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Nondigestible Carbohydrates in the Diets of Infants and Young Children: A Commentary by the ESPGHAN Committee on Nutrition

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ABSTRACT
The consumption of nondigestible carbohydrates is perceived as beneficial by health professionals and the general public, but the translation of this information into dietary practice, public health recommendations, and regulatory policy has proved difficult.

Nondigestible carbohydrates are a heterogeneous entity, and their definition is problematic. Without a means to characterize the dietary components associated with particular health benefits, specific attributions of these cannot be made. Food labeling for "fiber" constituents can be given only in a general context, and the development of health policy, dietary advice, and education, and informed public understanding of nondigestible carbohydrates are limited.

There have, however, been several important developments in our thinking about nondigestible carbohydrates during the past few years. The concept of fiber has expanded to include a range of nondigestible carbohydrates. Their fermentation, fate, and effects in the colon have become a defining characteristic; human milk, hitherto regarded as devoid of nondigestible carbohydrates, is now recognized as a source for infants, and the inclusion of nondigestible carbohydrates in the diet has been promoted for their "prebiotic" effects.

Therefore, a review of the importance of nondigestible carbohydrates in the diets of infants and young children is timely. The aims of this commentary are to clarify the current definitions of nondigestible carbohydrates, to review published evidence for their biochemical, physiologic, nutritional, and clinical effects, and to discuss issues involved in defining dietary guidelines for infants and young children. ***JPGN 36:329–337, 2003.*** © 2003 Lippincott Williams & Wilkins, Inc.

INTRODUCTION AND AIMS

Nondigestible carbohydrates (NDC) are important constituents of the diet, and in adults, inadequate intake of some NDC has been considered in the pathogenesis of certain gastrointestinal disorders, including constipation, irritable bowel syndrome, diverticular disease, and colorectal cancer. Inclusion of some (but not all) NDC in the diet is associated with a lower prevalence of some of these diseases, as well as of hypercholesterolemia, obesity, diabetes mellitus, and coronary artery disease (1).

Diet during infancy and early childhood must not only support normal growth and development (2) but is also the foundation of adult health (3). National surveys of the diets of children in Europe and North America report a decrease in the consumption of NDC (4–6) associated with increased intakes of fat- and energy-dense foods (7) and with the prevalence of childhood obesity (8,9). On the other hand, inappropriately high intakes of NDC in

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infants and young children can be associated with malabsorption and fermentative diarrhea (10). Too much or too little NDC in early life could have immediate and long-term adverse effects.

DEFINITIONS

Nondigestible carbohydrates are a complex, heterogeneous group of dietary substances that are derived principally from plant material. The declared NDC contents of some foods differ between countries according to the analytic methods used, and lack of universally agreed definitions means that dietary recommendations cannot be directly compared. The actions of 1 g of NDC depend on the type consumed and vary, for instance, according to whether it is expressed as "dietary fiber" (sum of cellulose, hemicellulose, pectins, gums, lignin, and some resistant starch) or as "nonstarch polysaccharides" (NSP) alone. Figure 1 summarizes the essential groups of NDC in relation to some of the analytic methods used.

Fiber and Nonstarch Polysaccharides

Burkitt's (11) original concept of dietary fiber as "indigestible plant remnants" has evolved to include the edible parts of plants or analogous carbohydrates that are resistant to digestion and absorption in the human small intestine with complete or partial fermentation in the large intestine (12). The definition of Trowell et al. (13) is based on an analytical method that measures plant cell wall and other indigestible plant polysaccharides plus lignin. The Englyst analytical method (14) concentrates on NSP. The method of the Association of Official Analytical Chemists (AOAC) International (15) also determines lignin and a portion of resistant starch. A comprehensive review of the definitions of fiber, the components of NDC measured by various analytic methods, and the implications for dietary recommendations has recently been published (16).

Starches

Approximately 10% of ingested starch passes through the small intestine unchanged. Resistant starch (RS) is defined as "the sum of starch and products of starch degradation not digested and absorbed in the small intestine of healthy individuals" (17). RS can be divided into three types: 1) physically inaccessible starch as found in intact grains of cereals; 2) raw starch found in potatoes and green bananas as large (type B) granules (composed of a super helical three-dimensional structure that resists α-amylase); and 3) retrograded amylose, starch that has recrystallized during or after processing to form a B-type starch that resists human α-amylase, such as found in cooked and cooled potatoes.

