

Dietary Carbohydrate (Amount and Type) in the Prevention and Management of Diabetes

A statement by the American Diabetes Association

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Diabetes has long been viewed as a disorder of carbohydrate metabolism due to its hallmark feature of hyperglycemia. Indeed, hyperglycemia is the cause of the acute symptoms associated with diabetes such as polydipsia, polyuria, and polyphagia (1). The long-term complications (retinopathy, nephropathy, and neuropathy) associated with diabetes are also believed to result from chronically elevated blood glucose levels (2–6). In addition, hyperglycemia may contribute to the development of macrovascular disease, which is associated with the development of coronary artery disease, the leading cause of death in individuals with diabetes (7–9). Thus, a primary goal in the management of diabetes is the regulation of blood glucose to achieve near-normal blood glucose.

What determines the postprandial blood glucose response?

Blood glucose concentration following a meal is determined by the rate of appearance of glucose into the blood stream (absorption) and its clearance/disappearance from the circulation (10). The rate of dis-

appearance of glucose is largely influenced by insulin secretion and its action on target tissues (11).

The component of the diet that has the greatest influence on blood glucose is carbohydrate. Other macronutrients in the diet, i.e., fat and protein, can influence the postprandial blood glucose level, however. For example, dietary fat slows glucose absorption, delaying the peak glycemic response to the ingestion of a food that contains glucose (12–14). In addition, although glucose is the primary stimulus for insulin release, protein/amino acids augment insulin release when ingested with carbohydrate, thereby increasing the clearance of glucose from the blood (15–17).

Both the quantity and the type or source of carbohydrate found in foods influence postprandial glucose level (18,19). Although most experts agree that the total carbohydrate intake from a meal or snack is a relatively reliable predictor of postprandial blood glucose (18,20–22), the impact and relative importance that the type or source of carbohydrate has on postprandial glucose level has continued

to be an area of debate (23–26). Over the last two decades, investigators have attempted to define and categorize carbohydrate-containing foods based on their glycemic response or their propensity to increase blood glucose concentration (27,28). Two methods that have been investigated as potential tools for meal planning and/or assessing disease risk associated with dietary carbohydrate intake are the glycemic index and the glycemic load. The purpose of this statement is to review the available scientific data regarding the effect of the type or source of carbohydrate on the prevention and management of diabetes and to clarify the position of the American Diabetes Association on this important topic.

What is the glycemic index?

The glycemic index is a measure of the change in blood glucose following ingestion of carbohydrate-containing foods. Some foods result in a marked rise followed by a more or less rapid fall in blood glucose, whereas others produce a smaller peak along with a more gradual decline in plasma glucose (19). The specific type of carbohydrate (e.g., starch versus sucrose) present in a particular food does not always predict its effect on blood glucose (28,29).

The glycemic index is a ranking of carbohydrate exchanges according to their effect on postprandial glycemia. It is a means of quantifying the relative blood glucose response to carbohydrates in individual foods, comparing them on a weight-for-weight basis (i.e., per gram of carbohydrate). As measured/analyzed under laboratory conditions, the glycemic index is the increase in blood glucose (over the fasting level) that is observed in the 2 h following ingestion of a set amount of carbohydrate in an individual food. This value is then compared with the response to a reference food (glucose or white bread) containing an equivalent amount of carbohydrate (27).

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A table elsewhere in this issue shows conventional and Système International (SI) units and conversion factors for many substances.

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What is glycemic load?

While the glycemic index provides a ranking of foods based on their blood glucose response, it does not take into account the effect of a typical amount of carbohydrate in a food portion on glycemia. In an effort to improve the reliability of predicting the glycemic response of a given diet, Salmeron et al. (30) have suggested the use of the glycemic load. As defined, the glycemic load of a particular food is the product of the glycemic index of the food and the amount of carbohydrate in a serving. By summing the glycemic load contributed by individual foods, the overall glycemic load of a meal or the whole diet can be calculated (30).

If carbohydrates increase blood glucose, why not restrict total carbohydrate intake in individuals with diabetes?

