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Food as a source of mono- and disaccharides; biochemical and metabolic aspects

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Abstract

Carbohydrates are important and necessary components of human diet. Although they primarily play an energetic function, they also have structural and functional roles. According to the European Food Safety Authority, carbohydrate intake should range between 45 and 60 percent of the energy in adults and children older than one year of age. An important part of carbohydrates available in foods are mono and disaccharides, commonly referred to as sugars. Dietary sources of sugars include fruits, fruit juices, vegetables, milk and milk products, and foods containing added sucrose and starch hydrolysates. Despite their importance in daily life, there is currently no clear and adequate terminology on the various types of carbohydrates, particularly sugars. Nor are there available sugar intake recommendations or food composition tables. Without these recommendations or reference values, dietary unbalances might occur, which subsequently may end in the premature onset of most chronic or degenerative diseases of our society. The aims of the present work are: to classify dietary carbohydrates, to define the biochemical and common terms for sugars, to explain their nutritional value and their metabolism as well as their food sources and to carry out a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis about the nomenclature and dietary intakes of sugars.

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Key words: *Carbohydrates. Sugars. Food intake. Food composition tables.*

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LOS ALIMENTOS COMO FUENTE DE MONO Y DISACÁRIDOS; ASPECTOS BIOQUÍMICOS Y METABÓLICOS

Resumen

Los hidratos de carbono constituyen una parte importante y necesaria en la alimentación humana. Aunque desempeñan una función primordialmente energética, también tienen funciones estructurales y funcionales. Según la Agencia Europea para la Seguridad Alimentaria, la ingesta de hidratos de carbono debe oscilar entre un 45 y 60% de la energía en adultos y niños mayores de un año. Una parte importante de los hidratos de carbono disponibles en los alimentos la componen los mono y disacáridos, comúnmente denominados azúcares. Las principales fuentes dietéticas de azúcares son las frutas, los zumos de fruta, algunos productos vegetales, la leche y los productos lácteos, y los alimentos que contengan sacarosa añadida e hidrolizados de almidón. A pesar de ser fundamentales en nuestra vida diaria, no existe una terminología adecuada y clara sobre los diversos tipos de hidratos de carbono, y de forma muy especial de los azúcares. Tampoco en lo referente a las recomendaciones de ingesta y contenido en los alimentos. Sin recomendaciones ni valores de referencia, pueden producirse desajustes alimentarios, que pueden asociarse con la aparición precoz de la mayor parte de las enfermedades crónicas o degenerativas en nuestra sociedad. Los objetivos de este trabajo son: clasificar los hidratos de carbono presentes en los alimentos, establecer definiciones claras sobre todos los términos bioquímicos y comunes relacionados con los azúcares, explicar su valor nutricional y describir su metabolismo, así como las fuentes alimentarias que contienen tanto mono como disacáridos y, finalmente, realizar un análisis DAFO (Debilidades, Amenazas, Fortalezas y Oportunidades) sobre la nomenclatura y las ingestas de azúcares.

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Palabras clave: *Hidratos de carbono. Azúcares. Ingesta de alimentos. Tablas de composición de alimentos.*

List of abbreviations

1,3-BPG: 1,3-bisphosphoglycerate.
ADP: Adenosine diphosphate.
AMP: Adenosine monophosphate.
ATP: Adenosine triphosphate.
CO_2: Carbon dioxide.
SWOT: Strengths, Weaknesses, Opportunities and Threats.
DHAP: Dihydroxyacetone phosphate.
EFSA: European Food Safety Authority.
F1P: Fructose-1-phosphate.
FAO/WHO: Food and Agriculture Organisation of the United Nations and the World Health Organisation.
GA: Glyceraldehyde.
GAP: Glyceraldehyde-3-phosphate.
GAPDH: Glyiceraldehyde-3-phosphate dehydrogenase.
GLUT: Glucose Transporters.
GOT: Glutamate-oxaloacetate transaminase.
GTP: Guanosine triphosphate.
HK: Hexokinase. GI: Glycaemic Index.
K^+: Potassium.
Mg^{++}: Magnesium.
NAD^+: Oxidised nicotinamide adenine dinucleotide.
NADH: Reduced nicotinamide adenine dinucleotide.
PEP: Phosphoenolpyruvate.
PEPCK: Phosphoenolpyruvate carboxykinase.
PFK-1: Phosphofructokinase-1.
P_i: Inorganic phosphate.
TIM or TPA: Triose phosphate isomerase.
UTP: Uridine triphosphate.

Introduction

The health of individuals is determined by genetic and environmental factors, of which the most important is diet. An adequate diet should satisfy individual daily nutritional requirements, incorporating cultural and gastronomic values, and personal satisfaction. Recent studies in the field of nutrition show that dietary imbalances are the main cause of the premature development of the majority of chronic and degenerative diseases in today's society. Therefore, the possibility of making better eating patterns part of our lifestyle habits and reducing the overall risk factors in the general population, is in our hands.

Carbohydrates are the world's main source of food energy, particularly in developing countries. Carbohydrates should provide between 50 and 55% of total dietary energy and should also be evaluated for their potential energy, their sweetness and their high fibre content[1,2]. The European Food Safety Authority (EFSA) has recently advised that carbohydrate intake should range from 45 to 60% for both adults and healthy children over one year of age[3].

Carbohydrates are found in most cereals and tubers, as well as legumes, fruit and vegetables, and contribute to the texture and flavour of these foods. They are directed to and absorbed in the small intestine and, to a lesser degree, some of them are partially fermented in the large intestine.

A significant proportion of dietary carbohydrates are mono- and disaccharides, commonly referred to as sugars. The main dietary sources of sugar are fruit, fruit juices, certain vegetables, milk and certain dairy products and foods which have added sucrose or starch hydrolysates (for example, glucose syrup or with high levels of fructose) such as carbonated drinks, pastries, sweets and confectionary[1-3].

