ANNUAL REVIEWS **Further**

Click here for quick links to Annual Reviews content online, including:

- Other articles in this volume
- Top cited articles
- Top downloaded articles
- Our comprehensive search

Designing Food Structures for Nutrition and Health Benefits

Jennifer E. Norton,[1] Gareth A. Wallis,[2] Fotis Spyropoulos,[1] Peter J. Lillford,[1] and Ian T. Norton[1]

Schools of [1]Chemical Engineering and [2]Sport, Exercise and Rehabilitation Sciences, University of Birmingham, Birmingham BE15 2TT, United Kingdom; email: j.e.norton@bham.ac.uk, g.a.wallis@bham.ac.uk, f.spyropoulos@bham.ac.uk, p.lillford@bham.ac.uk, i.t.norton@bham.ac.uk

Annu. Rev. Food Sci. Technol. 2014. 5:177–95

First published online as a Review in Advance on January 2, 2014

The *Annual Review of Food Science and Technology* is online at http://food.annualreviews.org

This article's doi:
10.1146/annurev-food-030713-092315

Keywords

food microstructure, functionality, health, nutrition, GI tract, in vivo, in vitro

Abstract

In addition to providing specific sensory properties (e.g., flavor or textures), there is a need to produce foods that also provide functionality within the gastrointestinal (GI) tract, over and above simple nutrition. As such, there is a need to understand the physical and chemical processes occurring in the mouth, stomach, small intestine, and large intestine, in addition to the food structure-physiology interactions. In vivo techniques and in vitro models have allowed us to study and simulate these processes, which aids us in the design of food microstructures that can provide functionality within the human body. Furthermore, it is important to be aware of the health or nutritional needs of different groups of consumers when designing food structures, to provide targeted functionality. Examples of three groups of consumers (elderly, obese, and athletes) are given to demonstrate their differing nutritional requirements and the formulation engineering approaches that can be utilized to improve the health of these individuals. Eating is a pleasurable process, but foods of the future will be required to provide much more in terms of functionality for health and nutrition.

1. INTRODUCTION

Traditionally, foods are designed to provide nourishment, with a focus on the development of specific flavors, tastes, or textures to create pleasurable eating sensations. Although the consumer experience is still of paramount importance, nowadays there is a public health need and great commercial interest to produce foods that provide improved nutrition or health benefits. For example, the reduction of salt, sugar, and fat in nutritional products is a key focus of the food manufacturing industry, as is the development of functional ingredients or foods to underpin specific nutrition and health claims. In addition, different population groups (e.g., young, elderly, overweight/obese) have varying needs and expectations from nutritional products, and therefore a tailored approach to delivering nutrition or health benefits is required.

The success of efforts to design nutritional products with improved healthiness, while maintaining consumer satisfaction, requires a detailed understanding of food microstructure and the interaction of food structures with physiological and behavioral processes occurring upon ingestion. The gastrointestinal (GI) tract, and particularly the mouth, stomach, and intestines, is the primary interface for the food structure-physiology interaction. This article provides a review of food microstructure design, with a focus on producing foods for health or nutritional benefits with specific functionality in the GI tract.

The review is separated into two sections. The first we term Design Principles, which introduces our current understanding of the mouth, stomach, and intestines and the methodologies for designing foods for functionality in these parts of the body. It describes the physical and chemical processes occurring during food transit through the GI tract and the in vitro models and in vivo techniques currently used to further our understanding of these processes. Of particular interest is where our knowledge and ability to design foods with improved nutrition or health benefits might go in the future. In the second section, which we term Case Studies, we provide three examples of consumer groups who seek differing benefits or have differing nutrition and health needs: the elderly, the obese, and athletes. Specifically, we discuss how their differing needs might be addressed with food microstructures.

2. DESIGN PRINCIPLES

We can treat the human digestive process as a series of stirred batch reactors: the mouth, stomach, small intestine, and large intestine. **Figure 1** illustrates the transit of food through the human GI tract, describing the processing operations that occur and the nutrients that are digested and absorbed at each stage.

2.1. Food Structure Design for Functionality in the Mouth

This section introduces the mouth, more specifically, its anatomy, the processes that occur during the consumption of food, interactions between food structures and the mouth, and the subsequent sensory perception of those structures. The in vivo techniques currently used to measure or visualize oral behavior and the in vitro models used to progress our understanding are also described.

2.1.1. The processes occurring in the mouth. This section begins with a description of oral physiology and our understanding of human masticatory processes (including chewing, bolus formation, and swallowing) (see **Figure 1**); food and oral cavity interactions dictate our sensory experience of foods and determine what we choose to eat throughout our lives (oral processing has also been reviewed previously by Chen 2009 and Lillford 2013).