Monosaccharides and Disaccharides

Lactose may be incompletely digested in the small intestine, especially in infants (18), and thereby serves as a substrate for colonic fermentation. Fructose, included in some juices and soft drinks, and lactulose, found in some infant formulas, may pass to the large bowel where they can have an osmotic effect and are fermented.

Oligosaccharides and Polysaccharides

These are saccharides with at least three sugar moieties. Many occur naturally, such as the oligosaccharides

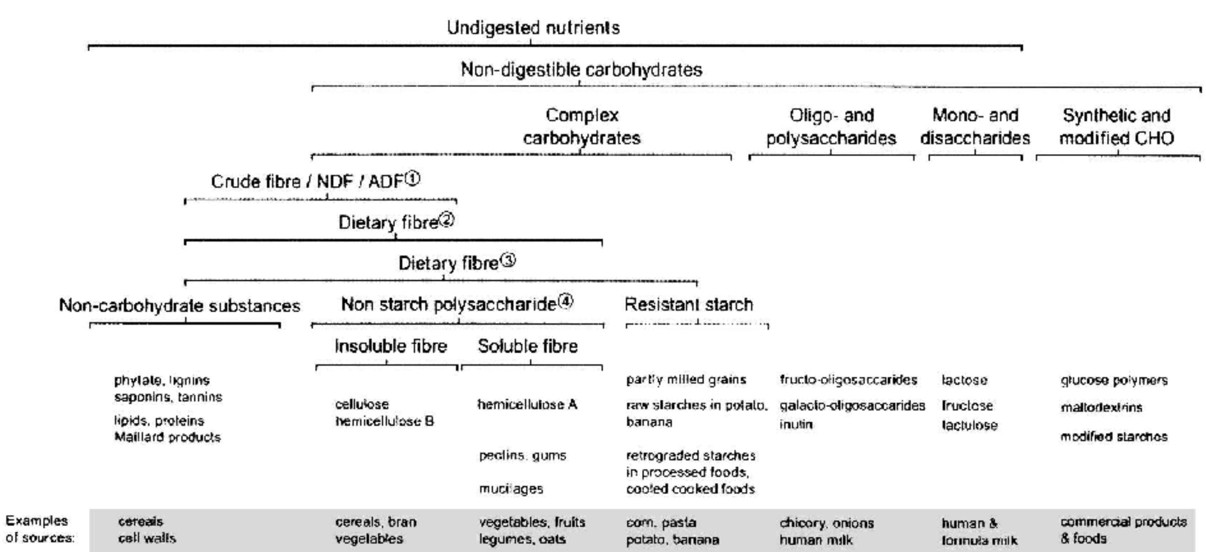

FIG. 1. Classification of nondigestible carbohydrates (NDC). (1) Old analytic method not suitable for dietary fiber. NDF, neutral detergent fiber; ADF, acid detergent fiber. (2) Trowell et al. (13). (3) AOAC method, Prosky et al. (15). (4) Englyst and Cummings (16).

in human milk. Others can be extracted from plant tissues or synthesized, such as inulin, fructooligosaccharides (FOS), galactooligosaccharides (GOS), and trans-galactooligosaccharides (TOS). All are largely resistant to small intestinal enzymes and are fermentable (19). There are also a number of trisaccharides and tetrasaccharides in or derived from plants, such as raffinose and stachyose, which resist small intestinal digestion.

Synthetic and Modified Complex Carbohydrates

These are included in some enteral feeds as an energy source (glucose polymers, maltodextrins, and other polysaccharides), and they may be consumed as fat substitutes (esters of sucrose, Olestra®) and as thickeners and sweeteners (polyalcohols). Their digestion in the small intestine may be incomplete, and they can pass into the large bowel where some may be fermented.

Noncarbohydrate Substances

Some noncarbohydrate components of plant cell walls, such as lignins, phytate, and saponins, are associated with NDC in foods, and this association has nutritional implications (see below). There are also some lipids and proteins that are not digested, including Maillard products (glycated proteins) generated during food processing.

