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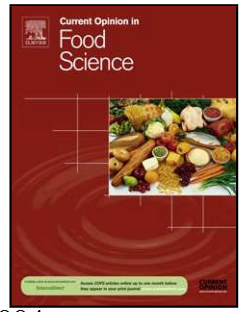

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Food: More than the sum of its parts

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Abstract

The food we eat and enjoy is not just a collection of macro and micro nutrients, it has structure and texture that affect our response to it. This short review of recent research touches on many of the issues linking different types of food structure to the digestion and absorption of macronutrients. The behavior of both protein and lipid in the gastric compartment can be key to what gets emptied when and thus the kinetics of nutrient absorption, which can in turn influence risk factors for disease. Because of this there is increasing emphasis on understanding the role of gastric processing in digestion kinetics. The use of MRI has significantly improved our understanding of gastric behavior and offers new possibilities for controlling digestion kinetics. In addition, the role of fiber in the upper GI tract is also starting to be better understood. This will also lead to further opportunities to improve the health of the Western diet.

Keywords

Food structure; digestion; macronutrients, dietary fiber, health

Introduction

In the study of nutrition, food is generally considered at the nutrient level, meaning that the impact of food structure is often ignored. This reductionist approach linking one nutrient to one health effect, may partly explain some of the discrepancies between a predicted health effect of a food based on its nutrient content and its actual health effect when consumed as a whole food or indeed as part of a diet [1]. Things are now starting to change and so it is worth looking at recent work highlighting the role of food structure in nutrient release and food related diseases. The fundamental dichotomy is that while human studies provide the only way to definitively show causal links between food and health, it can be very difficult to develop a detailed mechanistic understanding of the role of food structure from such studies. Because of this, the work described in this review will cover not just the results of human studies but the data coming from increasingly widely used simulations of digestion, such as that developed in the Infogest project [2] or more sophisticated models [3]. Increasingly, digestion of the same food systems is being investigated both *in vivo* [4] and *in vitro* [5]. It will become evident from what follows that an accurate simulation of the gastric phase of digestion is key to understanding digestion kinetics and the link to food structure as illustrated by Figure 1.

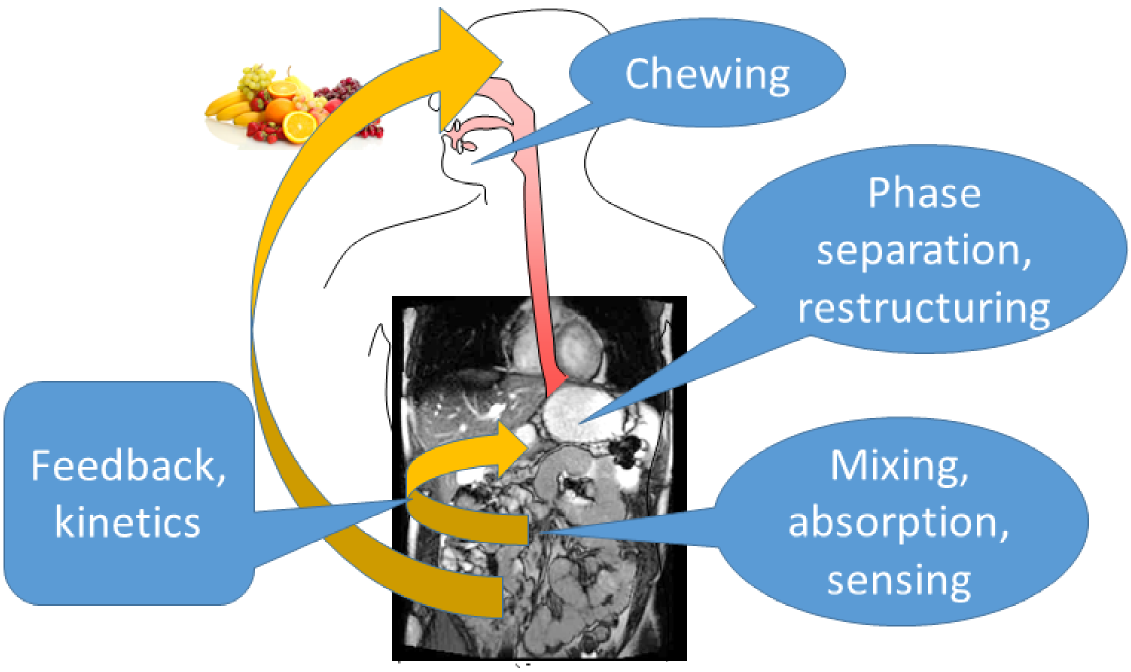

Figure 1 A schematic showing the aspects of digestion where food structure has a key role to play.

