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Wheat and **Rice** in **Disease Prevention** and **Health**

Benefits, risks and mechanisms of whole grains in health promotion

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BENEFITS, RISKS AND MECHANISMS OF WHOLE GRAINS IN HEALTH PROMOTION

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CHAPTER

25

Glycemic Index of Indian Cereal Staple Foods and their Relationship to Diabetes and Metabolic Syndrome

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INTRODUCTION

India is a land of diversity, not only in culture and geography but also in foods. The two most important cultures that have influenced Indian cuisine and food habits are the Hindu and Muslim religious traditions. Rice has been domesticated in Northern peninsular India since 5000 BC, subsequently spreading to the Indus Valley Civilization (2300–1900 BC) in the Gangetic plain, and later to Southern India (2000–1400 BC). However, wheat and barley were domesticated in both northern and southern regions.[1,2] Cereal staples such as rice and wheat continue to provide the principle source of energy for most of the Indian population.[3]

In earlier days, less refined cereal-based traditional diets were nutrient-dense and high in fiber; however, modern diets have, due to processing and milling technologies, made cereals more refined and energy-dense. A recent national survey in India conducted by the National Sample Survey Organization (NSSO) has reported that there has been a decline in percentage of expenditure on cereal since 1987.[4] Despite the decline, currently cereal staples provide two-thirds of the daily carbohydrates and almost half of the daily calories in Indian diets.[5] Higher intakes of refined cereals probably contribute to India's growing diabetes epidemic. According to a recent national study, currently there are 62.4 million people with diabetes and 77.2 million people with pre-diabetes in India.[6] Diabetes mellitus is mainly characterized by rise in blood glucose level, which can depend on the quality (the glycemic index or GI) and the quantity of ingested carbohydrate. The combination of these two factors is termed the glycemic load (GL), and reflects the total glycemic impact of ingested carbohydrate-rich foods. Indeed, GI has proven to be a more useful nutritional concept than the chemical classifications of carbohydrates, as there is a correlation between physiological effects of carbohydrate-rich foods and diseases like diabetes or cardiovascular disease (CVD). A recent epidemiological study had shown the positive association of high GI and GL foods, like refined grains, with the risk of type 2 diabetes.[7] It is possible that, along with decreased physical activity, diets with higher GI and GL are contributing to India's growing diabetes epidemic.[8] Many Western studies have shown the protective effect of whole grains against chronic diseases such as diabetes and cardiovascular disease.[9]

Additionally, the GI of foods also plays a role in weight management, in sports nutrition, and in the prevalence of childhood obesity. However, the glycemic responses vary for different foods containing the same amount and even type of carbohydrate, depending on processing technologies and food characteristics, such as structure, ripeness (e.g., in fruits), the amylose : amylopectin ratio, the food composition, and cooking methods.[10] Today, there are many food ingredients that can be included in the formulation of foods to lower their GI. Many of these ingredients are natural products of cereals, while others are modified carbohydrates.[11]

The first international GI table was developed by Foster *et al.* in 1995, with values for 565 foods; this was further expanded in 2002.[12,13] In 2008, Atkinson compiled

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an international table for GI and GL for 2480 individual food items. Although both these tables do provide data on over 100 Indian foods, the GI methodologies used at that time were before the evolution of the standardized GI protocols in 1998.[14,15] Hence, it is important to develop a new database on the GI of Indian foods using the current international GI protocol.

INDIAN CEREAL STAPLE FOODS

History

The agricultural era began about 10,000 BC, when excessive hunting of animal foods led to the decline of meat and emergence of vegetable foods as the staple diet.[16] Food is considered to be a staple when consumed by a community or society daily, and is also that food from which people obtain the major proportion of their daily caloric and nutrient requirements.[1] Biogeographical evidence suggests that peninsular India housed several diverse crop cultivars, including rice, wheat, barley, sorghum, and at least 10 different species of different millets. This clearly reflects the diversity of agricultural and culinary practices in India in ancient times.[17]

Production and Consumption of Cereals and Millets

Cereal and millet production in India is shown in Figure 25.1. Rice production increased 2.5-fold between the 1960s and second decade of this millenium, and India is now the second largest rice producer in the world. Wheat production increased 5.5-fold over the same period (i.e., from 133 to 734 million tonnes). However, post-Green Revolution, millet consumption has decreased tremendously.[18]

The National Nutrition Monitoring Bureau (NNMB) has recorded the decline in cereal intake from 383 to 344 g/CU per day between 2000 and 2006. Similarly, during the same period the consumption of millet reduced by >50% (from 105 to 52 g/CU per day).[19] In addition, the NSSO noted that the percentage contribution of calories from cereals also decreased between 2005 and 2010 among both rural and urban populations (from 67.5% to 60.4%, and 56.1% to 50.4%, respectively).[20] A recent epidemiological survey among Chennai (a metro city) adults indicated that white rice consumption (median intake of 253 g/d) contributes about 50% of the total calories, similar to other major rice-eating Asian populations (Chinese and Japanese).[7,21,22]

India has the second largest wheat consumption, next to China, and consumption is mostly in the form of homemade chapattis (unleavened flat bread), using custom-milled *atta* (whole wheat flour), and refined wheat flour used for the preparation of various wheat-based bakery products such as bread, biscuits, and processed foods.[23] Though India is the greatest consumer of millet in the world, average millet consumption is lower than that of other cereals.[24]

NUTRITIONAL COMPOSITION OF CEREAL STAPLE FOODS

Nutritional Composition of Cereals and Millets

The macronutrient composition of rice, wheat, and millets is given in Figure 25.2. Rice has good quality protein compared to other cereals,[25] and is rich in