BIOCHEMICAL, PHYSIOLOGIC, NUTRITIONAL, AND CLINICAL EFFECTS

The fate and effects of NDC in the gastrointestinal tract are the result of their mechanical and physicochemical properties as they pass down the gut. These effects include the retention of water, minerals, and organic compounds, and others are the consequences of bacterial fermentation within the distal large bowel. Interactions of NDC with other dietary components can have nutritional and clinical consequences (Fig. 2). These consequences have been measured largely in adults, and few studies have been performed in children.

Viscosity and Water-Holding Capacity: Impact on Uptake and Absorption

Soluble NDC, such as hemicellulose A, pectins, gums, and mucilages, swell with water in the gut, which may increase the viscosity of the gastrointestinal contents and thereby delay the rate of gastric emptying and the digestion and absorption of nutrients. Soluble NDC can also reduce mixing of the small intestinal contents and increase fecal elimination of fat and nitrogen. They are usually extensively fermented in the large intestine, which reduces their impact on stool mass, volume, and softness, and facilitates microbial degradation through greater penetration of bacteria into the polysaccharide structure.

Insoluble and coarsely ground NDC (cellulose, hemicellulose B) are more resistant to fermentation, and in the colon, water-holding capacity may reduce colonic transit time, and hence overall gastrointestinal transit time, through retention of water. Speeding up whole gut transit time further reduces the time for colonic salvage of the products of fermentation and possibly the absorption of nutrients and other substances. Fecal mass, softness, and frequency are increased (20), and insoluble NDC are used to manage constipation, as described below.

Slowing the rate of carbohydrate and fat digestion can inhibit the rapid absorption of lipid components and the rate and size of glycemic peaks and the insulin response (21). The glycemic index of foods highlights the capacity of "natural" or "whole" (unmodified) foods to achieve these positive effects more than the addition of crude fiber to starch-based foods. When comparing the glycemic response of carbohydrate-based foods with glucose or white bread, it is more "flattened" with some foods such as pasta, peas, beans, and lentils than with NDC-enriched refined cereals. Preparation processes and the effects of some noncarbohydrate substances (see below) may explain these differences, reflecting the integrity of the plant structure more than the amount of NDC (12). Some of the nutritional and clinical consequences of these physiologic effects are summarized below.

Interactions With Nutrient Absorption and Binding Properties

Some plant fibers (e.g., most soluble NDC) act as ion-exchange resins and therefore may influence the absorption of minerals, ionic compounds, and trace elements. Pectin and soy polysaccharides, for example, bind cations, such as calcium, magnesium, iron, copper, and zinc, and also bile acids and certain toxic substances. It is sometimes difficult to disaggregate the effects of the NDC from those of associated compounds such as phytates, hemoagglutinins, saponins, and tannins, which are tightly associated with soluble NDC in some vegetables.

The effects of dietary NDC on energy and micronutrient availability have been considered by some as insignificant (22), and mineral status seems likely to be compromised only in persons whose mineral intake is marginal or in those who consume an excess of NDC (23). Inulin and FOS can increase colonic absorption of calcium and possibly magnesium in rats (24), but the relevance of these effects to children is unknown. A tran-