The aims of this study are: to classify dietary carbohydrates, to define clearly all the biochemical and common terms for sugars, to describe their nutritional value and their metabolism, as well as food sources which contain both mono- and disaccharides, and finally to carry out a SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) on the nomenclature and intake of sugars.

TERMINOLOGY AND CLASSIFICATION OF CARBOHYDRATES

Dietary carbohydrates can be in the form of complex molecules (polymers or polysaccharides) or more simple molecules, commonly referred to as sugars, monomers (monosaccharides) or dimers (disaccharides). Of all the dietary sugars, the most important from a nutritional point of view are: glucose, fructose, galactose, maltose, lactose, sucrose and trehalose. There are many different classifications in the literature, but some of them can confuse consumers. Table I, below, details the classification of carbohydrates from the Food and Agriculture Organisation of the United Nations and the World Health Organisation (FAO/WHO) amended by the EFSA[1,3]. The latter has chosen to classify carbohydrates in two categories, according to how they raise blood sugar, called glycaemic carbohydrates and dietary fibre. The first category includes sugars, maltodextrins, starches and glycogen. Dietary fibre includes all dietary components which are not hydrolyzed in the small intestine, at least for the most part, i.e. non-amyloid polysaccharides (celluloses, hemicelluloses, pectins and hydrocolloids —gums, mucilages and glucans—), resistant oligosaccharides (fructooligosaccharides and galactooligosaccharides and other resistant oligosaccharides), type IV resistant starches and lignin (Table I)[3].

Classification of carbohydrates

Monosaccharides

Glucose

D-glucose is a reducing sugar that circulates freely in the blood of all mammals. It is absorbed by all cells

Table I
Classification of carbohydrates by the FAO/WHO amended by the EFSA[3]

Class (DP)	*Subgroup*	*Components*	*Monomers*	*Digestibility**
Sugars (1.2)	Monosaccharides	Glucose Galactose Fructose		+ + +
	Disaccharides	Sucrose Lactose Trehalose Maltose	Glucose, Fructose Glucose Galactose Glucose Glucose	+ ± + +
Oligosaccharides (3-9)	Maltooligosaccharides	Maltodextrins	Glucose	+
	Other oligosaccharides	α-Galactosidases (GOS) Fructooligosaccharides (FOS) Polydextroses Resistant dextrins	Galactose, Fructose Fructose, Glucose Glucose Glucose	– – – –
Polyalcohols	Maltitol, Sorbitol Xylitol, Lactilol			+ or –
Polysaccharides (< 9)	Starches	Amylose Amylopectin Modified starches Resistant starches Insulin	Glucose Glucose Glucose Glucose Fructose	± ± – – –
	Other polysaccharides	Cellulose Hemicellulose Pectins Other hydrocolloids (gums,. mucilages, β glucans)	Glucose Variable Uronic acids Variable	– – – –
Related substances	Lignin			

DP: Degree of polymerization.
* Digestibility in the small intestine, + digestible, ± mainly digestible, + or – partially digestible, - non-digestible.

by means of specific transporters. Glucose is found in most fruits and many vegetables. It is an abundant reserve polymer in animals (glycogen) and in plants (starch). Most glucose is present as a non- digestible polymer (cellulose). Glucose can be produced through starch hydrolysis by enzymes. Also, some glucose can be isomerised to fructose with the use of glucose isomerase. Both glucose and mixtures of glucose and fructose in the form of syrups can be added to various foods, in particular sweets, confectionary and pastries, as well as soft drinks and other products, like sweeteners[2,4].

Fructose

It is the sugar which has the most sweetening power. It is absorbed passively, more slowly than glucose. It is abundant in fruit. There are fructose polymers, both natural (inulin) and synthetic (fructooligosaccharides), but these compounds don't contribute significantly to the sweetness of foods and are poorly digested, so they behave like soluble fibre[2,4].

Galactose

Galactose forms part of glycolipids and glycoproteins of cell membranes, especially neurons. It is synthesised by the mammary glands in mammals to produce lactose, therefore, the majority of dietary galactose comes from consuming lactose in milk. It is absorbed in the intestines together with glucose using the same transporter[2,4].

Disaccharides

Sucrose

It is the sugar par excellence. It consist of one fructose and one glucose molecule linked by a glycosidic bond. It is hydrolysed in the intestine by the action of the sucrase-isomaltase enzyme complex. It is a non-reducing sugar which is very soluble in water and crystallizes easily. It is extracted industrially from sugar cane and sugar beet. It is also used to sweeten foods, to improve the sour and bitter taste of many of them and to

preserve them by increasing osmotic pressure, which prevents the growth of many microorganisms[2,4].

Maltose

It is a reducing sugar composed of two glucose molecules linked by a glycosidic bond, present in some fruits where it accounts for 15% of the total sugars. Its sweetness if 50% when compared to sucrose. It is hydrolysed in the intestine by the action of maltase. Maltose forms part of maltodextrins and glucose syrups, and is an ingredient used in many foods as a source of energy. It is produced industrially through the hydrolysis of rice or corn starch[2,4].

Lactose

It is the sugar in milk and is formed by the union of two galactose and glucose molecules linked by a glycosidic bond. It is hydrolysed by the action of lactase, an enzyme whose activity decreases from 2 or 3 years of age in most humans. It is extracted, in purified form, from cow's milk and whey, it has a low solubility in water and its sweetness is only 40% relative to sucrose. In infants and young children, lactose not only provides energy, but also aids the development of gut microbiota (bifidobacteria and other lactic acid bacteria), increases the bioavailability of calcium and other mineral elements and provides galactose which is directly usable for developing the nervous system[2,4].