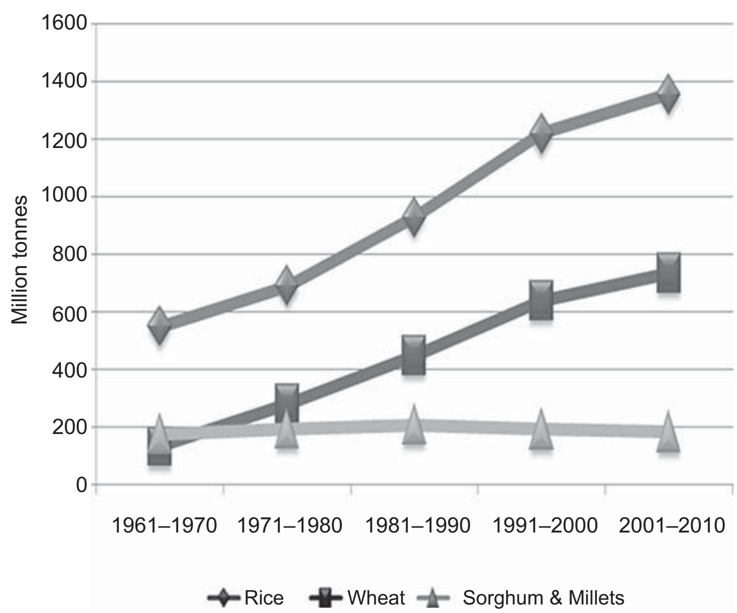

FIGURE 25.1 Production of rice, wheat, sorghum and millets. *Source: Adapted from FAOSTAT 2013.*[18]

branched-chain amino acids such as leucine, isoleucine, and valine. Moreover, rice fat is rich in essential n-6 fatty acids.[26] Rice bran layers consist of non-starchy polysaccharides (cellulose and lignin), fat, and dietary fiber. The aleurone layer and germ contains protein, fat, and good amount of vitamins and minerals.[25] Hence, on polishing there is a decrease in the protein, fat, and dietary fiber content, and a proportionate increase in the available carbohydrate content is more obvious as polishing removes the bran, including the aleurone and germ portions of rice kernel, leaving behind the starchy endosperm.[27]

Wheat is also a good source of trace minerals such as selenium and magnesium – nutrients essential to good health.[28,29] However, when wheat is milled as refined flour, 75% of the dietary fiber is lost (Fig. 25.2B). Millets are far superior to either rice or wheat in terms of nutritive content, and are a rich source of minerals like iron, magnesium, phosphorus, potassium, and dietary fiber.[30] Finger millet (Ragi) has the highest calcium content among all the food grains. The protein content of millet is comparable to that of wheat and maize. The bran layers of millets are good sources of B-complex vitamins.[30]

Traditional hand-pounded rice is known for its nutritional superiority, as less bran is lost during hand pounding and winnowing, compared with polished white rice, where almost all of the bran is lost. Today, in India, polished white rice and its flour-based preparations are used exclusively. Similarly, wheat in the traditional diet was in the form of coarse flour and grits, but today wheat is used as a refined flour (white flour), refined semolina, and finely pulverized whole wheat flour, all of which could impact carbohydrate quality (GI) and metabolic health.

Glycemic Index and Glycemic Load

The glycemic index (GI), the concept of measuring the glycemic impact of foods primarily from carbohydrates and first developed in 1981 by Jenkins, became popular in the 1990s. However, the GI concept continues to be a controversial subject. GI is a dynamic parameter that reflects the influence of foods in raising blood glucose and the glucose clearance rate.[31] It compares the postprandial glycemic response of 50 g available carbohydrates (measured by capillary blood glucose at intervals of 15 minutes for the first hour, followed by half-hourly for the second hour) of the test food with the standard food (glucose set to a GI scale of 100). The GI is calculated as the incremental area under the curve (IAUC) for the ingested test food over a period of 2 hours expressed as a percentage of the reference standard food area under

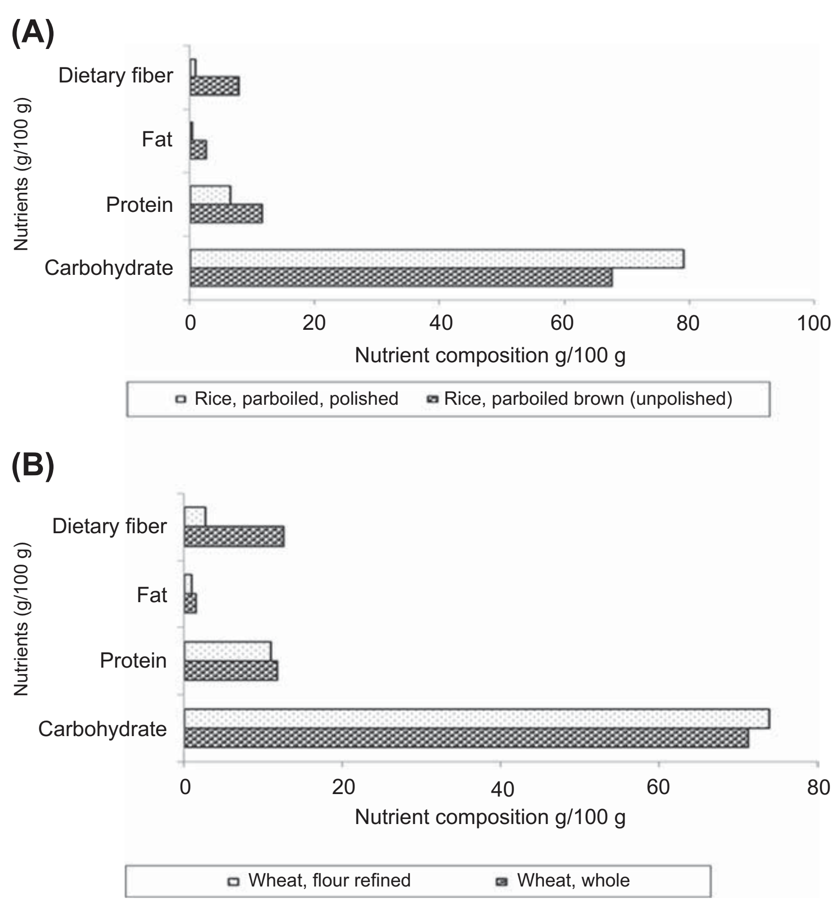

FIGURE 25.2 Proximate composition of brown rice vs white rice (A) and whole wheat vs refined flour (B). *Source: Adapted from Gopalan et al. 2010.*[26]