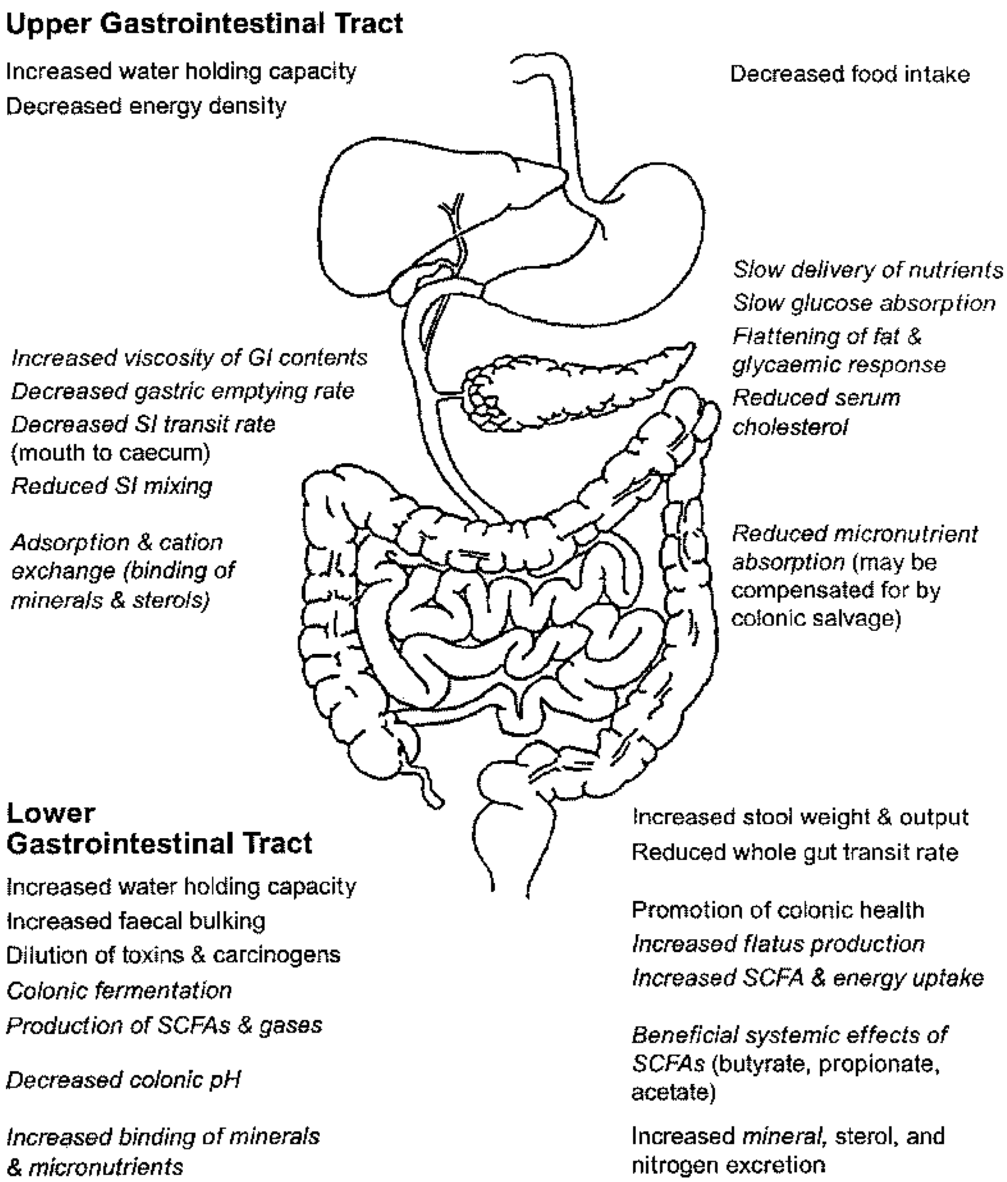

FIG. 2. Biochemical, physiologic, nutritional, and clinical effects of dietary NDC. Those in italics are characteristic of soluble (as opposed to insoluble) nondigestible carbohydrates (NDC). SCFA, short chain fatty acid; SI, small intestine.

sient adverse effect on calcium–phosphorus balance has been reported among infants aged 6 months to 12 months given foods containing approximately 7.5 g/d insoluble fiber (25), but in formula-fed infants receiving their first complementary foods, NDC have no negative effects of the absorption of energy or nutrients (26). Worries about the effects on iron absorption, particularly with high phytate-containing foods (27), are probably relevant more to strict vegetarians and children in developing countries where other dietary factors may also contribute (28). The binding capacity of NDC components is pH dependent and can be inhibited by substances such as ascorbic acid.

Colonic Fermentation

Nondigestible carbohydrates are fermented in the colon to the short chain fatty acids (SCFA), acetic, propionic, and butyric acids, lactic acid, and gases, including hydrogen, carbon dioxide, and methane. The colonic mucosa and some other tissues use SCFA for energy. In adults, it is estimated that the SCFA generated from fermentation provide at least 2 kcal/g of NDC (29). SCFA also modulate sodium and water cotransport, intestinal motility, and epithelial growth (30). Acetate is used for energy and fat synthesis, whereas propionate is gluconeogenic and may influence fat and cholesterol metabolism. Butyrate is the main fuel of the colonocyte and stimulates differentiation and apoptosis in cancer cell lines in vitro (31).