Blood glucose is increased in individuals with diabetes in both the fed and fasted state. This abnormal metabolic response is due to insufficient insulin secretion, insulin resistance, or a combination of both. Although dietary carbohydrate increases postprandial glucose levels, avoiding carbohydrate entirely will not return blood glucose levels to the normal range. Additionally, dietary carbohydrate is an important component of a healthy diet. For example, glucose is the primary fuel used by the brain and central nervous system, and foods that contain carbohydrate are important sources of many nutrients, including water-soluble vitamins and minerals as well as fiber (31). Given the above, low-carbohydrate diets are not recommended in the management of diabetes. Recently, the National Academy of Sciences–Food and Nutrition Board recommended that diets provide 45–65% of calories from carbohydrate, with a minimum intake of 130 g carbohydrate/day for adults (31).

What determines the glycemic effect of a carbohydrate-containing food?

Both the amount (grams) of carbohydrate as well as the type of carbohydrate in a food will influence its effect on blood glucose level. The specific type of carbohydrate (e.g., starch versus sucrose) present in a particular food does not always accurately predict its effect on blood glucose (28,29). For example, sugars such as sucrose and fructose have a lower glycemic response/glycemic index despite their

shorter chain length (32–36). In fact, a variety of factors intrinsic to a given food can influence its impact on blood glucose. These include the physical form of the food (i.e., juice versus whole fruit, mashed potato versus whole potato), ripeness, degree of processing, type of starch (i.e., amylose versus amylopectin), style of preparation (e.g., cooking method and time, amount of heat or moisture used), and the specific type (e.g., fettucine versus macaroni) or variety (e.g., long grain versus white) of the food (26). Extrinsic variables such as the coingestion of protein and fat, prior food intake, fasting or preprandial glucose level, and degree of insulin resistance will also alter the effect of a specific carbohydrate-containing food on blood glucose concentration (19,26,28).

Which has a greater influence on blood glucose, the type of carbohydrate or the total amount of carbohydrate?

Both the amount (27,37) and the source (27,38) of carbohydrate are important determinants of postprandial glucose. The relative effects of each have been recently studied. Brand-Miller et al. (in response to a letter from Mendosa [39]) reported that they analyzed the relative impact of the glycemic index and total carbohydrate content of individual foods on glycemic load (the product of glycemic index and total grams of carbohydrate) using linear regression analysis. Carbohydrate content (total grams) alone explained 68% of the variation in glycemic load, while the glycemic index of the food explained 49%. When total carbohydrate and glycemic index were both included in the regression analysis, the glycemic index accounted for 32% of the variation.

Wolever and Bolognesi (21,22) tested the hypothesis that both the type and amount of carbohydrate influence glycemic response in normal subjects. Their findings demonstrated that the amount of carbohydrate ingested (whether in a single food or as part of a meal) accounted for 57–65% of the variability in glucose response, while the glycemic index of the carbohydrate explained a similar amount (60%) of the variance (21,22). Together, the amount and the glycemic index of carbohydrate accounted for ~90% of the total variability in blood glucose response, indicating the cumulative effect of both

factors on postprandial blood glucose concentration.

Wolever and Mehling (40) examined the long-term effect of varying the type or amount of dietary carbohydrate on postprandial plasma glucose, insulin, and lipid levels in 34 subjects with impaired glucose tolerance. After 4 months, mean plasma glucose concentrations over 8 h were lowered by the same amount on both the low-carbohydrate, high-monounsaturated fat and the high-carbohydrate, low-glycemic index diets when compared with values in subjects on the high-carbohydrate, high-glycemic index diet. Thus, in patients with impaired glucose tolerance, reducing the glycemic index of the diet for 4 months reduced postprandial plasma glucose by the same amount as reducing carbohydrate intake.

What are some of the issues regarding the glycemic index?

1) The glycemic index takes only the type of carbohydrate into account, ignoring the total amount of carbohydrate in a typical serving, although both the type and amount of carbohydrate influence the postprandial glycemic and insulin response of a given food as typically consumed (18,22,26).

By definition, the glycemic index is a ranking of foods according to their effect on postprandial glycemia. It compares equal quantities of carbohydrate and provides a measure of carbohydrate quality but not quantity. Thus, the glycemic index provides information about how carbohydrate-containing foods affect blood glucose following ingestion of a single food in addition to that obtained from knowledge about the total amount of carbohydrate. As such, the index is not intended to be used in isolation, but rather can and should be used in conjunction with other food and nutrition strategies (e.g., total amount of carbohydrate, modification of dietary fat intake, portion control).