TABLE 25.1 Description of Indian Foods Planned in Table 25.2

Food Items	Description
HIGH GI MENU ITEMS	
Idly-white rice	It is a white spongy cake made by steaming the fermented batter of rice and black gram dhal in the proportion of 2:1
Chutney onion	Chutneys are ground paste onion and seasoning with mustard seeds is optional
Coffee with milk & sugar	Coffee prepared with 3% fat milk, and sugar and instant coffee powder
Samosa	Dough made from refined wheat flour is folded into triangular shape and stuffed with cooked mixture of potato, peas, carrot, onion and spices and deep fried in oil
White rice	Non parboiled common Indian rice variety *Bapatla* cooked in pressure cooker in the ratio of 1: 2.5
Sambhar	Made out of red gram dhal, tomatoes, onion, vegetables cooked in tamarind pulp along with spices
Potato/dum aloo/shallow fry	Boiled potatoes mixed with turmeric and chilli powder and shallow fried in frying pan (*'kadai'*) with oil
Oothapam-white rice	The preparation is similar to dosa but it is cooked as thick pan cake in tava
Kurma vegetable	Vegetables like carrot, peas, potato etc are cooked with spices and coconut paste to thick consistency usually served as accompaniment for rice/chapathi/parotta
LOW GI MENU ITEMS	
Idly brown rice-vegetables	It is a white spongy cake made by steaming the fermented batter of brown rice and black gram dhal in the proportion of 2:1
Onion Sambhar	As mentioned in the high GI menu
Coffee with milk & sugar	As mentioned in the high GI menu
Butter milk	Prepared from whipped curd diluted with water and salt. Asafoetida, curry leaves are optional
White Peas sundal	Dried white peas (bean) soaked for few hours and cooked in pressure cooker and seasoned with Indian spices
Brown rice	Parboiled common Indian brown rice variety *Bapatla* cooked in pressure cooker in the ratio of 1: 2.5
Sambhar	As mentioned in the high GI menu
Dhal-fry	It is made by cooking green gram dhal/red gram dhal/masoor dhal with tomatoes. Ghee is usually used for seasoning with cumin seeds and garnished with coriander leaves and served along with chapathi/ phulka/plain rice
Coffee with milk & sugar	As mentioned in the high GI menu
Masala vadai	It is prepared with coarsely/finely ground paste of split bengal gram and mixed with onion, coriander leaves,ginger and hand pressed into circular shape and then deep fried in oil.
Dosa-brown rice	It is made from fermented batter of parboiled brown rice and split black gram (4:1), and cooked in shallow pan (*'tava'*) with oil
Mint chutney	Chutneys are ground paste made greens (mint); seasoning with mustard seeds is optional

Source: Developed from EpiNu database.[50]

the curve for the same duration. Hence, the GI depends on the food characteristics rather than the characteristics of the individual who consumes the food.[32] Capillary blood glucose is recommended because of the ease in obtaining it; also, the capillary rise is higher than the venous rise, and hence the differences between foods are larger and it is easier to detect the significance of GI values.[15] Unfortunately, most of the foods were tested by means of venous samples (Table 25.1).

A study on GI of the same foods tested in India and UK using identical methods showed that the glycemic response to the foods (sweet biscuit, sweet meal biscuit, malted whole wheat cereal, malted wheat cereal, and cereal biscuit) was higher in Asian Indians than in their UK counterparts, despite there being no difference in the GI values of the same foods.[33] Glycemic responses could be ethnic-specific due to the inherent biological variations.[34] In addition to GI, a newer concept, the food insulin index (FII), has also been studied. The basis for the FII is that diets/foods that stimulate less insulin secretion may potentially aid in the prevention and management of diabetes. Foods ranked based

TABLE 25.2 Sample High and Low GI Indian Diet Menu

	High GI Diet				Low GI Diet			
Meal	**Menu**	**Portion Size**	**GI**	**GL**	**Menu**	**Portion Size**	**GI**	**GL**
Break Fast	Idly-white rice	50 g	86	12	Idly brown rice-vegetables	50 g	68	4
	Chutney onion	25 g	43	1	Onion Sambar	150 g	24	2
	Coffee with milk & sugar	150 ml	60	8	Coffee with milk & sugar	150 ml	60	8
Mid Morning	Biscuits salt	5 g	85	3	Butter milk	150 ml	36	3
	Coffee with milk & sugar	150 ml	60	8	White Peas sundal	100 g	35	3
Lunch	White rice	250 g	83	54	Brown rice	280 g	59	33
	Sambar	150 ml	24	4	Sambar	150 ml	24	4
	Potato fry	150 g	73	20	Dhal-fry	150 g	24	3
Evening	Coffee with milk & sugar	150 ml	60	8	Coffee with milk & sugar	150 ml	60	8
	Samosa	100 g	83	41	Masala vadai	30 g	10	1
Dinner	Oothapam-white rice	79 g	83	18	Dosa-brown rice	30 g	62	6
	Kurma vegetable	150 g	58	4	Mint chutney	25 g	27	0
Bed Time	Water melon	150 g	76	4	Apple	120 g	36	5
Average			73	184	Average		44	81

Source: Developed from EpiNu database.[50]

on FII could be more precise than carbohydrate counting in adjusting the insulin dosage for type 1 diabetics, since evidence has shown that mixed meals with similar carbohydrate content produce varied insulin response.[35] Sample high and low GI Indian menu plans are shown in Table 25.2.