Food has complex structures both physically and nutritionally which will affect digestion and absorption and may lead to interactions within the food matrix both pre and post consumption that alter its bioactive properties. Such interactions can alter the extent and kinetics of nutrient absorption in ways that are not always predictable, at least not from the information on nutrition labels [6]. Evidence from recent studies has shown that the food matrix can modify the nutritional properties of a food [7]. For example, plant-based foods contain cellular structures that need to be degraded before the encapsulated nutrients and bioactive compounds can be released and absorbed. This may be achieved by processing (industrial as well as cooking at home) and by oral processing such as mastication. Despite this, release of nutrients may be limited in some foods such as almonds [8] or apple [9]. Hence, for some nutrient dense foods, such as almonds, the food matrix attenuates postprandial lipaemia after consumption [8]. People spend the majority of the day in a postprandial state and postprandial lipaemia is acknowledged as an independent risk factor for cardiovascular disease (CVD) [10]. A slower release of nutrients from naturally encapsulated systems has also been shown to increase satiety after consumption [11]. This paradigm also applies to other foods and other ways in which food structure alters digestion and is the main point of discussion in the following review.

Macronutrients

Although macronutrients are not eaten in isolation, most studies tend to concentrate on the outcomes associated with a particular nutrient. Thus, the approach taken here will be based on individual macronutrients.

Protein

Protein is a key constituent of the diet and has been much studied, particularly in relation to muscle building. Muscle growth (hypertrophy) after resistance exercise is a fundamental adaptation to an increased resistive workload. However, muscle growth can only occur if there is net anabolism within the muscle. That is, muscle protein net balance (synthesis minus breakdown) is positive during the period in which hypertrophy occurs [12]. This is true not just for athletes but also for the elderly, where a study on men with a mean age of 72 [13] showed that fast-digesting soluble milk proteins improved postprandial muscle protein synthesis and shows that the kinetics of bioavailability of amino acids and especially essential amino acids is important for health. The high bioavailability of peptides and proteins can also be detrimental to health in the case of allergy [14] and much work has been undertaken on the ability of specific protein families to resist processing and subsequent digestion [15, 16]. This link will not be discussed further here as there are other reviews that cover this topic [14, 17].

It is clear that many different processes can have an effect on protein structure, altering properties including allergencity [18]. A limiting factor for hydrolysis is the accessibility of the enzyme in question to the substrate. Proteolysis initially occurs in the gastric compartment where recent studies have shown that the digestion of the protein gels is influenced by the microstructure of food matrices, caused by immobilization of the substrate in the network, and the steric hindrance of pepsin diffusing into and peptides diffusing out of the gel [19]. Of course heating in the presence of polysaccharides that are not digested in the upper GI tract can also have a marked effect. In a study on the heat induced gelation of beta lactoglobulin-xanthan mixtures at 70-90 °C for 20 minutes, a considerable decrease in the rate of proteolysis was seen. The formation of a dense protein network created a fine pore structure which restricted pepsin access into the gel thereby slowing proteolysis. This is in contrast to thermally induced protein unfolding that may increase hydrolysis [20]. At the supermolecular level, proteins can be used to make a very wide range of different structures and dairy proteins in particular have been used to investigate this. By tuning the conditions under which dairy products are formed, the underlying structure can be altered. This has been shown to have a marked effect on simulated digestion [21, 22] with homogenization increasing protein hydrolysis in milk but solid matrices such as cheeses being more resistant to protein digestion than liquid or semi-solid matrices. Although in the latter study by Islam et al., no relationship could be seen between disintegration kinetics and rheological properties of the cheese. These results suggest a significant influence of the meal microstructure (resulting from heat treatment) and macrostructure (resulting from gelation processes) on the different phases of protein digestion.

The effect of processing and structure on many other sources of protein has been also investigated, including meat [23] and plants [24]. For example, the cooking temperature of meat has been shown to inversely effect the digestibility, with well cooked meat less digestible than slightly cooked or raw [23, 25]. The extent of digestion was not significantly affected in either study confirming that meat is a consistently good source of amino acids. The results show that the structure of the meat is responsible for only limited changes digestion kinetics. This is in contrast to data on plant proteins such as those from beans that can be very slow to digest depending on the processing used [26].

Lipid

The digestion and absorption of lipid is complicated by the poor solubility of all the components involved except the enzymes and the low density of triglycerides relative to the aqueous environment of the gut [27]. There has been a significant amount of research in this area and a number of recent reviews addressing the effect of structure [28, 29].