Polysaccharides

Starch is abundant in the plant world and it is the substance that we refer to when, in terms of nutrition, we are taking about 'complex polysaccharides'. It is a polysaccharide consisting of glucose bonds in position α1-4 and branches in position α1-6. The partial hydrolysis of starch leads to the industrial production of dextrins or maltodextrins, which are formed by glucose units of varying size with some branches. Its sweetening power depends on the degree of hydrolysis. Only dextrins that have an increased reducing power (a degree of dextrose equivalent to 25-45) contribute, to some extent, to the sweetness of foods.

Glycogen only exists in the animal world (liver and muscle) and, as with starch, it does not contribute to the sweet flavour of foods, as well as being a polysaccharide consisting of glucose bonds in position α1-4 and abundant branches in position α1-6.

Cellulose and *hemicellulose* form part of the cell wall of all vegetables. They are polysaccharides formed by glucose bonds in position β1-4.

Pectins are part of the middle lamella of plant cell walls. They are polysaccharides of galacturonic acid in position 1-4, with the carboxyl groups which are often methoxylated. They are plentiful, especially in fruit.

Gums and *mucilages* are especially found in seeds and pulses. They are complex polysaccharides in terms of the type of saccharide component, branching and degree of polymerisation. All of these polysaccharides have the common feature that they are not broken down by digestive enzymes and make up a large part of what is known as dietary fibre[2,4].

Carbohydrate terminology

The two main categories of digestible carbohydrates, and therefore glycaemic, are sugars and starch. Both, in general, present problems when it comes to being defined and characterised, causing complications when their daily intake and the impact they have on health need to be examined[3,5].

Sugars

There are many terms used to describe sugars and their components, like for example: sugar(s), total sugars, total available glucose, free sugars, added sugars, refined sugar(s), simple sugars, intrinsic and extrinsic sugars, non-milk extrinsic sugars and caloric sweeteners.

The existence of many of these different terms and their use in various countries has meant that it's not possible to compare the different intake studies currently being carried out. In the same way, the possibilities of comparing food intakes and making recommendations about them, and establishing the relationship between food consumption and risk factors, is limited.

The different terms and their current definition or general meaning are shown in table II[4].

Starch

The term starch refers to the total starch present in food. However, starch can be subdivided by the degree and extent to which they are digestible. Resistant starches are not digestible in the small intestine and, therefore, should not be considered as digestible carbohydrates, but so far, there is no explicit separation of the intake measurements that were conducted on the populations. There are three types of starch in the diet, those which are digested quickly that we can find in recently cooked foods and foods that are rich in starch, those that are poorly digested which are found in pasta and cereals, and finally resistant starches[5].

Table II
A general listing of the different terms used to describe sugars[4]

Term	*Description*
Total sugars	All mono- and disaccharides in food, whether they are natural and/or added during their production.
Added sugars	Sugars and syrups which are added to food during production or preparation. In accordance with the US Department of Agriculture, only mono- and disaccharides. On the other hand, the US Economic Research Service includes oligosaccharides derived from corn syrup in their definition. Other: all refined sugars (for example, sucrose, maltose, lactose, glucose and dextrin) used as ingredients in processed foods.
Free sugars	Traditional: any sugar in food which is not combined, including lactose. Recent: all monosaccharides and disaccharides added to food by the manufacturer and consumer, plus sugars naturally found in honey, syrups and fruit juices.
Refined sugars	For most European countries sucrose, fructose, glucose, hydrolysed starch (glucose syrup, high fructose corn syrup) and other isolated sugar preparations, such as the components of foods used during the manufacture and preparation of foods.
Non-milk extrinsic sugars	Total sugars, except for lactose in milk and milk products, and sugars present in the cellular structures of fruit and vegetables.
Sugar (without 's')	It has many meanings, in certain cases it only refers to sucrose, while in others it includes 'all monosaccharides and disaccharides; or ' any free monosaccharide or disaccharide in food'.
Caloric sweeteners	Sweeteners which are consumed directly as well as an ingredient in food, such as sucrose, from refined sugar candy and sugar beet, honey, dextrose, edible sugars and commercial sweeteners, as well as oligosaccharides.

The nutritional value of carbohydrates

Carbohydrates are the cheapest and most important source of energy. Even though they are not essential in nature as they can be synthesized by the body, they should form part of our diet and should make up 45-60% of energy intake[3]. Their considerable importance rests on the fact that they are the primary energy source for all countries; 50% in developed countries and 90% in developed countries. The energy contribution of carbohydrates is 4.1 kcal/g. Although, at first glance one might think that the sole function of carbohydrates is as an energy source for human and animal metabolism, sugars have other significant structural functions in living creatures, such as important components of membrane antigens and proteins secreted by many cells.

Complex carbohydrates are part of foods like cereals or their derivatives, such as bread, pasta, corn tortillas, etc., as well as pulses, which also contain many other extremely important nutrients for daily consumption like fibre, vitamins, proteins and minerals. On the other hand, refined sugars themselves don't contribute to the value of other nutrients, but they supply large amounts of energy to the diet without helping meet the daily nutritional demands of other nutrients. However, the fact remains that simple sugars, in the context of a moderate and balanced diet, contribute to the intake of other nutrients by making them more appetising. Carbohydrates are also found in high volume foods and those with a more complex structure, they slow down the digestive process and make the absorption of glucose a slow and gradual process, preventing postprandial hyperglycaemia. However, simple sugars are absorbed rapidly and cause hyperglycaemia[1,3].

The concept of glycaemic index (GI)

Glycaemic index is defined as the incremental area under the blood glucose response curve of a 50g portion of carbohydrates absorbable from a test food, expressed in a response rate for the same quantity of glucose ingested by the same subject[3]. There are research studies which describe how meals that contain low GI foods reduce both postprandial blood sugar and insulin response. Some epidemiological studies indicate that a low GI diet is associated with a reduced risk of developing type II diabetes in humans. Clinical trials on normal, diabetic and hyperlipidaemic subjects show that low GI diets reduce average blood sugar concentrations, insulin secretion and serum triglycerides in individuals with hypertriglyceridaemia.