The glycemic load (GL) estimates the total glycemic impact of the food's carbohydrate on postprandial blood glucose. Thus, GL is calculated as GI% × amount of available carbohydrates provided by the portion of the food eaten.[15] GL foods/meals/diets can be altered either by decreasing the total carbohydrates or by lowering the GI. This indicates the practical challenges each country has in dealing with cultural diets. Perhaps this could be the reason that high GL diets show different physiological effects across countries. For example, we showed that those within the highest quartile of GL had 4-fold increased risk for type 2 diabetes as compared to those within the lowest quartile of GL (OR = 4.25; 2.33–7.7 CI).[7] The variations in GL of Indian diets mainly come from the change in quantity of carbohydrates between those with the lowest and highest quartiles of intake (294 g/d vs 587 g/d, respectively), while GI between these quartiles is less varied (65 vs 71, respectively) due to the unavailability of low GI foods, and hence not reported by this population.[7] It was observed in the US that high-carbohydrate diets were also high in GI, whereas in Scandinavian countries many low GI staples were included in high-carbohydrate diets.[36,37]

Glycemic Index of Indian Foods

Despite increasing evidence of the benefits of low GI foods for many populations, the concept of GI is still not widely accepted. Though the usefulness of the GI is questioned in many developed nations, it appears to be a useful concept in countries such as India, where carbohydrate consumption is high.[5,26] Moreover, low GI foods come with added benefits such as higher fiber and phytonutrient content that are beneficial to overall health. Indeed, there is no scientific evidence to show any deleterious effects of low GI diets. Thus, creating a GI database for Indian foods tested in India will be a valuable resource for dieticians to plan menus and food exchanges effectively, and for food scientists to consider low GI ingredients in food formulation. The recently published international GI table has given values for more than 50 staple cereal-based Indian foods which cannot be considered for application for the various reasons given in Table 25.3.[14,38–49]

GLYCEMIC INDEX AND METABOLIC HEALTH

Blood glucose concentration is tightly regulated by homeostatic regulatory systems in humans. Observational studies indicate that the GI of the diet may have a major influence on glucose homeostasis and metabolic regulations. The major sources of carbohydrate in the

TABLE 25.3 Glycemic Index of Asian Indian Staple Foods as Given in the International GI Table (2008)

Food Items	Authors	GI (Glucose = 100) Normal	Type 2 diabetes	Limitations
RICE AND RICE BASED FOOD ITEMS				
Idiappam, Appam, Puttu, Idli, Pongal, Dosai, Brown Rice boiled, White Rice, Parboiled rice, porridge, Dhokla	Vijayan 1997[38], Urooj 2000[39], Kurup 1992[40], Chaturvedi 1997[41], Kanan W 1998[42], Kavita MS 1997[43], Shobana 2007[44], Pathak P 2000[45]	35–76	31–90	• Half or one hour intravenous samples considered for 2 or 3 hours • Portions of test food and reference food provide 75 g of available carbohydrate which was not measured directly as recommended in the new GI protocol. • Handheld Glucometers were used which are not recommended
Wheat and Wheat Based Food Items				
Wheat Porridge, Chapatti and with different , combinations, Poori , Wheat, Semolina cooked in different forms	Shobana S 2007[44], Chaturvedi 1997[41] Sumathi A 1997[46], Urooj 2000[39], Dilawari JB 1981[47], Kavita MS 1997[43], Mani UV 1992[48]	39–66	46–90	
Other Cereal Based Products				
Upittu , Barley, Chapatti, barley, Maize flour made into chapatti, Varagu, Bajra flour chappati	Urooj 2000[39], Shukla K 1991[49] Mani UV 1993[50]	48–69	37–67	
Millets and Millet Based Products				
Millet/Ragi, Millet/ Ragi flour, Porridge, made from finger millet, and pulses, Jowar, roasted bread, Laddu ; Uppuma kedgeree	Kavita MS 1997 [43], Mani UV 1993[50] Shobana S 2007[44], Pathak P et al 2000[45]	18–77	19–104	

Source: Adapted from Atkinson et al 2008.[14]

diet in India are refined cereals, which have high GI values and have been linked to the widespread occurrence of type 2 diabetes and CVD.[50]

Mechanisms of Action of High GI Foods

Rapid glucose absorption after consuming a high GI meal challenges body homeostasis and disrupts the transition from the postprandial to the post-absorptive phase. Following a high GI meal, during the postprandial phase there is relative hyperglycemia along with increased concentrations of gut hormones such as glucagon-like peptide-1 (GLP-1) and glucose-dependent insulinotropic polypeptide (GIP), which stimulates insulin release from pancreatic beta cells and inhibits glucagon release from pancreatic alpha cells. The resulting high insulin: glucagon ratio aggravates the normal response to eating, including uptake of nutrients by insulin-responsive tissues; stimulation of glycogenesis; lipogenesis; suppression of glycogenolysis; and lipolysis. Beyond 2 hours into the postprandial phase, nutrient absorption in the intestine decreases but the effects of the high insulin: glucagon ratio persist and there is often a drop to the hypoglycemic range. This rapid fall in metabolic fuels results in increased hunger, and increased food intake can lead to obesity.[51–53]

Within 4–6 hours of a high GL meal the decreased concentrations of glucose and free fatty acids trigger certain counter-regulatory hormones, such as glucagon, which restores euglycemia through stimulation of glycogenolysis, gluconeogenesis, and lipolysis, and elevates free fatty acids (FFA) concentrations to higher levels than those observed after a low GI meal. The combined increase in counter-regulatory hormones and FFA resembles the overnight fasting state.[54,55]

