The Science of Sugars, Part I

A Closer Look at Sugars

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As carbohydrates, sugars play many important roles in our food. They are a source of calories and, in addition to sweetening, perform many essential technical functions both in processed foods and in foods prepared in the home. However, the complex terminology used to describe sugars can be confusing. Communications regarding the definitions of various sugars, the role of sugars in our food and health, and the methods used to measure sugar consumption would be enhanced among regulators, scientists, manufacturers, health professionals, and consumers if commonly accepted definitions were harmonized. Nutr Today. 2012;47(3):96–101

Sugars are desirable for their sweet taste and for their palatability. People have sought the many forms of sugars for millennia, including even the biblical reference of Canaan as the "land of milk and honey." The Americas, too, owe much of their growth to the European demand for sugar, which fueled industrial growth. In addition, we endearingly pay tribute to our love of sweets, calling favored ones "honey" and "sugar."

More recently, however, individuals searching for a cause of the increased prevalence of obesity have suggested that sugars and other sweets may be a significant part of the problem.

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This series of 4 articles will explore what is known about the science of sugars. The first article examines the types of sugars, their functionality in foods, and the various words used to describe sweeteners. The second article will examine the role of sugars in a healthful diet. Part 3 of this series will explore the relationship between sugars and both obesity and prevalent chronic diseases. The final article will review the association between sugars and dental health, between sugars and cognitive function, and between sugars and physical activity.

A vast amount of research has been conducted on sugars and health. Although there is an emotional tie to sugar, this review attempts to separate fiction from the scientific facts.

TERMINOLOGY

The terminology used to describe sugars can be confusing and imprecise.[1–3] Researchers use a variety of terms to describe nutritive or caloric sweeteners. *Sugar* generally refers to sucrose, which is manufactured primarily from sugar cane or sugar beets. In addition to sucrose, other sugars include invert sugar (sucrose molecule in which the disaccharide bond has been cleaved), high-fructose corn syrup (HFCS), crystalline fructose, and glucose. The term *sugar-sweetened* refers to those products sweetened during manufacture with either sucrose, one of the above-named sugars, or a combination of these sweeteners.

The term *added sugars* also has a variety of definitions. As defined by the US Department of Agriculture (USDA), *added sugars* refer to sugars that are added to foods either during processing or at the table. They include those sugars listed above, apple or grape juice concentrates, agave juice, and honey. By that definition, sugars that are naturally occurring in foods such as fructose in fruit or lactose in milk are not deemed "added sugars."[4] Others have defined added sugars in a slightly different manner, at times omitting the sugars from fruit juices or other small differences.

This review also uses the terms *nutritive sweeteners* and *caloric sweeteners* to indicate the above-named sugars. It would be beneficial if there were a harmonization of commonly accepted definitions because this would facilitate communication among regulators, scientists, manufacturers, health professionals, and consumers.[1]

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Class (DP*)	Sub-Group	Components
Sugars (1-2)	Monosaccharides	Glucose, galactose, fructose
	Disaccharides	Sucrose, lactose, trehalose
	Polyols	Sorbitol, mannitol
Oligosaccharides (3-9)	Malto-oligosaccharides	Maltodextrins
	Other oligosaccharides	Raffinose, stachyose, fructo-oligosaccharides
Polisaccharides (>9)	Starch	Amylose, amylopectin, modified starches
	Non-starch polisaccharides	Cellulose, hemicellulose, pectins, hydrocolloids

DP * = Degree of polymerization

FIGURE. Food and Agriculture Organization/World Health Organization carbohydrate classification based on the degree of polymerization.

A useful way of classifying sugars is by the degree of polymerization, or DP.

The Food and Agriculture Organization and the World Health Organization recommend classifying dietary carbohydrates by the number of saccharides, also called degree of polymerization (DP; Figure).[5] So-called simple sugars contain 1 saccharide (monosaccharide); simple sugars may be strung together necklace-like into linear chains of 2 or more saccharides or connected like the branches of a tree. The number of monosaccharides hooked together indicates the DP. Chains of 3 to 9 monosaccharides are called oligosaccharides and those of more than 9 are called polysaccharides.[5]

Sugars occur naturally in a wide variety of fruits, vegetables, milk, and dairy foods. In addition, they are produced commercially and added to foods both for their sweetness and other functions such as the texture of foods. When metabolized, sugars have approximately 4 calories per gram, the same as both protein and other carbohydrates. Some common sugars found in foods are as follows:

- **Glucose:** A simple sugar found naturally in corn. Glucose is the primary source of energy for the body and is the only fuel used by brain cells. Starch digestion in the body yields glucose; even nondigestible carbohydrates (eg, cellulose) are composed primarily of glucose. Glucose is sometimes referred to as dextrose.
- **Fructose:** A simple sugar found in fruits, honey, and root vegetables. When it occurs naturally, fructose is always found along with other sugars such as glucose. Fructose makes up half of the sugar of sucrose and about half of the most common form of HFCS. Pure fructose is also a caloric sweetener added to foods and beverages in crystalline or liquid form (made from corn syrup in a process similar to making HFCS).
- **Galactose:** A simple sugar that is unique to milk and dairy foods. Galactose is not found free in nature, but is bound to glucose to form lactose.
- **Sucrose:** Often called table sugar, sucrose is a disaccharide composed of 1 glucose unit and 1 fructose unit joined together by a chemical bond that is readily broken in the small intestine. Sucrose is found naturally in fruits and vegetables but in the highest quantities in sugar beets and sugar cane. When sucrose is digested or placed in an acidic environment (such as in many ready-to-drink beverages), it "inverts" and yields 50% glucose and 50% fructose.
- **Lactose:** A disaccharide found naturally in milk, it is composed of 1 galactose unit and 1 glucose unit. Lactose is sometimes called milk sugar.
- **Maltose:** A disaccharide composed of 2 glucose units. It is found in molasses and is also used for fermentation.
- **Corn syrup:** Contains either glucose or combinations of glucose and fructose monosaccharides. The term *corn syrup* can refer to any of several corn-derived products, according to the Food and Drug Administration. Corn syrup, which is found in the baking section of the market, is usually 100% glucose. Occasionally, there is some confusion, as the term *corn syrup* may be used to describe HFCS, pure fructose, or glucose derived from corn.
- **HFCS:** A mixture of glucose and fructose derived from corn. The most common form of HFCS (HFCS-55) is similar in composition to sucrose, having 55% fructose and 42% glucose. Another commonly used form of HFCS is HFCS-42, with 42% fructose, which is less fructose than found in sucrose (table sugar). Less common and used primarily to make the other forms of HFCS is HFCS-90, having 90% fructose and 10% glucose. High-fructose corn syrup is only used commercially and is not sold in the supermarket.
- **Other sugar products:** Sugars are part of the makeup of fruit juice concentrates, honey, molasses, hydrolyzed lactose syrup, and whey. Other sources of sugars found in food ingredient lists include evaporated cane sugar, agave syrup, brown rice syrup, maltodextrins, and date syrup—all composed of the same basic sugars described above, with agave syrup particularly high in fructose.

Functions of Sugars in Foods

In addition to sweetening, sugars perform many functions in foods. They contribute to food preservation by binding water in products such as jams, jellies, and cured hams,

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TABLE Functions of Sugars in Foods[6]
Retard spoilage by binding water
Add flavor, texture, color to baked goods
Provide fuel for the growth of yeast in breads
Contribute "bulk" or volume in ice cream, baked goods, preserves, and jams
Enhance the creamy texture of frozen desserts
Control crystallization in confectionary products
Provide body and texture in foods and beverages
Enhance flavor and balance acidity in nonsweet foods, eg, salad dressings, sauces, condiments
Preserve the flavor, aroma, and color of fruits in preserves, jams, and jellies
Help preserve natural color and shape of fruits used for canning and freezing
Improve flavor and texture of canned and frozen fruit

thereby making them susceptible to microbial growth (see Table for additional functions).

Digestion and Metabolism

Once ingested, carbohydrates (polysaccharides and disaccharides) are broken down into their component monosaccharides. In the digestion of sucrose, both glucose and fructose are released into the bloodstream. Glucose, but not fructose utilization, is insulin dependent. Under normal circumstances, glucose is the only fuel used by the brain and is the primary fuel used by working muscles. To protect the brain from a potential fuel shortage, the body maintains a relatively constant glucose level in the blood. Dietary glucose is stored in the liver and muscle cells in polysaccharide units called glycogen. When the level of glucose in the blood starts to fall, liver glycogen can be converted to glucose to maintain blood glucose levels. Blood glucose levels are maintained by the regulatory hormones, insulin and glucagon. Insulin also allows the muscles to take up circulating glucose. Human metabolism does not distinguish between sugars that are added to foods and sugars that occur naturally in foods, as they are chemically identical.[1]

Fructose is predominantly metabolized in the liver, and unlike glucose, it does not require insulin to be used by the body. The rate of fructose metabolism is more rapid than that of glucose, as metabolites bypass the rate-limiting step in glycolysis. Glucose and fructose are metabolized via separate pathways but converge at a common point for energy production.