Reversal of colonic fluid secretion induced by enteral feeding has been reported in healthy adult volunteers by direct infusion of mixtures of SCFA into the colon (32). The fermentation of NDC helps to maintain the microecology of the colon. Its flora are also capable of fermenting protein and metabolizing other dietary and endogenous substrates, including fats, mucin, and bile acids, some of which can produce toxins or cancer promoters in adults. The full role of the colonic microflora in the pathogenesis of disease is unclear, but it is of potential importance when defining recommendations for dietary NDC in children.

Diet, Colonic Flora, and Fermentation in Infants

Breast-fed babies have more bifidobacteria and lactobacilli in their colonic flora than formula-fed babies, who have more *Enterobacteriaceae* and *Bacteroides* spp (33). These differences may contribute to the decreased incidence of gastrointestinal infections in breast-fed babies (34). Special properties and components of human milk may be responsible for the characteristic microflora of breast-fed infants. Among these are oligosaccharides and other NDC that are asserted to have prebiotic properties. Prebiotics are defined as substances that selectively encourage the growth of a colonic microflora with resistance to enteropathogens and have other beneficial effects (35).

The colonic microbiologic ecology and metabolic activity of breast-fed and formula-fed infants differ. The fecal microflora of breast-fed babies produce more lactic acid and less propionic acid and are less able to ferment NDC than the microflora of formula-fed babies (36). This difference persists well into infancy, and studies of the fecal bacterial activity of infants suggest slow maturation of the flora toward adult fermentation capacity during the late weaning period (7–9 months) (37). Moreover, starch can be found in the feces of children aged up to 3 years (38).

Strategies proposed to modify the fecal flora and colonic metabolic activity of formula-fed infants include alteration of the protein, lipid, and mineral contents of their feeds (39) and the addition of NDC with prebiotic properties. The effects of FOS and GOS on colonic function and on the growth of bifidobacteria and lactobacilli is the subject of current research seeking to define the possible health benefits of adding NDC to infant feeds (40). There are reported differences in the colonic microflora of atopic and normal infants (41), which are reflected in different patterns of fecal SCFA (42). Consequently, it has been suggested that modulation of the colonic flora might benefit allergic children.

NDC and Gastrointestinal Diseases

Nondigestible carbohydrates (particularly insoluble fiber such as in wheat bran) increase stool weight and frequency, soften feces, increase fecal bulk, and reduce gastrointestinal transit time (11,43). Breast-fed infants pass a greater number of softer and larger stools per day than formula-fed infants (44), which could be partly caused by the oligosaccharides in human milk among other factors, such as protein and lipid. There are geographic and racial differences in the bowel habit, gut transit time, and NDC intake of children (45), and low NDC intake may be a factor in the etiology of constipation (46). NDC can be used to manage childhood constipation (47), but they are not always effective (48), and evidence that increasing the NDC intake of children reduces the prevalence of constipation is not strong (49,50).

Epidemiologic cross-sectional comparisons, case–control studies, and trends in food intake show higher rates of colorectal cancer in populations consuming diets low in NDC and vegetables (51,52). Associations between intake in early life and later health advantages are not strong (53). Moreover, whether NDC consumption is of causal importance or simply a marker of other factors related to risk of colorectal cancer is controversial (54,55). A prospective study found no protective effect of dietary fiber against colorectal cancer or adenoma in women (56), and supplementation of the diet with calcium and fiber has been reported to increase the risk of recurrence of colorectal adenomas in adults (57).

Some epidemiologic studies have suggested protection against appendicitis by consumption of green vegetables (58), but evidence for a protective effect of NDC is inconclusive (59,60). Some NDC (such as pectin) could promote gastrointestinal mucosal adaptation in adults with short bowel syndrome (61), and others (such as soy polysaccharide) can aid recovery after acute diarrhea (62).

NDC, Energy, and Growth

Diets rich in NDC may potentially reduce energy intake or reduce the availability, digestion, and absorption of fat and carbohydrates through mechanisms outlined above. Fecal loss of energy may increase with increased NDC intake by infants and young children (63). Squashes and fruit juices that contain NDC (fructose, sugar alcohols, pectins) may cause diarrhea (64). The "immature" capacity of the small intestine and exocrine pancreas in early life may contribute to maldigestion (65). Complementary and infant foods that are bulky from excess fluid or NDC can be of low energy density (66) and may have adverse effects through malabsorption and fermentative diarrhea (67).