Mechanism of Action of Low GI Foods

Ingestion of a low GI meal leads to slow release of glucose and prevents hypoglycemia; elevated hormones and FFA levels do not occur for a 6-hour period due to continued absorption of nutrients from the intestine, paralleled by increasing hepatic glucose output. Low GI foods are associated with increased amounts of carbohydrate escaping digestion in the small intestine (dietary fibers, indigestible oligosaccharides, and resistant starch [RS]) and hence lead to increased colonic fermentation. The short-chain fatty acids (SCFAs) produced during colonic fermentation have local and systematic effects that could contribute to the mechanism for beneficial effects of low GI foods in diabetes, cardiovascular disease, and cancer.[56] Hence, diets containing identical energy and nutrients, but varying in their GI, can elicit markedly different physiological responses.[57]

GI and Chronic Diseases

Non-communicable disorders (NCDs) such as obesity, cardiovascular disease (CVD), diabetes, and its

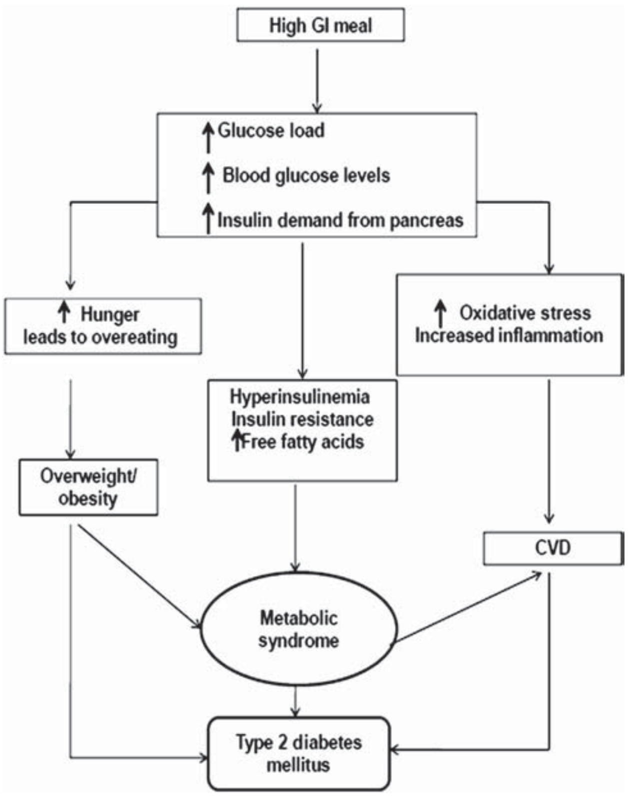

FIGURE 25.3 Physiological effects of high GI foods and link to diabetes. *Source: Adapted from Ludwig DS. The glycemic index: Physiological mechanisms relating to obesity, diabetes and cardiovascular disease. JAMA* 2002;**287**(18):2414–23.[54]

complications are responsible for over 55% of deaths in India. It is unfortunate that these chronic diseases afflict Indians at a younger productive age, leading to human capital wastage for a growing Indian economy.[58] Evidence has shown that GI has strong relevance to chronic diseases and their associated metabolic regulations (Fig. 25.3).

GI and Diabetes

The links between GI/GL diets and diabetes are related to glucose and insulin responses. High GI diets lead to elevated blood glucose and insulin levels. Hyperinsulinemia further increases β-cell dysfunction and results in insulin resistance, which is a risk factor for type 2 diabetes.[59] On other hand, a low GI diet tends to delay glucose absorption, thereby reducing the peak insulin concentrations and overall insulin demand. Available scientific evidence largely supports that low GI/GL diets, through their effect on postprandial glycemia and glycated proteins, may help in the prevention and treatment of diabetes.[60] A review of randomized control trials, lasting from 4 weeks to 12 months, in diabetic subjects showed that low GI diets compared to high GI diets lowered protein markers of glycemic control measured as HbA1c decreased by 0.5% (95% CI −0.8 to −0.2; $P<0.001$). This 0.5% reduction is clinically significant, as it corresponds to a lower dosage of medications for newly diagnosed patients; moreover, the UK Prospective Diabetes Study (UKPDS) suggests that a 1% reduction in mean HbA1c levels corresponds to a 21% reduction in risk for deaths related to diabetes and its complications.[61,62]

Recent GI testing of three popular Indian rice varieties, namely "Sona Masuri," "Ponni" and "Surti Kolam," showed them all to be high GI food choices, because these rice varieties are highly polished (refined grains).[63] A recent epidemiological study among urban adults has shown that higher refined grain consumption is associated with dyslipidemia (low HDL and high TG), metabolic syndrome, and increased risk for type 2 diabetes.[64]

GI and Obesity

A high GI diet results in high insulin and low glucagon levels, inducing glucose storage, inhibiting lipolysis, and consequently reducing glucose availability for metabolic oxidation. This stage could be seen as a fasting state, and triggers glucagon release and hunger signals.[56] Low GI foods, however, tend to maintain glucose and insulin at moderate levels, avoiding the hypoglycemic state. Low GI meals have also shown inverse association with cholecystokinin (CCK) response and satiety.[65] Intervention studies have shown improved fat loss/weight loss with low GI diets compare to high GI diets, the diets having similar nutrient contents.[66] Our study has also shown positive association of GL and refined grains with BMI and waist circumference (WC) among Asian Indians, who have genetic vulnerability to insulin resistance and diabetes.[7,64]

FACTORS INFLUENCING GI OF STAPLE FOODS

The glycemic response of food depends on the rate of gastric emptying, digestion, and absorption of carbohydrates from the small intestine, and in addition on the effects of other food factors in potentiating non-glucose mediated insulin secretion. Various chemical and physical phenomena contribute to differences in carbohydrate digestion and therefore the blood glucose response. A range of food factors have been identified as important determinants of the glycemic response to carbohydrate foods; these are given in Table 25.4.[67]

Particle Size

Particle size affects the digestibility of starch: the larger the particle size, the lower the digestibility of starch. The fibrous coating around cereals and millets serves as a physical barrier delaying the action of enzymes on starch.[67] Further milling, beating, shearing, and refining of foods affects cell and granule integrity. These processes