Because of the solubility issue with lipid and many bioactives, there has been a significant amount of research into how to optimize delivery of poorly soluble compounds using different structures [30-32]. The size of the lipid droplets and the available surface area is important for the rate of lipolysis, although overall fat absorption in healthy subjects is not affected by differences in initial droplet size because of efficient fat digestion by pancreatic lipase in the small intestine [33]. Despite this, it has been shown that the initial emulsion droplet size can have a significant effect of satiety [34]. This was most likely due to phase separation in the stomach. The behavior of emulsions under different physiological conditions is also important however [22] and numerous efforts have been made to control rates of lipid hydrolysis by changing gastric behavior [35] or tailoring the composition of the interface [36-38]. In particular coating the interface with polysaccharides such as pectin [39] or alginate [40] has been used, largely unsuccessfully to decrease rates of lipolysis. A far more effective way of altering the timing of the fat digestion is by inducing phase separation in the stomach, as demonstrated in studies using MRI [41]. Other factors that may also effect lipid digestion such as coalescence and droplet structure (e.g. emulsion containing solid fat) highlight that the principal cause of altered lipolysis is the destabilization of the emulsion within the stomach [42].

In addition to emulsified lipid, fat may be delivered in an encapsulated form in plant based foods [7, 43]. In such systems, oral processing is important to break open cellular structures [8] because the cell walls that are completely intact limit lipid digestibility, due to an encapsulation mechanism that hinders the diffusion of lipase into the intracellular environment and lipolysis products out of the cells.

Complex carbohydrates vs simple sugars

Carbohydrates in the diet range from simple sugars such as glucose to highly complex polysaccharides but only monosaccharides are absorbable. The slow release and absorption of sugars through inclusion of cereal fiber has been shown to be beneficial to health [44] by lowering risk factors for metabolic disease. As a result there is significant interest in altering rates of carbohydrate digestion and glycemic response in a predictable way [45]. Starch provides most of the carbohydrate in the human diet and its structure is a key driver of digestion kinetics [46, 47]. Raw granular starch is very resistant to amylolysis. In contrast, freshly gelatinized starches are highly susceptible to hydrolysis. Starch granule characteristics considered to influence susceptibility to attack by α-amylase include: crystallinity, granule size, amylose to amylopectin ratio, etc. [48]. The retrogradation of the amylose and amylopectin in starch after cooling varies and in amylose is rapid, resulting in high resistance to amylolysis. In contrast, amylopectin is slow to retrograde and may still be degraded by amylase [49, 50]. In addition, the surrounding matrix can also have a significant effect. For example, the gluten proteins in pasta can interact with amylase and slow down starch hydrolysis [51].

By definition, dietary fiber does not provide a source of nutrients directly to the body. However, it is becoming increasingly apparent that it is important for health for multiple reasons. The ability of dietary fibers to alter digestion and metabolism depends upon their physical properties and there are clearly large differences between soluble and insoluble fiber. The benefits of fiber in the upper GI tract are thought to be a consequence of the increase in viscosity that can be induced by soluble fiber [52]. The viscosity that can be imparted by soluble fiber depends on a number of factors including molecular weight and the extent of hydration. In general, higher viscosity meals tend to cause increased gastric retention in comparison to the equivalent lower viscosity meal [53]. As confirmation of this, a recent *in vitro* study, the impact on digestion of the addition of oat bran to biscuits was assessed. In particular, the viscosity of the chyme was measured throughout digestion [54], showing that the viscosity was maintained throughout the gut up to the ileal compartment and that the highest viscosity was obtained with biscuits containing soluble fiber. The effect of viscosity on digestion was also determined and protein hydrolysis decreased with fiber enrichment, i.e. increased viscosity [55]. This increase in viscosity has a number of benefits from a health perspective. Firstly it decreases luminal mixing, which can decrease mass transfer in the gut [56]. This involves the decreased transport of hydrolysis products to the site of absorption and the changes in interactions between enzymes and substrate. It can also effect the composition of chyme that is emptied from the ileum into the cecum. For example decreasing bile recycling by taking more bile into the colon and thus lowering blood cholesterol as the liver uses some of the available cholesterol to replenish bile reserves. In addition to viscosity effects in the intestinal lumen and the consequent impact on gastrointestinal motility, mixing and rates of hydrolysis, the soluble fiber may interact with the intestinal mucus and alter its permeability [57] or secretion rate. Indeed there is some evidence that it can also have an effect of intestinal morphology, at least in the small intestine of pigs [58].

Conclusions

It is clear that the health benefits of many foods are associated with their structure and the way that they deliver nutrients to the body. However, with a few exceptions, this association has not led to a clear mechanistic understanding of the role of the food structure. In the case of plant based foods, the different roles of cellular structure in combination with soluble and insoluble fiber fractions throughout the GI tract has yet to be elucidated. If we are to increase fiber intake and improve the health of the western diet then we need a better understanding of the effect of structure on digestion and the evidence above strongly suggests that the gastric phase of digestion is the place to focus.

Conflicts of interest

I declare that there are no conflicts of interest in the production of the article

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Highlights

Food structure can affect the rate and extent of digestion

Digestion kinetics can affect disease risk factors

Methods such as MRI are helping to improve our understanding of gastric behaviour

The role of dietary fibre in the upper GI tract is starting to be better understood