There are reports of poor growth and nutritional status of children taking large amounts of NDC, such as vegans

(68) and anecdotal evidence of children eating little but muesli (69). In children aged 7 years to 8 years, diets relatively rich in NSP were associated with no difference in growth compared with children eating less than 5.6 g/1,000 kcal/d (70). Children eating a "macrobiotic" diet with an NDC intake averaging 13 g/d of fiber (almost twice the intake of children eating a "nonmacrobiotic" diet) showed growth faltering during the weaning period but catch up thereafter (71). It is difficult to know whether these effects were caused by high NDC intake, low energy density, energy deficiency, or other factors.

On the other hand, the lower energy density of foods rich in NDC, their satiety effects, "flattening" of the postprandial glycemic response through slowing the rate of food ingestion, gastric emptying, and digestion may be helpful for the prevention of obesity (8) and for the dietary management of diabetes mellitus (21,72). Improved glucose tolerance, reduced insulin requirements, decreased serum cholesterol and triglycerides, and better weight control have all been reported in patients with diabetes when NDC consumption is increased (73).

In particular, soluble NDC decreases blood levels of cholesterol (74,75). In a meta-analysis of 67 controlled studies focused on soluble dietary fiber, a significant reduction of serum cholesterol with increased soluble fiber intake was reported (76). Satiety studies in adults indicate small long-term effects, but these have not been well performed in children (77).

SOURCES AND INTAKE OF NDC BY INFANTS AND YOUNG CHILDREN

Most NDC in the diet of young children is obtained from cereals, legumes, and vegetables, some from fruits and their juices, and some as thickeners, stabilizers, and fat substitutes in processed food (Fig. 1).

Milk and Complementary Foods

Mature human (breast) milk contains approximately 70 g/L lactose, more than 90% of which is digested in the small intestine (17). Additionally, a large variety of oligosaccharides are present in concentrations of approximately 5 g/L to 10 g/L (78). Some infants receive feeds that are claimed to prevent regurgitation, which contain rice and rice-based products, carob and guar gums, pectins, or cellulose for thickening (79). FOS, GOS, inulin, soy polysaccharide, RS, and gums are also added to some dietary products, enteral formulas, and breast milk substitutes. In addition to these substances that are added intentionally, the processing of some infant foods (e.g., by autoclaving) may increase RS. Some milk contains NDC, such as lactulose or Maillard products, which are formed adventitiously during manufacture or sterilization.

Diversification of the diet exposes infants to a widening range of NDC in fruits, vegetables, legumes, and cereals (80,81). Cereals form the basis of many complementary foods, and in general 65% to 75% of their total weight is carbohydrate, largely starch. Most raw cereals contain starch, which becomes rapidly digestible when cooked. Partly milled grains and seeds contain resistant starch (82). Rice, potato, and other nonwheat cereals are usually the cereal base for complementary foods, and fruit and vegetables are often added for flavor. Because they do not usually include peel, skins, or the husks of grains, they can be relatively low in NDC. Fruit juices are also a source of NDC, including pectins (83).

Family Foods

Family foods eaten by young children may contain increasing amounts of NDC, particularly those rich in fruit, vegetable, cereals, and composed of whole or unprocessed foods. Vegetable foods may contain a variety of NDC, including soluble and insoluble components, and their combination influences the properties and effects of each, as outlined above. High extraction flours (100% extraction rates), such as whole meal flour, contain more of the outer layers of cereal grains, which are a rich source of NDC, whereas the finer, whiter flours (70% extraction rates) have a smaller proportion of the original grain. Whole-grain cereals are an important source of NDC for young children (84). Synthetic NDC may be consumed in the form of food thickeners and sweeteners, as described above. Some "sugar-free" foods contain sugar alcohols.

In many European and North American countries, a daily fiber intake for adults of approximately 20 g/d to 35 g/d or 10 g/1,000 kcal/d to 13 g/1,000 kcal/d is recommended (85,86). This usually includes approximately 25% soluble and 75% insoluble NDC (87). The rationale for these recommendations is empirical and based largely on dietary surveys. It is not possible to extrapolate for children directly from adult dietary recommendations because expression of guidelines for NDC intake per kg body weight or per kcal of energy generates different recommendations. For example, based on a recommended daily intake of 20 g fiber or 10 g/1,000kcal by a 70-kg man, a male infant aged 1 year (weight, 10 kg) would be expected to take 3 g/d according to weight or 10 g/d according to energy intake. The American Academy of Pediatrics (AAP) has recommended a daily intake of 0.5 g/kg body weight of fiber for children (88), but this figure becomes high for those in the late teens. Energy-linked recommendations could lead to excess amounts in toddlers. A dietary fiber intake in grams according to age in years plus 5 has been advocated for those aged 3 years onward, aiming to progressively reach levels recommended for adults (89,90). These recommendations are pragmatic and have no firm physiologic basis.