Therefore low GI foods raise the amount of carbohydrates that enter the colon and increase fermentation and the production of short chain fatty acids. Table III shows the GI values of certain foods[6].

CARBOHYDRATE METABOLISM

The glucose used by the tissues comes from starch, sucrose and lactose in the diet and from the body's

stores of liver and muscle glycogen, or from hepatic or renal synthesis, via gluconeogenic precursors such as the carbon skeleton of certain aminoacids, glycerol and lactate; these sources enable the concentration of blood sugar to be maintained within the appropriate ranges.

The balance between oxidation, biosynthesis and glucose storage depends on the hormonal and nutritional state of the cell, tissue and organism. The predominant metabolic pathways of glucose vary in different types of cell depending on physiological demand. Thus, the liver plays a fundamental role in glucose homeostasis in the body. Glucose can by completely oxidised by the hepatocytes to obtain energy and can be stored in the form of glycogen or supply carbons for fatty acid and aminoacid synthesis.

The heart and skeletal muscles can completely oxidise glucose or store it in the form of glycogen. Glucose can be partially broken down in the fatty tissues to provide glycerol, necessary for triglyceride synthesis, or oxidised completely and supply two units of carbon (acetyl- CoA) for fatty acid synthesis.

The brain depends on a continuous supply of glucose, which it can oxidise completely until it is CO_2 and water. On the other hand, erythrocytes have a limited capacity for oxidising glucose as they don't have mitochondria, but energy production depends entirely on such metabolic fuel partially oxidising it to lactate via glycolysis. Other specialised cells, such as corneal cells, the lens, the retina, leucocytes, testicular cells and renal medulla cells, are predominantly glycolytic[5].

Most mammalian cells capture glucose, as well as other sugars and polyalcohols, through membrane transport proteins which are known as glucose transporters (GLUT *Glucose Transporters*). So far thirteen members of this family are known, which are characterised by

Table III

The glycaemic index of 62 common foods[6]

Foods high in carbohydrates		*Breakfast cereals*		*Fruit and their derivatives*		*Vegetables*	
White bread, wheat	75 ± 2	Cereals	61 ± 6	Apple	36 ± 2	Boiled potato	78 ± 4
Brown bread	74 ± 2	Wheat crackers/biscuits	69 ± 2	Orange	43 ± 3	Freshly chopped potato	87 ± 3
Special grain bread	53 ± 2	Oatmeal	55 ± 2	Banana	51 ± 3	Fried potato	63 ± 5
Unleavened bread, wheat	70 ± 5	Rolled oats	79 ± 3	Pineapple	59 ± 8	Boiled carrot	39 ± 4
Roti, wheat	62 ± 3	Rice porridge	78 ± 9	Mango	51 ± 5	Boiled sweet potato	63 ± 6
Chapatti	52 ± 4	Millet	67 ± 5	Watermelon	76 ± 4	Boiled pumpkin	64 ± 7
Corn tortilla	46 ± 4	Muesli	57 ± 2	Dates	42 ± 4	Plantain	55 ± 6
Cooked white rice	73 ± 4			Peach	43 ± 5	Boiled taro	53 ± 2
Cooked brown rice	68 ± 4			Strawberry jam	49 ± 3	Vegetable soup	48 ± 5
Barley	28 ± 2			Apple juice	41 ± 2		
Sweet corn	52 ± 5			Orange juice	50 ± 2		
Spaghetti (white flour)	49 ± 2						
Spaghetti, serving	48 ± 5						
Rice noodles	53 ± 7						
Japanese noodles (Udon)	55 ± 7						
Couscous	65 ± 4						
Dairy products and alternatives		*Pulses*		*Snack products*		*Sugars*	
Whole milk	39 ± 3	Chickpeas	28 ± 9	Chocolate	40 ± 3	Fructose	15 ± 4
Skimmed milk	37 ± 4	Kidney beans	24 ± 4	Popcorn	65 ± 5	Sucrose	65 ± 4
Ice cream	51 ± 3	Lentils	32 ± 5	Crisps	56 ± 3	Glucose	103 ± 3
fruit yoghurt	41 ± 2	Soya	16 ± 1	Soft drinks	59 ± 3	Honey	61 ± 3
Soya milk	34 ± 4			Rice cakes	87 ± 2		
Rice milk	86 ± 7						

Data expressed in g/100g or g/100ml in mean ± standard error of mean, adapted from Atkinson et al. 2008 *Diabetes Care* 31: 2281-3.

their twelve transmembrane fragments and a series of aminoacids that are well-preserved in the different species, which are implicated directly in their function.

The various GLUT isoforms differ in their tissue location, their kinetic properties and whether they are dependent or not on insulin. In fact, glucose absorption is regulated by the expression and location of the various GLUT in different cells and in different metabolic states. GLUT2, 3 and 4 are good examples to illustrate the regulation of glucose absorption by these type of transporters. So, GLUT3 is the main glucose transporter in the brain and it has a Km (1 mM) far below normal blood sugar levels (4-8 mM), which indicates that it constantly transports glucose into the cells which express it.

On the other hand, GLUT2 has a high K_m (15-20 mM) therefore the cells which express it only absorb glucose when blood sugar is elevated. This transporter is expressed, among others, in the intestinal and pancreatic β cells in which glucose entry is a sign that blood sugar levels are elevated and that the necessary mechanisms for insulin release should be triggered (adenosine triphosphate (ATP) via the breakdown of glucose with the consequent inhibition of the K^+-ATP channel, activating calcium entry and as a result the release of insulin from endosomes into the blood). Finally, GLUT4 is a transporter which is expressed in the muscles and fatty tissue. The location of this transporter in the cell and, therefore its activity, depends on blood insulin levels, as the latter is needed for the receptor, which is normally found in the intracellular vesicles, is transported to the plasma membrane[7].