THE SUGAR ALCOHOLS

Sugar alcohols, also called polyols, are hydrogenated carbohydrates in which one end, the aldehyde, has been reduced to a hydroxyl or "alcohol." They occur naturally in a wide variety of fruits and vegetables but are also commercially produced from other carbohydrates such as sucrose, glucose, and starch. Common sugar alcohols used in foods include sorbitol, xylitol, mannitol, maltitol, maltitol syrup, lactitol, erythritol, isomalt, and hydrogenated starch hydrolysates. Although most sugar alcohols are approximately half as sweet as sucrose, maltitol and xylitol equal the sweetness of sucrose.

The polyols (sugar alcohols) have unique properties in addition to being noncariogenic.

Sugar alcohols are slowly and incompletely absorbed from the small intestine into the bloodstream. The incomplete absorption causes some of the sugar alcohol to move through the small intestine, where it is fermented by bacteria in the large intestine. Thus, consumption of sugar alcohols may result in abdominal gas and gastrointestinal discomfort in some individuals. However, there are differences among polyols with regard to these effects.[7] For example, erythritol has been reported to produce less gastrointestinal distress than other sugar alcohols[8,9] and is well tolerated at 1 g/kg of body weight per day.[10] Reviewing the health aspects of polyols, Livesey[11] found that they have a role in reducing constipation and promoting health.

Because of their incomplete absorption, sugar alcohols have fewer calories than other sugars do and may be useful in weight management. The caloric content ranges from 0 to 3 kcal/g compared with about 4 kcal/g for sucrose and most other sugars.

Incomplete absorption of polyols makes them beneficial for people with diabetes. Sugar alcohols have little impact on blood sugar compared with glucose, and cellular uptake does not require insulin. The American Diabetes Association[12] notes that "the total amount of carbohydrate in meals or snacks will be more important than the source or type." In essence, all types of carbohydrates, including sugars and sugar alcohols, can be included in the diet. Nonetheless, all carbohydrates need to be accounted for in the carbohydrate intake of people with diabetes.

Sugar alcohols are not acted upon by bacteria in the mouth and therefore do not contribute to dental caries.[7,11] Xylitol has been found to inhibit oral bacteria and is often used in sugarless mints and chewing gums. The Food and Drug Administration has authorized a health claim stating that sugar alcohols do not promote tooth decay.[13]

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CONSUMPTION OF SUGARS

Nutrition researchers, economists, and statisticians use different methods to measure consumption of sugars, namely, disappearance data and food consumption surveys. Each method has advantages and drawbacks. For many years, the USDA's Economic Research Service (ERS) has measured the "disappearance" of sugar (sucrose) and other sweeteners from the food supply.[14] These data report the amounts of sugars that are manufactured or the deliveries of sugars to manufacturers and consumers. [Note: According to the USDA Farm Service Agency, sugar deliveries are defined as "the movement of refined sugar from a cane sugar refiner, a sugar beet processor, a sugarcane processor, or a trader, to end-users or brokers for consumption, either as sugar or for use in products containing sugar, including sugar delivered to manufacturers for use in products to be exported."[15]]

These disappearance data do not measure actual consumption, but they can be useful for indicating trends in sugar usage. The data do not account for loss or waste during shipping, storage, manufacturing, or in the home. Moreover, expressing sugar disappearance per capita assumes equal usage across population groups and does not allow for investigating the use of sugars by different ages, genders, and socioeconomic or ethnic groups.[3] The ERS data show that from 1966 to 1999, annual per capita sugar disappearance increased from approximately 113 lb to approximately 151 lb. Since 1999, sugar deliveries have decreased and stabilized at about 137 lb per capita per year.[14]

Recently, the ERS began adjusting its food availability data for losses such as waste and converting the resulting data into daily per capita servings as defined by the 2005 Dietary Guidelines for Americans and its supporting guidance document MyPyramid Plan. These data show that when losses (nonedible food parts and food lost through spoilage, plate waste, and other losses in the home and marketing system) are subtracted, daily per capita consumption of caloric sweeteners decreased from approximately 135 lb in 1999 to 121 lb in 2007.[16] The ERS notes that its disappearance calculations are "first estimates" intended to serve as starting points for discussion and further research.[17]

