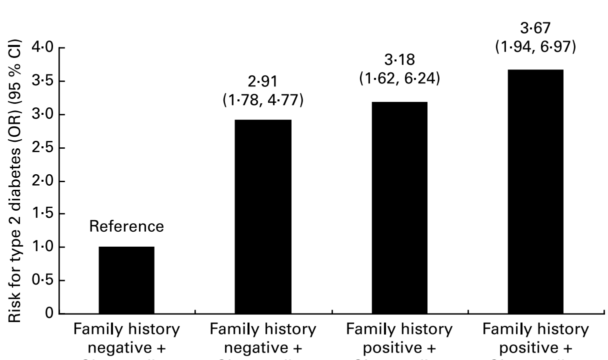

Fig. 1. Synergistic effect of heritability and glycaemic load (GL) on the risk of type 2 diabetes adjusted for age (years in quintiles), sex (males, females), BMI (continuous), cigarette smoking (categorised as non-smokers and habitual smokers), alcohol (never, past and current consumers), physical activity (strenuous, moderate, sedentary), income in Indian rupees (<2000, 2000–5000, >5000–10 000, >10 000) and dietary fibre/1000 kJ. *P* for trend <0·001. The OR and 95 % CI are shown above the bars.

type 2 diabetes, particularly polished white rice being the major contributor; this result is consistent with our previous study findings of association with components of the metabolic syndrome[30]. These findings corroborate those of Burkitt[31], who correlated the introduction of roller mills in the USA and the West with a large number of diseases including diabetes.

We found that total carbohydrate intake was much higher in the present study (first quartile 294 g/d; fourth quartile 587 g/d) compared with that reported in Westerners (first quintile 162 g/d; fifth quintile 238 g/d)[32] and in another Asian (Chinese) population (first quintile 233·3 g/d; fifth quintile 321·9 g/d)[7]. However, the percentage of carbohydrates contributing to total energy was 65·6 %, which is not much higher than that recommended by the WHO guidelines of 55–65 % for the prevention of chronic diseases[33]. Bread, potatoes and sugar added in soft drinks are the main sources of dietary carbohydrates in Western populations[34]. However, in south Indians, neither tubers nor sugars were associated with type 2 diabetes. These results were consistent with previous studies[35–37]. In India, tubers are consumed more as an accompaniment and sugar intake was mainly as added sugar in hot beverages (tea and coffee). In this population, the carbohydrate was predominantly derived from polished white rice (66·1 % of total carbohydrate intake). In addition, those who eat more rice, also eat less of virtually all other foods such as legumes, tubers, fruits and vegetables and dairy products.

Epidemiological data on dietary carbohydrates and type 2 diabetes are not consistent[14–16]. In a cross-sectional study among Japanese female farmers[17], GL and GI were positively associated with fasting plasma glucose, whereas no correlation was observed among elderly women[38]. It is known that the association between dietary carbohydrates and type 2 diabetes may be mediated through other components, for example, low cereal dietary fibre[14]. However, in the present study, the association between dietary carbohydrates and GL and diabetes remained unchanged even after adjustment for total dietary fibre. This suggests that carbohydrate intake and GL may be independent risk factors for type 2 diabetes in Asian Indians. In the present study GI was also associated with type 2 diabetes; however, the association was stronger for GL than for GI. It is likely that both genes and the environment, particularly diet, act together and have a cumulative effect on the risk of type 2 diabetes. Hence, in the present study, we studied the combined effect of GL and family history of diabetes in increasing the risk of type 2 diabetes. We found that while both family history and GL were independently associated with type 2 diabetes risk, the highest risk was observed among those subjects with a higher intake of GL who also had a positive family history of diabetes.