Glycolysis

Glycolysis is the central pathway of glucose catabolism. It breaks down glucose with a dual purpose: to obtain energy in the form of ATP and to supply precursors for the biosynthesis of cell components. Glycolysis occurs in all mammal cells and is the exclusive or almost exclusive source of energy for certain cells and tissues, such as erythrocytes, the renal medulla, the brain and the testicles.

Glycolysis takes places entirely in the cytoplasm and during the process one glucose molecule is divided into two pyruvate molecules. This pathway can be separated into two phases: the preparatory phase, in which glucose is converted to two triose phosphate molecules and the pay off phase, where two triose molecules are converted to two pyruvate molecules and ATP and NADH are obtained (reduced nicotinamide dinucleotide) (Fig. 1).

Preparatory phase

During this phase glucose is modified to produce fructose-1,6-bisphosphate which is divided to form two triose phosphates with ATP consumption. The preparatory phase of glycolysis can be divided into the following stages (Fig. 1):

a) *Glucose phosphorylation*. During this irreversible reaction glucose is phosphorylated by a kinase at the expense of ATP to become glucose-6-phosphate. The kinase which catalyses glucose phosphorylation in all cells is hexokinase (HK). Like all kinases, it needs ATP and magnesium (Mg^{++}). HK is not specific for glucose and can therefore phosphorylate other sugars, although it does have a high affinity for glucose (K_m 100 mM).
b) *Conversion of glucose-6-phosphate to fructose-6-phosphate*. In the following reaction, catalysed by phosphohexose isomerase (phosphoglucose isomerase), glucose-6-phosphate is converted to fructose-6- phosphate. It is the first reversible stage of the pathway. Phosphohexase isomerase also needs Mg^{++} as a cofactor and is specific for glucose-6 phosphate and fructose-6-phosphate.
c) *Formation of fructose-1.6-bisphosphate*. Fructose-6-phosphate is phosphorylated, at the expense of ATP and Mg^{++}, to be converted to fructose-1.6-bosphosphate by another kinase, the phosphofructokinase-1 (PFK-1). It is called PFK-1 to distinguish it from phosphofructokinase-2 which catalyses the production of fructose-2.6-bisphosphate from fructose-6-phosphate.
d) *The breakdown of fructose-1.6-bisphosphate*. Fructose-1,6-bisphosphate is divided into two trioses, glyceraldehyde-3-phosphate (GAP) and dihydroxyacetone phosphate (DHAP). This reaction is catalysed by fructose-1,6-bisphosphate aldolase, usually known simply as aldolase.
e) *Interconversion of the triose phosphates*. Only one of the trioses, GAP, can be broken down through glycolysis, therefore two trioses are isomerised to GAP in a reaction catalysed by triose phosphate isomerase (TIM).

Pay-off phase

In the pay-off phase two GAP molecules are converted to a pyruvate and the energy from the broken down glucose is preserved in the form of ATP and reducing power in the form of NADH. This phase is divided into the following stages:

a) *Oxidation of glyceraldehyde-3-phosphate*. GAP is converted to 1,3-bisphosphoglycerate (1,3-BPG) in a reaction catalysed by glyceraldehyde-3-phosphate dehydrogenase (GAPDH). This enzyme requires inorganic phosphate (Pi) and NAD^+ as cofactors.