Statistics on sugar consumption were included in the deliberations of the 2010 Dietary Guidelines Advisory Committee. The Dietary Guidelines Advisory Committee delved into the sources of calories and how the dietary makeup has changed. They considered changes in both nutrient composition and the food sources of those nutrients. Between 1970 and 2008, despite an increase in total caloric consumption, the percentage of calories from caloric sweeteners (as well as meat, eggs, and nuts) declined.[17]

The other way estimates of intakes of sugars can be obtained is from food consumption surveys, although calculating accurate estimates for sugar intake for individual populations has proved challenging. One persistent problem is that food consumption study participants may not be aware of some of their sugar consumption. In addition, a number of people are known to underreport their intake and may particularly underestimate intakes of sugars or sugar-containing foods. Overweight and obese populations show a greater disparity between actual intake and reported intake.[18,19]

Another drawback is that consumption surveys rely on food composition databases to calculate the amount of sugars in each individual food reported as consumed. These calculations frequently overestimate sugar content as they are based on recipe data or food label values* rather than chemical analyses. Such overestimation may be due to several factors: (*a*) failure to account for sugars that are unavailable because they are either not consumed or lost to waste or (*b*) processes such as the Maillard reaction, caramelization, or fermentation (leavening), which occur during cooking or baking and break down the sugars.[3]†

Food intake survey information was obtained primarily from 2 nationwide monitoring surveys: the USDA's Continuing Survey of Food Intakes by Individuals (CSFII) and the National Health and Nutrition Examination Survey (NHANES) conducted by the Department of Health and Human Services. In 2002, these 2 studies were combined into a single, population-based national nutrition survey known as "What We Eat in America—NHANES." National Health and Nutrition Examination Survey 2003–2004 data estimates total sugar intake at 133 g/d, which is close to the ERS loss-adjusted availability data discussed above. This is approximately 24.2% of energy intake.[20]

Consumption and disappearance data need to be reconciled so that communications about sugars are more straightforward.

Sigman-Grant and Morita[3] recommend that accurate and precise measures are essential for scientists, educators,

*Browning reactions involving sugars produce many different compounds, but the amount of free sugar is substantially reduced. Caramelization and the Maillard reactions are examples of the effect of high temperatures on sugar. See McGee H. *On Food and Cooking*. New York, NY: Scribner; 2004:778–779 for further discussion. Food labels based on database calculations are unable to account for such reduction in sugars and lead to overestimates of the sugar content of certain foods.

†There are no published estimates for the amount of sugar "lost" due to yeast action, caramelization, or browning in baked goods. However, this could be a significant amount. The USDA food composition database shows that mixed grain bread contains 2.6 g of sugar per slice (26 g) and an English muffin has 1.80 g of sugar. Using an average of 2 g of sugar per serving, the USDA Factbook indicates that Americans consumed 10 servings of grain per day, on average; this amounts to 20 g of sugar per day from grain servings or roughly 16 lb per person per year. (Source: *USDA Agricultural Fact Book 2001–2002*, Chapter 2: Profiling Food Consumption in America).

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regulators, and the public to communicate about the health aspects of sugar consumption. To obtain a more accurate picture of intakes of sugars, methods for obtaining both individual intake data and economic availability estimates should be improved and reconciled. This could be accomplished by (1) improving methods for determining intakes to reduce underreporting, (2) accounting for manufacturing losses and other nonfood and nonalcoholic beverage uses of sugars to reduce overestimation, and (3) measuring the exact sugar content of foods rather than obtaining data from calculations from recipes.[3] Steps to control underreporting include the multiple-pass technique for dietary recalls refined by NHANES.