2) The glycemic index for any particular food item is highly variable.

The glycemic response to a particular food is subject to significant variation, both within individuals and between individuals (intraindividual coefficient of variation 23–54%) (26,41–43). This variability, however, is similar to that seen for the oral glucose tolerance test (42,43). When the glycemic response is expressed

as a percentage of an individual's response to a standardized food (i.e., 50 g white bread or glucose), the between-individual variation is reduced to ~10% (27,44,45).

Variation in individual glycemic response may also reflect differences in the physical and chemical characteristics of specific foods, as well as differences in methodology. For example, the type of blood sample (capillary or venous), the experimental time period, and the portion of food all influence the glycemic index of a given food. Recently, findings from a collaborative study demonstrated that similar glycemic index values can be obtained when methodology is standardized (45), although some foods continue to show wide variation in response secondary to botanical differences (46).

3) As defined, the glycemic index only measures the response to an individual food consumed in isolation. What is perhaps more relevant, however, is the ability of the index to predict blood glucose concentration when the food is part of a meal.

In general, the glycemic response to mixed meals can be predicted with some accuracy by summing up the glycemic index of the component foods (43,47–52), although not all studies have found a direct relationship between calculated and measured glycemic index of mixed meals (53–55).

4) The glycemic index does not predict postprandial blood glucose response as accurately in individuals with diabetes as it does in healthy persons.

Although the glycemic response following carbohydrate ingestion is higher in individuals with diabetes, the relative response to foods and mixed meals that vary in glycemic index is similar in individuals with diabetes and healthy subjects (44,48,52,55–57).

What studies have examined the effectiveness of the glycemic index on overall blood glucose control?

There have been several randomized trials that have examined the efficacy of diets consisting of low glycemic foods to control glycemia. The results have been mixed, with some showing (58–64) and others not showing (65–67) significant improvement. In part, this may be due to the fact that many of the studies have involved small numbers of subjects, been of relatively short duration, and shown only a modest effect. Significant variation in study design, subject characteristics, and

diet composition also makes summative conclusions regarding the effectiveness of low glycemic diets on blood glucose control more challenging.

In an attempt to clarify the issue of the effect of low-glycemic index diets in the management of type 1 and type 2 diabetes, Brand-Miller et al. (68) recently conducted a meta-analysis of available studies on this topic. Their findings indicate that implementing a low-glycemic index diet lowered A1C values by 0.43% when compared with a high-glycemic index diet. The findings were similar in both type 1 and type 2 diabetes.

The findings of the meta-analysis are also consistent with the results of the EU-RODIAB study, a cross-sectional study involving nearly 3,000 subjects with type 1 diabetes in 31 clinics throughout Europe, in which the glycemic index of self-selected diets was positively and independently related to A1C level (69).

What studies have examined the utility of the glycemic load?

The glycemic load has been primarily used in epidemiological studies to examine the effect of diet on the risk of developing chronic diseases such as diabetes, heart disease, and cancer. Although the findings from epidemiological studies indicate a possible relationship between the propensity of the diet to raise blood glucose and the development of diabetes, they do not demonstrate cause and effect. There remains a need to demonstrate a direct relationship between the calculated glycemic load of a food or meal with a proportional change in postprandial blood glucose and/or the secretion of insulin (i.e., a physiological basis). Additionally, to determine the clinical utility of glycemic load, longer-term trials in which high-glycemic load diets are compared with low-glycemic load diets and outcomes related to long-term glucose control (i.e., A1C) and lipids are measured will be required.

Recently, Brand-Miller et al. (41) published data that examined the relationship between glycemic load, blood glucose level, and insulin response following ingestion of individual foods. Stepwise increases in glycemic load for a range of foods produced proportional increases in blood glucose and insulin. In addition, the investigators demonstrated that portions of different foods with the same glycemic load produced similar gly-

cemic responses. Although the study was small and only examined healthy, normal-weight individuals, its findings demonstrate that calculated glycemic load can predict the blood glucose response to individual foods across a range of portion sizes. These are important findings in establishing a physiological basis for glycemic load; however, it will be necessary to examine the effect of the glycemic load of a mixed meal on postprandial glucose and insulin levels, as well as the effects on day-long glucose and insulin levels.

Does a diet with a high glycemic index or load lead to diabetes?