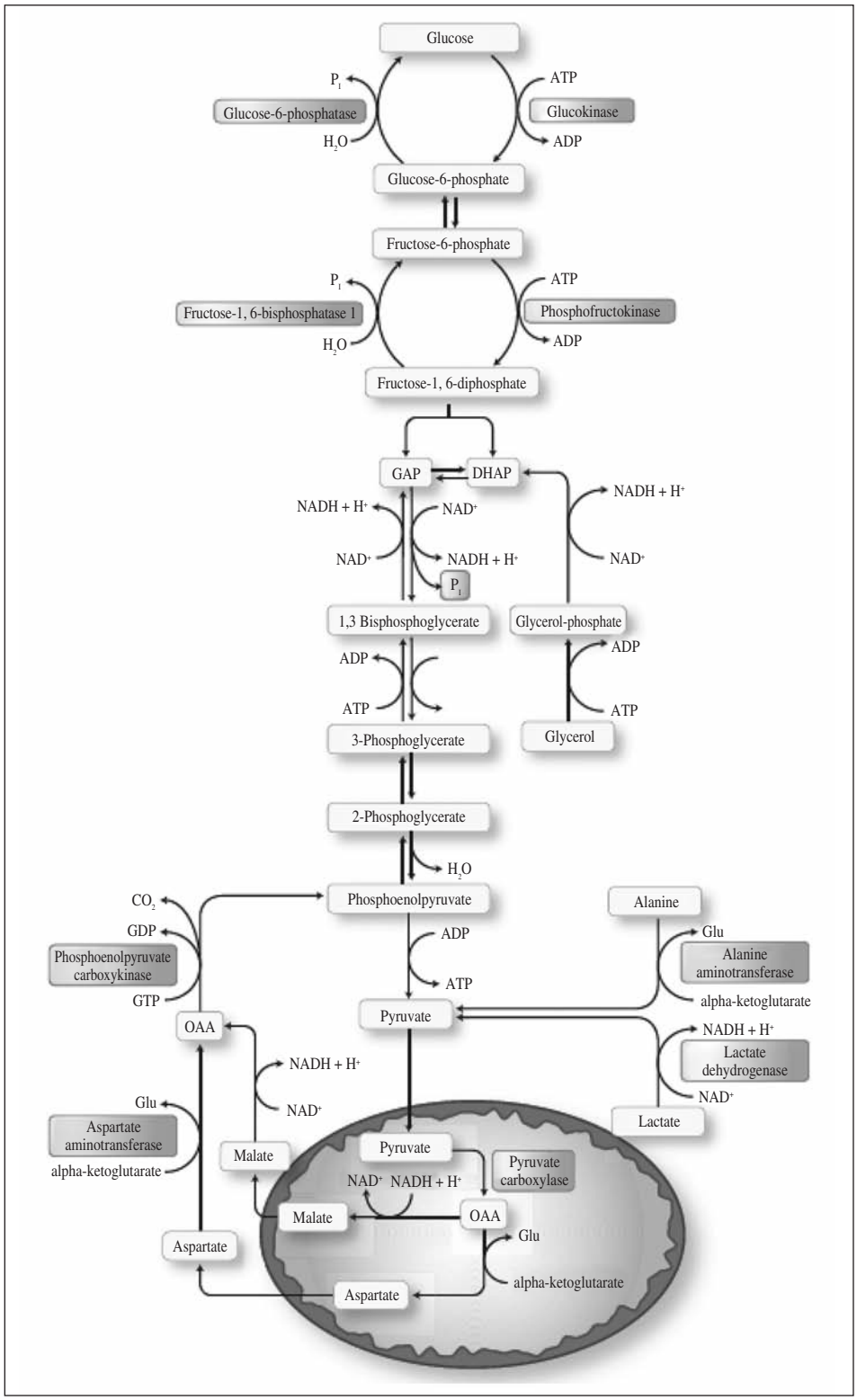

Fig. 1.—Overall diagram of glycolysis and gluconeogenesis. DHAP: dihydroxyacetone phosphate; GAP: glyceraldehyde-3 phosphate; OAA: oxaloacetate. Taken from Gil, A. Tratado de Nutrición, 2.ª Ed. Vol. I, Editorial Panamericana, Madrid, 2010.

b) *The formation of ATP from 1,3-bisphosphoglycerate*. In the following reaction, catalysed by phosphoglycerate kinase, 1,3-BPG is converted to 3-phosphoglycerate and ATP is synthesised. It is a substrate level phosphorylation reaction, during which 1,3-bisphosphoglycerate gives up its phosphate, which is energy-rich, to adenosine diphosphate (ADP). This is a reaction which is reversible in the cell and requires Mg^{++} as a cofactor.

c) *Conversion of 3-phosphoglycerate to 2-phosphoglycerate*. 3-phosphoglycerate is isomerised, in a

reversible way, to 2-phosphoglycerate mutase which requires Mg^{++} as a cofactor. The reaction occurs in two stages. During the first of them the enzyme, phosphorylated into a histidine residue, transfers phosphate to the C_2 hydroxyl of 3-phosphoglycerate, forming 2,3-bisphosphoglycerate. In the following stage 2,3-bisphosphoglycerate transfers phosphate to the enzyme C3 and releases the phosphorylated enzyme and the 2-phosphoglycerate.

d) *Phosphoenolpyruvate formation*. The 2-phosphoglycerate is dehydrated and forms phosphoenolpyruvate (PEP), which is an 'energy-rich' enol phosphate, in a reversible reaction catalysed by enolase.

e) *The synthesis of pyruvate* PEP transfers its phosphate to ADP in a reaction catalysed by pyruvate kinase, which requires Mg^{++} y K^+ (potassium), in order to form pyruvate.

f) *Glycolysis balance*. In the breakdown of glucose, via the glycolytic pathway, two pyruvate molecules, two molecules of ATP and two of NADH are obtained. Although four ATP molecules are obtained, two are consumed in the formation of fructose-1,6-bisphosphate. Therefore, the net balance of the reaction is:

$$\text{Glucose} + 2\,P_i + 2\,ADP + 2\,NAD^+ \rightarrow$$
$$\rightarrow 2\,\text{Pyruvate} + 2\,ATP + 2\,NADH + 2\,H^+ +$$
$$+ 2\,H_2O$$

Gluconeogenesis

Gluconeogenesis is the pathway through which glucose is generated from non-glucidic precursors. The importance of this pathway comes from the fact that certain tissues and organs (the central nervous system, renal medulla, lens, retina, testicles and erythrocytes) need a permanent supply of glucose (Fig. 1).

Phosphoenolpyruvate formation from pyruvate

The first stage of gluconeogenesis is the conversion of pyruvate to PEP. The glycolytic reaction in irreversible, given that it has a very negative standard free energy change and to reverse it, a detour would be needed using two enzymes from a different location: pyruvate carboxylase, which is located in the mitochondria, and phosphoenolpyruvate carboxykinase (PEPCK), which is cytosolic.

As a consequence, the pyruvate should initially be transported to the mitochondria where the pyruvate carboxylase will catalyse its conversion to oxaloacetate. This enzyme requires biotin, ATP and carbon dioxide (CO_2).

Oxaloacetate should leave the mitochondria. However, it doesn't have a transporter in the mitochondrial membrane, therefore it has to be converted to malate or aspartate so that it can be transported. In order to convert it to malate, oxaloacetate is reduced to mitochondrial malate dehydrogendase, using NADH as a reducer. Malate enters the cytosol and is oxidised by cytosolic malate dehydrogenase using NAD^+ as an acceptor and in this way, as well as oxaloacetate, NADH is obtained for the reduction which takes place during an earlier reaction catalysed by GAPDH.

Oxaloacetate can also be converted to aspartate by mitochondrial glutamate-oxaloacetate transaminase (GOT); the aspartate enters the mitochondria and because of cytosolic glutamate-oxaloacetate transaminase it converts to oxaloacetate.

Once it is in the cytosol, oxaloacetate is decarboxylated by PEPCK which gives rise to PEP. This enzyme requires Mg^{++} and guanosine triphosphate (GTP) as a phosphate donor.

Conversion of fructose-1,6-bisphosphate to fructose-6-phosphate

Fructose-6-phosphate is produced by a hydrolytic reaction, during which inorganic phosphate is released, catalysed by fructose-1,6-bisphosphatase which requires Mg^{++} as a cofactor. Fructose-1,6-bisphosphotase is the most important control point of the gluconeogenic pathway, it is activated by ATP and citrate and is inhibited by adenosine monophosphate (AMP) and fructose-2,6-bisphosphate.