TABLE 25.4 Factors Contributing to Low and High GI of Foods

Factors/Food Variables	Low GI	High GI
Particle size	Larger particle size, entrapped starch molecules, delays action of digestive enzymes	Small particle size, poor granule integrity, activates action of digestive enzymes
Cell structure/ cell wall integrity	Raw foods	Ripe foods
Starch structure	Granular structure, high crystallinity and recrystallinity	Gelatinization
Amylose : Amylopectin ratio	High amylose : amylopectin ratio	Low amylose : amylopectin ratio
Cooking methods	Less exposure to gelatinization	More exposure to gelatinization, grinding, milling
Protein	Increases insulin secretion and lowers GI	–
Fat	Delays gastric emptying and lowers GI	–
Fructose : glucose ratio	High fructose : glucose ratio	Low fructose : glucose ratio
Dietary fibers	Slow gastric emptying and digestion lowers GI	–
Water and carbohydrate in liquid form	–	Higher quantity accelerates gastric emptying and increases GI
Organic acids	Delays gastric emptying and lowers GI	–
Amylase inhibitors	Restricts digestion and lowers GI	–
Chewing	Less chewing	Extended chewing

Source: Adapted from Nord.[55]

decrease particle size and promote absorption of water and breakdown by enzymes.[68] A study comparing four types of wheat – whole grain, cracked grain, coarse and fine whole meal flour – in 10 healthy subjects resulted in glucose responses to whole grain of approximately one-third the response to fine flour. Insulin responses were similar.[69] Studies were carried out to compare breads made of different particle sizes. Consumption of standard white bread and ultrafine ground whole wheat flour breads by middle-aged men and women resulted in lower glycemic indices compared to glucose, but glycemic indices of whole wheat breads, although lower than white bread, were not different.[70,71]

The only whole grain food with a high GI is rice – specifically, low amylose rice. Rice starch is very easily gelatinized during cooking, and is easily acted upon by digestive enzymes. Along with particle size, the degree of mastication varies significantly between individuals and may be a cause for the considerable interindividual variation observed in the glycemic response (GR) to a single food.[72] A study carried out on factors affecting the GI of barley showed that the GI decreased more significantly in whole grain barley pasta (26 ± 4) than in white pearled barley pasta (35 ± 3); the study also stated that the GI of barley is not predicted by its content of amylose or other starch characteristics.[73]

Processing Conditions

Processing of foods can either increase or decrease the GI of different foods. The nature of starch is influenced by various processing conditions. The gross structure of starch molecules is influenced by grinding, milling, or heat treatment. A study to determine the GI of different varieties of milled and brown rice showed that the Sinandomeng variety, with low dietary fiber, had a GI = 75, while its brown rice had a GI = 55. Brown rice (IR64) with 23% available carbohydrates and dietary fibers of 2.5 g/100 g had a low GI = 51.[74] Cell wall integrity and cellular structure change with the ripening process, and GI in turn increases with ripening. Green bananas have a high content of RS, and only a negligible amount remains after ripening.[75] The maintenance of high starch crystallinity plays an important role in the low GI of the food. In most ready-to-eat food items the starch crystallinity is greatly reduced during commonly applied food processing conditions, resulting in more or less complete gelatinization. However, pasta is unique in this regard. Pasta has a low GI because of the physical entrapment of ungelatinized starch granules in a sponge-like network of protein (gluten) molecules in pasta dough.[76] A comparative study on the consumption of pasta and bread in 10 type 2 diabetic subjects showed a lower rise in postprandial glucose on consumption of pasta than in bread.[77]

Starch can be indigestible due to its botanical structure (amylose : amylopectin ratio) or become resistant during processing due to retrogradation; this is known as resistant starch (RS). RS formation or digestibility of starch is affected by various processing conditions, and the nature of the starch. When heat and moisture are applied simultaneously (as in normal cooking procedures like boiling, steaming, etc.) to amylopectin-rich starch, it loses its granular definition and gelatinization takes place; this increases the GI of the food. On the other hand, high amylose starch resists gelatinization during most normal food processing methods, like baking and roasting, due to its granular structure; it also contributes to RS formation in the food.[78] Processing conditions like roasting, baking, boiling, and shallow frying have shown high RS formation in commonly consumed cereal and cereal-based products in India, whereas cooking conditions such as steaming and frying showed low RS. When analyzed, the puffed, flaked, and extruded cereal products obtained from the market also showed considerably less retention of RS content.[79]

Dietary Factors

Carbohydrates

Traditionally, carbohydrates have been classified as simple and complex based on the degree of polymerization, and this classification was assumed to reflect their quality. Thus, simple carbohydrates such as simple sugars (mono- and disaccharides) were thought to increase the blood glucose quickly compared to complex carbohydrates such as starchy foods (containing polysaccharides). Further studies on the physiological effects of carbohydrates and fibers, however, showed that not all complex carbohydrates raise blood glucose slowly.[80] Therefore, the quality of carbohydrates is classified based on their glycemic nature. Food composition tables unfortunately do not mention the glycemic nature of carbohydrate foods, such as particle size and nature of the starch.

Available carbohydrates are the carbohydrates that are absorbed in the small intestine and metabolized in the body via pathways which can, at least potentially, yield glucose.[56] Available carbohydrates may influence blood glucose by four major mechanisms: (1) the nature of the monosaccharides absorbed; (2) the quantity carbohydrates absorbed and metabolized; (3) the amount of carbohydrates consumed; and (4) the rate of absorption.