ADDED SUGARS

The term *added sugars* refers to sugars added to foods in the home kitchen or during commercial food preparation. Guthrie and Morton[21] examined the 1994–1996 CSFII and found that the mean intake of added sugars and sweeteners for Americans 2 years or older is approximately 82 g/d (equivalent to approximately 66 lb per person per year) or about 16% of energy. Children and adolescents consumed 19% and 20% of energy, respectively. Relative intakes decreased in adulthood, ranging from about 12% to about 18% depending on age and gender.[2] Marriott et al[22] determined usual intakes from NHANES (2003–2006) data and found a mean intake of added sugars for all people 4 years or older to be 83 g, similar to the mean of 82 g reported by Morton and Guthrie from the 1994–1996 data. According to data from NHANES III (1988–1994) intake of energy from added sugars declines with age. The median daily intake of added sugars varies across population groups, ranging from 10 to 30 tsp (40–120 g/d).[23]

Marriott et al[22] also analyzed NHANES (2003–2006) data to determine the approximate contribution of specific food categories to added sugar intake. They found that regular soft drinks contributed almost one-third (30.7%) of the intake of added sugars. Sugars/sweets contributed 13.7% of added sugars, followed by sweetened grains (12.6%). Regular fruitades/fruit drinks contributed 10.3% of total intake. These 4 categories account for just over two-thirds (67.3%) of the intake of added sugars. These values have changed very little since 2000, when Guthrie and Morton[21] analyzed CSFII data. It should be noted, however, that recent data from the National Cancer Institute found that consumption of soda, fruit drinks, energy, and sports drinks combined accounted for 6.9% of average total caloric intake,[17] which varies by age group.[23]

Consumption of added sugars is declining, according to a 2011 report that reviewed NHANES data from 1999 to 2008.[24] Overall, consumption of added sugars decreased by 25%, from 101.1 to 76.7 g/d despite an increase in incidence of obesity. Two-thirds of this decline came from reduced intake of sugar-sweetened beverages. In fact, Americans consumed 37% less added sugar from soft drinks in that period. Added sugars as a percentage of total calories declined from 18.1% to 14.6%, with the reduction noted across all ages, ethnicities, and income groups.

Americans consumed 37% less added sugar from sugar-sweetened beverages from 1999 to 2008.

HIGH-FRUCTOSE CORN SYRUP

Using data from the CSFII and NHANES, Duffey and Popkin[25] reported that by 2004, HFCS provided roughly 8% of total energy intake, whereas total added sugars accounted for 17% of total energy intake. Most of the HFCS consumed comes from sweetened beverages (soda, fruit drinks), but other beverages (sports drinks) and foods (desserts, bread, ready-to-eat-cereals) also contribute to HFCS intake. The researchers conclude that most HFCS-containing foods are consumed as snacks rather than meals. Since 1998, sucrose use and HFCS use have been roughly equivalent. The question of whether substitution of HFCS for sucrose led to an increase in fructose intake has been examined, and most researchers now believe that the effect of this change on total fructose intake is minimal.[26]

FRUCTOSE

Increasing interest in the effects of fructose on nutrition and health has led researchers to examine existing data for consumption trends of fructose. This includes fructose from table sugar as well as from HFCS. Marriott et al[27] compared fructose intakes from the 1977–1978 Nationwide Food Consumption Survey with data from the NHANES 1999–2004. During this period, mean daily intakes of both added and total fructose increased in all gender and age groups, with total fructose intake rising from 37 to 49 g.[28] Lustig[28] came to a similar conclusion by analyzing USDA/ERS disappearance data. However, according to Marriott et al,[27] this increase "was dwarfed by greater increases in total daily energy and carbohydrate intakes." Between 1978 and 2004, estimated mean total fructose intake decreased from 18.6% to 17.1% of total carbohydrate intake.[27] They conclude that "sweetener consumption is only one part of the complex dietary component of trends in overweight." In addition, Forshee et al[29] found the typical diet to have a fructose-glucose ratio of 0.72 and that the dietary balance of fructose and glucose has not changed since the 1960s. Numerous researchers and clinicians

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attribute some of the chronic diseases of Western society to the consumption of fructose, noting the difference in absorption and metabolism from glucose. Investigators have examined the associations between fructose intake and diabetes, hypertension, and hyperlipidemia. These studies will be addressed in part 2 of this series. Nonetheless, the metabolic effects of fructose consumption, particularly as sugar consumption increased since the mid-1960s, continue to be of concern.

SUMMARY

This article summarizes the complex terminology used to define various sugars. There are overlapping uses of the term *fructose* to indicate pure fructose or fructose-containing sweeteners, such as HFCS. In addition, the term *added sugars* has varying definitions. The authors argue that the DP may provide a useful method to classify sugars.

Subsequent articles in this series will address the association between sugars and dietary quality, obesity and chronic diseases, dental health, and physical and cognitive performance.

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