Extraction of free glucose

The last stage of gluconeogenesis consists of the formation of free glucose from glucose-6-phosphate in a reaction catalysed by glucose-6-phosphotase, which, to be stable, has to be attached to a protein which in turn joins with Ca^{++}. Glucose-6-phosphate is generated in cytosol and should be transported to the lumen of the endoplasmic reticulum.

Metabolism of other monosaccharides

Fructose

Fructose is metabolised by means of its conversion to glycolytic pathway intermediaries. It is phosphorylated in most tissues by HK to fructose-6-phosphate which is a glycolytic intermediary. It follows a different pathway in the liver, it is phosphorylated to produce fructose-1-phosphate (F1P) in a reaction catalysed by ketohexokinase or fructokinase. Fructose-1-phosphate is divided by the action of aldolase B, to

form DHAP and glyceraldehyde (GA). To be able to metabolise GA, it has to be phosphorylated by triose kinase creating GAP, which enters the glycolytic pathway, along with dyhydroxyacetone phosphate, at the triose phosphate level (Fig. 2).

Galactose

The metabolism of galactose takes place via the conversion of glucose. The first stage of its metabolism is the formation of galactose-1-phosphate, in a reaction catalysed by galactokinase. This enzyme is found in the red and white blood cells and the liver. The following stage consists of the formation of uridine diphospahte-galactose from galactose-1-phosphate and uridine diphosphate-glucose, in a reaction catalysed by galactose-1-phosphate uridyl transferase.

Uridine diphosphate-galactose is epimerised to uridine diphosphate-glucose, in a reaction catalysed by uridine diphosphate-galactose-4-epimerase whose coenzyme is NAD^+. The enzyme catalyses the reaction in both directions and can also be used as a substrate of uridine diphosphate- N-acetylglucosamine or uridine diphosphate-N-acetylgalactosamine. The following stage is catalysed by uridine disphosphate glucose pyrophosphorylase, which facilitates not only the production of glucose-1-phosphate from uridine diphosphate glucose but also the formation of uridine diphosphate glucose from uridine triphosphate (UTP) (Fig. 2).

Mannose

Mannose comes from the digestion of polysaccharides and glycoproteins, it is phosphorylated by HK to mannose-6- phosphate and is subsequently isomerised by phosphohexose isomerase, giving rise to fructose-6-phosphate which enters the glycolytic pathway (Fig. 2).

DIETARY SOURCES OF MONO- AND DISACCHARIDES

Generally speaking, the composition of mono- and disaccharides are considered in three food groups and then the content of each of the sugars from those food groups are examined individually. Unfortunately, the international data bases such as the US Department of Agriculture (http://ndb.nal.usda.gov/ndb/search/list) and the FAO (http://www.fao.org/infoods/infoods/tablesand-databases/faoinfoods-databases/en/) do not provide a detailed composition

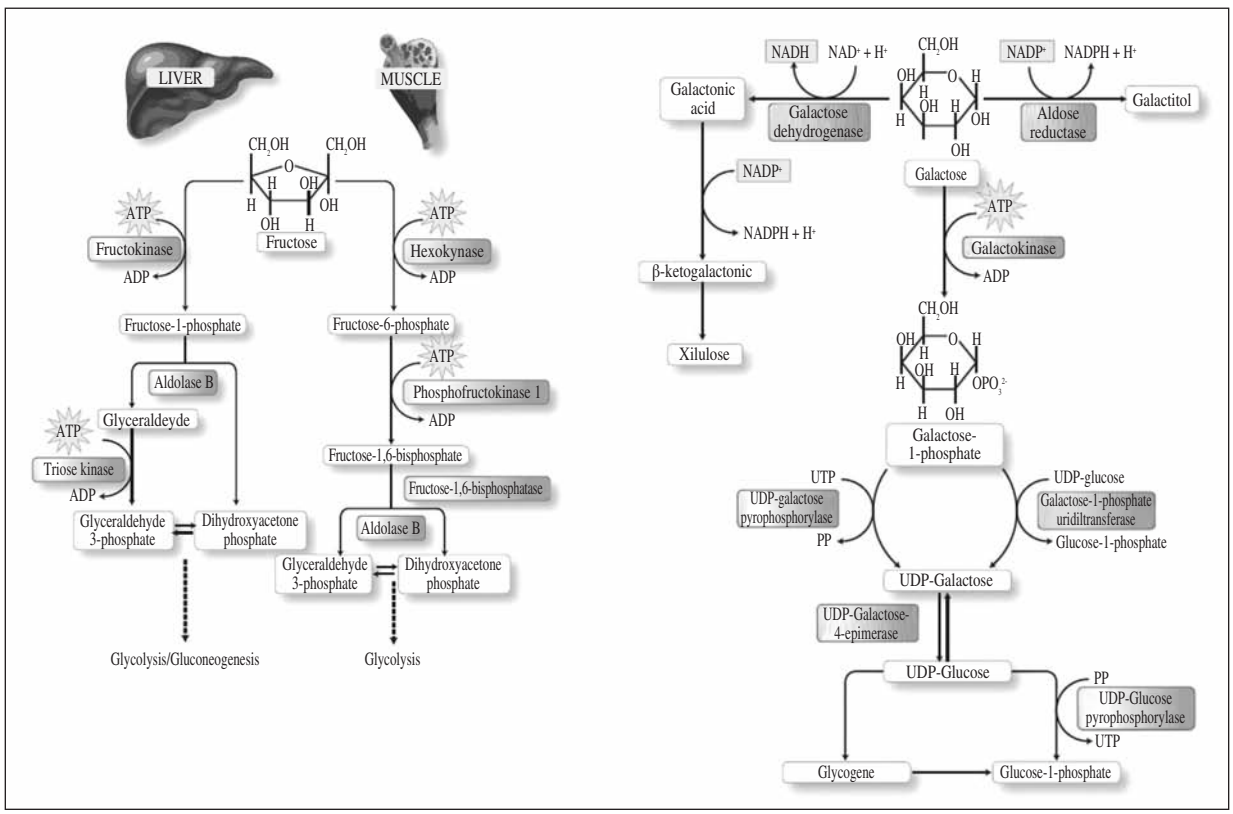

Fig. 2.—Reactions of fructose interconversions in the liver and muscle, and of mannose and galactose. Taken from Gil A. Tratado de Nutrición, 2.ª Ed. Vol. I, Editorial Panamericana, Madrid, 2010.