The majority of available carbohydrates are absorbed in the form of glucose (70–85%), while the remainder are a mixture of fructose and galactose. Glucose has a high GI (GI = 100), fructose has a low GI (GI = 23), and sucrose (a combination of glucose and fructose) has a GI = 65.[14] Fructose does not raise blood glucose appreciably because it is converted to glucose in the liver and only a small portion of this glucose is released to circulation.[81] Fructose absorption is also poorly understood, but it is passively absorbed in the intestine through GLUT5 and GLUT 2 transporters.[82] Hence the glycemic indexes of fruit juices are generally lower. Lactose present in milk has a lower GI than sucrose, maybe because the galactose in it elicits a lower glycemic response.[83,84] Polyols or sugar alcohols are naturally present in fruits, but are commercially produced by hydrogenation; those commonly consumed are sorbitol, mannitol, xylitol, lacitol, etc. Polyols elicit a small to moderate rise in plasma glucose in both normals and diabetics compared to glucose.[85]

Certain carbohydrates are not digested or absorbed in the human intestine, and are termed "unavailable carbohydrates." Carbohydrates can be unavailable because humans lack the enzymes necessary to hydrolyze them into their component monosaccharides – for example, fructooligosaccharides, non-starch polysaccharides (NSP), and resistant starch (RS). Monosaccharides, such as sorbitol and xylose, may be unavailable because they are incompletely transported into the intestinal cells and bloodstream. The term RS is defined as the fraction of dietary starch that escapes digestion in the small intestine,[86] and is of five types, namely RS1 (physically confined and mainly found in whole and fractionally milled grains, seed, and legumes); RS2 (resistant ungelatinized granules with type B crystallinity that is gradually hydrolyzed by α-amylase; food sources include raw potatoes, green bananas, and a few legumes and high amylase corn); RS3 (retrograded starch found in potatoes that are cooked and cooled, bread, cornflakes, and food products that have undergone repeated moist heat treatment); RS4 (starches that are chemically modified as a result of cross-linking chemical agents and are present in breads, cakes etc.); and RS5 (an amylase lipid complexed starch as a result of extended retrogradation, with reduced enzyme susceptibilities to pancreatic α-amylase and amyloglucosidase found in fried foods).[87,88]

The glycemic response is also affected by the rate of carbohydrate absorption, which can be reduced by the addition of viscous fibers, correlation between rates of digestion of starches *in vitro*, use of digestive enzyme inhibitors, the euglycemic hyperinsulinemic clamp, and oral carbohydrate loading.

Protein

Protein is an insulinotrophic substance that stimulates or affects the production of insulin when consumed along with a diet rich in carbohydrate.[89] This synergism was reported in type 2 DM adults where 50 g glucose with 50 g protein was found to increase the insulin secretion and reduce the plasma glucose level.[90] However, this effect varies with different types of amino acids and protein. Branched-chain amino acids that are found in animal protein (e.g., whey protein hydrolyzate) show an increased insulinemic response and glucose uptake. In diabetic adults, this type of response prevents lipolysis and excessive release of FFA, thereby reducing the risk for CVD.[91] Similarly, diets rich in leucine, tyrosine (non-essential amino acid), and phenylalanine (essential amino acid) increase the insulin responses when ingested along with carbohydrates.[89] In a randomized control study, protein in the form of soya protein concentrate was shown to increase the effect of maintaining glucose homeostasis three-fold compared with fat consumed in the form of corn oil, and this effect of protein was associated with high waist circumference and high dietary fiber intake.[92] It is known from evidence that food proteins also affect glucose metabolism due to their varied nutrient composition.[93–97] Milk contains 80% casein, which is insulinogenic, and 20% whey, which acts as an insulin secretagogue, although the factors that are responsible for this effect (such as rapid release of amino acids, release of bioactive peptide, and glucose-dependent insulinotropic polypeptide [GIP] secretion) are yet to be studied.[98] However, in the urban component of the Chennai Urban Rural Epidemiological Study (CURES) it was observed that intake of dairy products was inversely associated with the risk of type 2 diabetes among Asian Indians.[7] This finding needs further research to identify the mechanisms and factors related to milk composition.

Apart from the quality and quantity of protein, the rate of digestion also impacts the glycemic response. Proteins that are slowly absorbed do not show a rise in plasma amino acids, and thus do not stimulate the production of insulin. In 1990, Nuttall and Gannon proposed a study of this effect by supplementing the normal subjects with 50 g of egg white protein and cottage cheese protein, where the former reduced the insulin response and the latter increased the insulin response. On the other hand, the conversion of protein to urea was found to be lowered by 50% in subjects who consumed egg white protein compared to the cottage cheese protein.[99] On the contrary, protein also increases the plasma glucose concentration by stimulating glucagon secretion. A reduced percentage of energy from protein (12% to 0%) reduces the insulin requirement by 25% in type 1 DM, reduces hepatic glucose output and fasting insulin by 20%, and increases glucagon secretion by 24% in normal subjects.[100] However, the insulinogenic effect of protein also depends on individual insulin sensitivity.[101]