Our findings are consistent with previous prospective cohort studies[7,9,12,13] that have reported an association between GL and risk of type 2 diabetes. In the Nurses' Health Study, women with the highest dietary GL were 37 % more likely to develop type 2 diabetes mellitus than with the lowest dietary GL[9]. Similarly, both among Chinese women[7], and in an elderly Dutch population[8], a positive association was observed with GL and type 2 diabetes. Indeed, a meta-analysis of thirty-seven prospective studies involving nearly two million participants provides evidence that diets with a high GI, high GL, or both, are independently associated with an increased risk of type 2 diabetes[39]. However, the results are not consistent, as no association was observed in the Iowa Women's Health Study[14], and a borderline association with GL was noted in the Atherosclerosis Risk in the Communities (ARIC) Study[15]. These differences observed could be related to methodological issues. In the Iowa study, diagnosis of diabetes was based entirely on self-reported cases whereas the present study included newly detected subjects diagnosed by the oral glucose tolerance test. In self-reported diabetic subjects, dietary changes could have been made as a result of therapy. The ARIC study did not distinguish between type 1 and type 2 diabetes[15]. Misclassification of either exposure or disease status could have led to underestimation of the association in these studies.

We detected an inverse association for total dietary fibre, fruit and vegetable intake and diabetes risk. A similar association was observed in both the Iowa Women's Health Study[14] and the Nurses' Health Study[9]. In contrast, no significant association was observed in the Health Professionals study and in the ARIC study[15]. We have previously reported an inverse association between fruit and vegetable intake and cardiovascular risk factors[40], but diabetes was not included in that study. In the present study, 3–4 % fat milk was the predominantly consumed dairy product in this population. However, the mechanism behind the inverse association between dairy products and risk of type 2 diabetes remains unclear. Components such as Ca, vitamin D, Mg, P and dairy protein present in dairy products[41] have been shown to reduce the risk of type 2 diabetes and obesity.

Several mechanisms have been proposed to explain how the long-term consumption of carbohydrates may increase the risk of type 2 diabetes. The same amount of carbohydrates from high-GI foods produces a higher blood glucose concentration and a greater demand for insulin compared with low-GI foods. The prolonged increase in insulin demand may eventually result in pancreatic β cell exhaustion and thus lead to diabetes[6]. It is therefore clearly important to reduce the high GL of the diet either by reducing the carbohydrate content, or by increasing the intake of low-GI foods, or both.

The present study shows that both quantity of carbohydrates (total carbohydrate) and the quality of carbohydrates (GL) are important risk factors for type 2 diabetes in this population. It is unlikely that the total carbohydrate content of south Asian diets can be altered. It thus appears prudent to encourage the introduction of low-GI foods in the market as well as to promote high-fibre foods to reduce the total dietary GL. Increasing awareness about the consequences of consuming higher-GL diets is also necessary. These measures could be included as policies to be adopted in the National Programme for Prevention and Control of Diabetes/Cardiovascular Diseases and Stroke recently launched by the Government of India[42].

The present study has several limitations. First, being a cross-sectional study, it does not allow us to infer causation nor does it permit us to explore the temporal sequence of events between the consumption of carbohydrate-rich foods and development of type 2 diabetes. Second, although we have adjusted for various potential confounders, as in any observational study, residual confounding by unknown or imperfectly measured factors cannot be excluded. Third, there could be possible errors in the dietary calculation mainly resulting from the limited availability of food composition data, particularly with reference to available carbohydrates and dietary fibre among Indian foods. Fourth, adequate food and nutrition labelling on the Indian products limited our definition of refined grains. Fifth, some measurement error is inevitable in the assessment of dietary intakes of a population. However, our validation study indicated that the assessment of dietary carbohydrates, GI and GL using a detailed interviewer-administered FFQ was reasonably accurate[24]. Moreover, measurement error would be expected to weaken rather than strengthen the observed association.

The study also has several strengths, including the relatively large sample size, the use of newly detected diabetic subjects, the unique ethnic group on whom no data are available and the detailed information on diet that was obtained. As we included a representative population of Chennai, the results can be extrapolated to the whole of urban India. Finally, we carefully controlled for well-documented risk factors for diabetes and possible confounders.

In conclusion, our findings indicate that higher dietary carbohydrates and GL are associated with increased, and dietary fibre with decreased, risk of newly diagnosed type 2 diabetes among urban south Indians who habitually consume high-carbohydrate diets.

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V. M. designed the study. G. R., R. M. S. and S. R. T. led the data collection. G. R. and V. S. wrote the first draft of the manuscript and V. M. rewrote the subsequent drafts. A. G. assisted in doing the statistical analysis. V. M., G. R. and V. S. contributed to the interpretation of the data and all contributors participated in the revisions and final draft of the manuscript. They approved the final version and will take public responsibility for the content of this paper.

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