CONCLUSIONS

There is probably a minimal requirement for NDC in early life, supplied by milks to infants and by complementary foods to young children. Breast-fed infants receive NDC in the form of lactose and oligosaccharides. Toward the end of the first year, the progressive introduction of new foods, many in the form of vegetables, (whole) cereals, legumes, and fruit, accustoms the toddler to an increasing intake of NDC. The regular consumption of these, established during the transition from complementary to family foods, should increase the amount and variety of foods containing NDC that young children receive at meals (91). Foods rich in NDC are preferred to dietary supplementation. By school age, children who eat a variety of NDC are likely to be consuming at least 10 g/d, albeit of different sorts and sources. Early eating habits tend to persist over time; therefore, it is sensible to establish an adequate intake of NDC early in life because of the long-term advantages of healthy eating (2,3,92).

However, despite, or perhaps because of, our increased understanding of the physiologic impact of NDC, it is difficult to define precise quantitative and qualitative recommendations for the NDC content of the diets of infants and young children. It is important to remember that NDC are components of plant products and generally consumed as such. There is some evidence of deficient NDC intake, particularly in children eating too restricted a diet. On the other hand, adverse effects of overconsumption of NDC appear to be unlikely, except at extremes of intake. Because diets rich in NDC also tend to be rich in micronutrients and low in fat, they could reduce the excessive intakes of energy-dense, sweet, and fat-rich foods and drinks, and thereby the associated risk of obesity and diseases. The effect of NDC on bile acids may also reduce fat absorption, which could be beneficial. Counterbalancing these apparent advantages is the possibility that excessive fermentation could be detrimental rather than protective to the colonic mucosa (93).

Definitive guidelines that are applicable to disparate societies have to recognize the diversity of infant feeding practices and the choice and availability of foods for young children. Therefore, guidelines are necessarily general and are likely to remain so at least until the recommendations for action and research, presented below, are implemented. In the meantime, awareness of the ambiguities of labeling that arise from lack of clarity and agreement of analytical methods and definitions must be borne in mind. Caution should be observed concerning the addition of thickening agents (79) and prebiotic compounds (35) to feeds until assessment of their metabolic and clinical effects in infants and children has been undertaken (94). The excessive consumption of juices and squashes, especially in place of milk, should be avoided (10,83).

The questions of analytic methods, definitions, and labeling remain issues of debate in Europe (93) and North America (95), and it is likely that our understanding of the composition, properties, and effects of NDC will continue to grow. There are advantages and disadvantages of trying to combine the nondigestibility and plant cell origin of NDC in definitions (12,93). The physiology and chemistry of NDC are relevant to a full understanding. In infants and children, NDC other than NSP and starches are present in the diet and have fates and effects comparable with those derived from plants that enter the diet later (19). The recommendations for action and research below are by no means comprehensive but rather focus on current important topics relevant to infants and young children.

RECOMMENDATIONS FOR ACTION AND RESEARCH

Analysis, Definitions, and Labeling

- There should be standardized, internationally agreed methods for the analysis of NDC content of foods.
- These agreed analytic methods should be used for the labeling of foods and food products in food composition tables and data banks.
- Health professionals should be made aware of the diverse nature, effects, and sources of NDC.

EFFECTS ON HEALTH, GROWTH, AND NUTRITIONAL STATUS

There is a need for research leading to a greater understanding of the following:

- Metabolic effects and dose–response of individual components of NDC in early life;
- Influence of NDC on the early acquisition of, and changes in, the colonic microflora;
- Interaction of the colonic microflora with components of NDC and their implications for health;
- Effects of NDC on the bioavailability of micronutrients and other food components, and thereby on the growth and nutritional status of infant and children; and
- Long-term effects of different dietary NDC on adult health and gastrointestinal disease.

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