Fat

The postprandial glycemic response is determined mainly by the rate of gastric emptying.[102–105] Nutrients such as fat interact with the receptors in the small intestine to slow down gastric emptying, possibly due to their high calorie content and reduced absorption rate.[106] Gut incretin hormones such as glucagon-like peptide (GLP-1) and glucose-dependent insulinotropic polypeptide (GIP), which accounts for 50% rise in plasma insulin level, can, after an oral glucose load,[107] be attenuated by fat.[108] In a randomized cross-over study, fat in the form of olive oil ingested before a carbohydrate meal (potato meal) delayed gastric emptying and attenuated the postprandial glucose level, and insulin and GIP secretion. However, this effect of fat also depends on the lipolysis of triglycerides to fatty acids.[109] The effect of fatty acids such as SFA, MUFA, and PUFA on the insulinemic response has also been studied.[110,111] Diets high in linoleic acid (LA) (n-6 PUFA) and low in (n-3 PUFA) could increase the risk of metabolic syndrome in Asian Indians;[112] moreover, according to American Diabetes Association (ADA), the percentage of energy derived from oleic acid or EPA and DHA that is usually recommended for individuals with type 2 diabetes only leads to a modest reduction in the postprandial insulin response, compared to diets rich in palmitic acid or linoleic acid.[113] Similarly, the impact of different fat sources on the glycemic response has been studied, and results showed that safflower or olive oil decreased, and butter increased, the plasma glucose level, whereas triacylglycerol concentration increased with safflower oil;[114,115] this is consistent with the study result of Mekki *et al.* on the effect of postprandial lipemia after supplementation of a mixed meal containing 40 g fat as butter, olive oil, or sunflower oil.[116] This may possibly be due to the difference in the binding of specific fatty acids to FABP2 (fatty acid binding protein), which is then formed into chylomicrons in the endoplasmic reticulum. Fatty acids in butter (contains 25% fat as short- and medium-chain fatty acids) bind to FABP2 to a lesser extent than olive oil (75% oleic acid) or safflower oil (75% linoleic acid) because of its varied fat content and the type of fatty acids present in it. As a result, butter is more absorbed into the portal vein rather than transported for chylomicron synthesis, and this further increases the hepatic glucose output and thereby results in a high plasma glucose level.[117] Diets rich in MUFA help in stimulating GLP secretion by enhancing L cell sensitivity,[118] and these incretin hormones (including GIP) are being used as a new therapeutic approach in the treatment of type 2 diabetes.[119]

Fiber

Fiber comprises the edible parts of cereals, fruits, and vegetables that are resistant to digestion and absorption in the human small intestine.[120,121] Interest in the association of dietary fiber and risk for chronic diseases arose as early as 1970s, when Burkitt and Trowell hypothesized that lack of fiber in the diet was associated with increased incidence of obesity, type 2 diabetes, coronary heart disease, and some cancers among the Western population. Recent epidemiological studies have also confirmed this hypothesis and shown a protective role of dietary fiber in reducing the risk of chronic diseases.[122–125] Dietary fiber is a complex mixture of polysaccharides that has been shown to exert several physiological effects in the human gastrointestinal tract and hence may have an influence on disease risk. However, the effect of dietary fiber in foods on the glycemic response is undecided. Dietary fiber delays gastric emptying and decreases the absorption of nutrients, resulting in lower postprandial glucose and insulin response. Recent research has shown that the soluble versus insoluble fraction of fiber in foods may give a clear insight regarding the efficacy of dietary fiber on GI.[126]

The carbohydrate metabolism of grains is influenced by several factors, such as differences in structure and composition (particle size), amount and type of fiber, viscosity, presence of antinutrition factors, and cooking method and temperature.[127] The fiber content of rice has shown no positive correlation with its GI.[80] However, the

GI of brown rice is lower compared to that of its counterpart, polished white rice. This may be attributed to the differences in physiochemical properties, longer cooking time, and lesser gelatinization of brown rice, and the presence of other antinutritional factors such as phytates and polyphenols in brown rice which slow starch digestion and delay glucose absorption.[128,129]

Potential Ingredients to Lower GI

Today, many functional ingredients are available for exploitation in food formulation to lower the GI of processed foods. These functional ingredients come from grains, fruits and vegetables (β-glucans, non-digestible oligosaccharides and RS), and modified carbohydrates.[11]

Recent research has focused on the effect of viscous soluble fiber on the carbohydrate metabolism and blood glucose response. Two recent studies have demonstrated that a novel functional viscous fiber, PGX®, added to commonly consumed starchy foods, one of which was rice, resulted in a dose-dependant reduction in the GI (PGX added to rice=19% for a 2.5-g dose and 30% for a 5-g dose).[130,131] Recent studies from our center have also shown that when fenupower (a soluble dietary fiber rich in galactomannan extracted from fenugreek seeds) was incorporated into commonly consumed breakfast meal choices of Indians (idly- and whole wheat-flour pulkha), the GI dropped by 30% for idly- and 8.4% for whole wheat-flour pulkha compared to their controls tested without fenupower. Similarly, in another study the GI of whole wheat flour roti and atta mix roti was tested and it was found that although both had low GI values, the GI of the atta mix was considerably lower than that of the whole wheat flour mix. In this study, the galactomannan from bengal gram, psyllium, and fenugreek seeds present in atta mix may change the physical availability of carbohydrate to hydrolytic enzymes, thus converting the carbohydrates to a slow release form, resulting in lowering of the plasma glucose level.[132] In another study, the effect of 4 g and 8 g β-glucan added to Indian flat breads (chapatti) showed 43% and 47% reduction in GI values compared to control chapattis made from whole wheat flour.[10]

Thus, the effect of inherent fiber on the GI is still not well established. However, incorporation of viscous fiber products has shown their potential to reduce the GI. Further well-designed studies with respect to different components of fiber and its mechanisms are still needed, considering its effects in the prevention of diabetes and metabolic syndrome.

CONCLUSIONS

Cereal staples have served as major calorie contributors to Indian diets since ancient times. The recent shift to refined grains with a high GI could be one of the reasons for the increasing prevalence of diabetes and metabolic syndrome in India. It is unlikely that the total carbohydrate content of Indian diets could be altered, due to traditional dietary habits. It is thus reasonable to encourage the introduction of low GI foods and to promote high-fiber foods to reduce the GL of Indian meals. Moreover, low GI foods come with added benefits, such as a higher fiber and phytonutrient content, that are beneficial to overall health. Several mechanistic, prospective, and randomized clinical trials globally have proved that a low GI has beneficial effects on glycemic and insulinemic responses, but there are limited studies with Indian diets.

There is thus an urgent need to create a database of the GI of Indian foods using standardized methodology. This will enable those engaged in public health and clinical practice in health advocacy and counseling. Use of newer functional ingredients could help lower the GI, and hence better formulations of such foods need to be developed. Low GI foods could possibly help to tackle the epidemic of type 2 diabetes and metabolic syndrome in India, but randomized clinical trials are needed on this subject.

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