Epidemiological studies form the basis for the hypothesis that a diet with a high glycemic load or glycemic index leads to type 2 diabetes. Findings from the Nurses' Health Study demonstrated a positive association between dietary glycemic index and risk of type 2 diabetes; the relative risk was 1.37 when the highest quintile of glycemic index was compared with the lowest. Similarly, the glycemic load was positively associated with the development of type 2 diabetes (relative risk 1.47) in women (70). More recently, a follow-up study of the participants in the Nurses' Health Study confirmed the association between glycemic load and risk of type 2 diabetes (71). In men (Health Professionals' Follow-Up Study), however, neither glycemic load nor glycemic index were associated with diabetes risk, except when adjusted for cereal fiber intake (30). Finally, in the Iowa Women's Health Study, no significant relationship between glycemic index or glycemic load and the development of type 2 diabetes was observed (72). Thus, although some studies have observed an association between glycemic index or glycemic load and type 2 diabetes, this relationship has been equivocal or absent in others.

The inconsistency of findings from epidemiological studies may result from the difficulty in predicting glycemic index (and consequently glycemic load) precisely from the dietary assessment tools (food frequency questionnaires) currently in use. Food frequency questionnaires employed to assess dietary intake were not designed to measure glycemic index per se, and data validating their reliability in this regard are limited.

Of note, there is little evidence that total carbohydrate intake is associated with the development of type 2 diabetes

(30,70,73,74). Rather, a stronger association has been observed between total fat and saturated fat intake and type 2 diabetes (75,76), although not all findings are in agreement (30). Additionally, two prospective cohort studies have shown no risk of diabetes from consuming increased amounts of sugar (74,77), and in one study, a negative association was observed between sucrose intake and diabetes risk (72). Intakes of both whole grains (72,78) and dietary fiber (in particular, cereal fiber) are associated with lower risk of type 2 diabetes (30,70–72).

At this time, there is insufficient information to determine whether there is a relationship between glycemic index or glycemic load of diets and the development of diabetes. Prospective randomized trials will be necessary to confirm the relationship between the type of carbohydrate and the development of diabetes. The relative importance of the glycemic index or load of the diet to the development of obesity will also need to be considered, as excess body fat is the single most important determinant of type 2 diabetes (71). In addition, the findings of the Diabetes Prevention Program, conducted in the U.S., and the Finnish Diabetes Prevention Study clearly demonstrate that moderate weight loss markedly reduces the development of type 2 diabetes in individuals with impaired glucose tolerance (79,80).

Summary

- Regulation of blood glucose to achieve near-normal levels is a primary goal in the management of diabetes, and, thus, dietary techniques that limit hyperglycemia following a meal are likely important in limiting the complications of diabetes.
- Low-carbohydrate diets are not recommended in the management of diabetes. Although dietary carbohydrate is the major contributor to postprandial glucose concentration, it is an important source of energy, water-soluble vitamins and minerals, and fiber. Thus, in agreement with the National Academy of Sciences–Food and Nutrition Board, a recommended range of carbohydrate intake is 45–65% of total calories. In addition, because the brain and central nervous system have an absolute requirement for glucose as an energy source, restricting total carbohydrate to <130 g/day is not recommended.

- Both the amount (grams) of carbohydrate as well as the type of carbohydrate in a food influence blood glucose level. The total amount of carbohydrate consumed is a strong predictor of glycemic response, and, thus, monitoring total grams of carbohydrate, whether by use of exchanges or carbohydrate counting, remains a key strategy in achieving glycemic control.
- A recent analysis of the randomized controlled trials that have examined the efficacy of the glycemic index on overall blood glucose control indicates that the use of this technique can provide an additional benefit over that observed when total carbohydrate is considered alone.
- Although this statement has focused primarily on the role of carbohydrate in the diet, the importance of achieving/maintaining a healthy body weight (particularly in type 2 diabetes) in the management of diabetes should not be ignored. Moderate weight loss in overweight/obese individuals with type 2 diabetes results in improved control of hyperglycemia as well as in a reduction in risk factors for cardiovascular disease.
- Because much of the risk of developing type 2 diabetes is attributable to obesity, maintenance of a healthy body weight is strongly recommended as a means of preventing this disease. The relationship between glycemic index and glycemic load and the development of type 2 diabetes remains unclear at this time.

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