of the mono- and disaccharides in foods and are limited to only provide information on total carbohydrates 'by difference' in relation to the other nutrients, fibre and total sugars[8,9].

Milk and dairy products

Lactose is the main and sole carbohydrate in milk. The lactose content of milk depends on the species. Dehydrated dairy products vary in their average lactose composition, from 10% pp for evaporated milk up to 50% pp for powdered skimmed milk, and around 3 g for cream and 1.1g per 100 g of butter[10].

Lactose appears to have beneficial effects in the intestinal absorption of calcium. In people with lactose intolerance, milk consumption can produce symptoms of intestinal disorders, which to a greater or lesser degree, cause abdominal bloating, excessive intestinal gas, nausea, diarrhoea and abdominal cramps. People who don't tolerate milk well can substitute it for other dairy products, like cheese (since a large proportion of the lactose content is lost during the coagulation and maturing process), or fresh fermented products, such as yoghurt.

Cereals and their derivatives

The sugar and oligosaccharide content of cereals is low (1-3%) and is distributed between the germ, bran and endosperm. The principal sugar in all of them is sucrose, which can reach up to 1%; the average content of rice, oat and what flours is 0.13%, 0.25% and 0.56%, respectively, There are lower concentrations of glucose and fructose of 0.02-0.06% in rice, oat and wheat flours. Maltose is found in varying quantities depending on the degree of starch hydrolyses and, in the case of wheat flours, the content varies between 1.7 and 2.4. In cakes and pastries the energy value is very high, as they correspond to products that are rich in carbohydrates (37%-79%), especially starch. Furthermore, sucrose is added to many of them[11].

Sugars are a basic ingredient of biscuits, sweets and confectionary. In these products sucrose, glucose syrup, fructose and honey constitute 40% of the total carbohydrates[11].

Fruit, vegetables and honey

The main fruit sugars are sucrose, glucose and fructose. Whichever one is predominant depends on the type of fruit. So, drupes (plums, apricots, peaches, etc,) contain mainly sucrose, with the exception of cherries. As far as reducing sugars are concerned, the highest proportion is usually glucose. In pip fruits, called pomes (apples, quinces and pears) there is also glucose and fructose, but in this case the proportion of fructose is higher and continues to increase, even after they have been harvested. Other fruits like grapes or figs don't contain sucrose and their main source of sugar is glucose[12].

D-glucose is found naturally in honey (31%)13; fruit, like grapes and cherries (around 7%), apples and peaches (1%), vegetables like onions (2%), tomatoes, carrots, cucumber, green beans, potatoes and sweet corn (1%)[12].

Fructose is found naturally in honey (38%)12; fruit, like grapes and cherries (around 7%), apples and pears (6%), strawberries (2%) and peaches (1%), vegetables like onions, tomatoes, carrots, cucumbers, green beans (1%) and potatoes and sweet corn (0.3%)12. Sucrose is found in both fruit and vegetables such as peaches (7%), apples (4%), grapes and pears (2%); vegetables and fruits like beetroot (6-20%), peas (5%), carrots (4%), sweet corn (12-17%) and potatoes (3%)[12].

Maltose is found in honey (7%), produced by transglycosylation reactions, and in variable proportions in fruits, vegetables and cereals by enzymatic starch hydrolysis, which these foods contain[13].

SWOT ANALYSIS OF THE NOMENCLATURE, COMPOSITION OF FOODS AND SUGAR INTAKE

Strengths

Various international agencies have recently been concerned with providing a comprehensive overview of the terminology to be used for the different types of carbohydrate and, in particular, for sugars[1,3].

The intakes of different types of carbohydrate are being assessed systematically in several cohort studies which enables the current intakes of sugars and other carbohydrates to be established with a greater degree of safety.

Weaknesses

International food composition data bases do not provide detailed quantities of mono- and disaccharides in foods and are limited only to provide results for total carbohydrates 'by difference' in relation to the other nutrients, fibre and total sugars.

There are a number of major factors which limit the amount of comparable information on carbohydrate intake in adults, infants and small children. The first focuses on the limited number of studies conducted. The second, on the different approaches and varying results published in data bases on carbohydrates. The third is the large amount of terms used and finally the lack of information on global starch intakes.

Opportunities

The specific dietary recommendations for infants and children must be better addressed, on an individual basis, incorporating the possible interactions between diet and genes, which are crucial to understand the relationship that exists between diet and the risk of metabolic disease.

Future cognitive research should incorporate neurodevelopmental assessments, as well as measuring the general cognitive levels, associated with the intake of sugars and other carbohydrates. Prospective cohort studies are needed, covering infancy and childhood, so that the influence of consuming the different types of carbohydrates on obesity and diabetes can be established.

Threats

Based on the lack of information available on carbohydrate intake, particularly in infants and young children, the clearest threat is the growing and worrying relationship with the development of various illnesses, such as obesity, cognitive problems, insulin resistance and diabetes. It's necessary to evaluate and address each of the facts which help us to understand if there is such a relationship and which are the normal values necessary for a healthy diet; not for total carbohydrates but the values for their key components and, in particular, sugars.

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