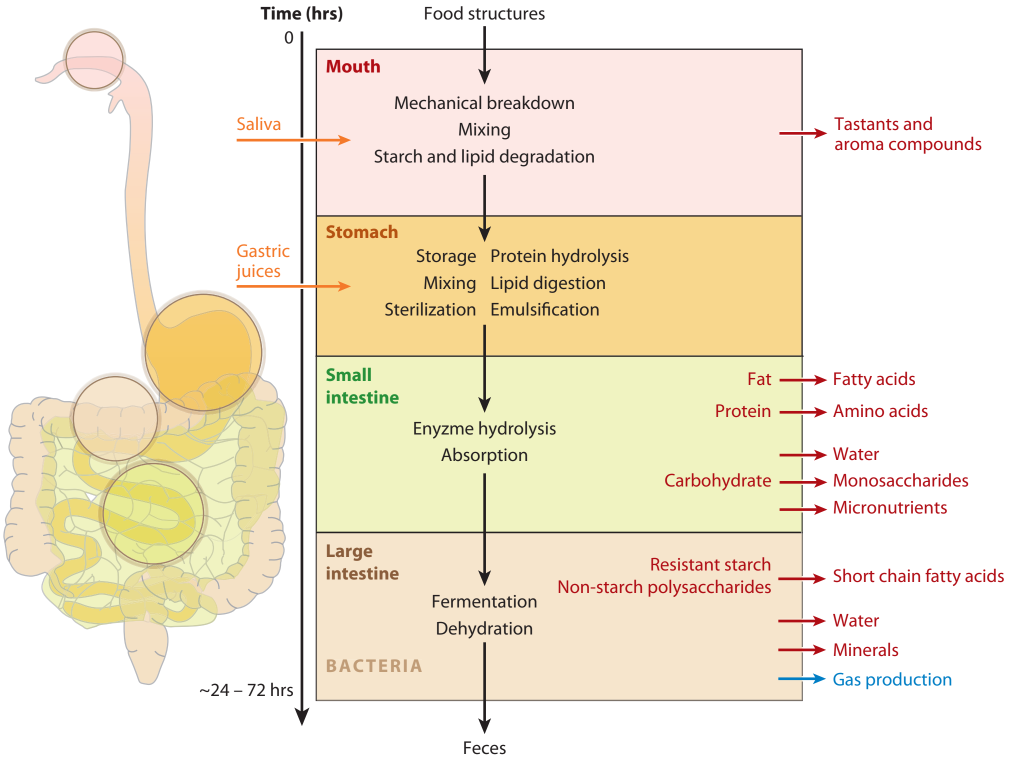

Figure 1

A schematic of the transit of food structures through the mouth, stomach, and small and large intestines (considered here as a series of batch reactors), illustrating the process operations taking place at each stage and the nutrients digested and absorbed. Adapted from Topping & Clifton (2001).

Our mouths are processing engines (Atkins 2009). We have soft flexible closures (lips) that contain the food inside the machine and a selection of teeth (incisors, canines, and molars) designed for cutting, crushing, and grinding. Our mouths are small, and our musculature is not particularly powerful: chewing forces are approximately 50–150 N, which limits the hardness of foods that we can eat. The total work of fracture may be limiting, not because the forces required are high, but because the deformation (strain) at break can be limiting. The best way to induce high strains is to have scissor-like teeth; instead, our molars are best equipped to crush and grind relatively soft brittle structures.

Mastication requires more than simple fracture and compression. The tongue is a stirring device that can change shape and move in three dimensions. It is used to position food for compression between the molars. Fracture or failure of the food occurs (which also allows the release of tastants and aroma compounds providing our experience of flavor), and then the tongue collects broken material into a bolus, which is propelled backward toward the epiglottis and swallowed.

Bolus formation requires that particles are reassembled and lubricated, to provide a viscoelastic mass. Some foods contain enough liquid (water, oils, and fats) and are self-lubricating; these are described as juicy or moist. Dryer materials require the active addition of saliva and are described as dry, mealy, or floury. Bolus formation normally occurs after approximately 15–20 chewing strokes. Foods that require more chewing, either to break down the initial structure or to lubricate and collect the bolus, are not preferred.

Finally, the mouth is not just a mechanical device but is also a chemical reactor. Saliva glands deliver lubricating liquid, which contains active enzymes (α-amylase) to hydrolyze starches and oils, and glycoproteins capable of emulsifying fats and oils. This injection of active agents is regulated by not only the mechanical properties of the food but also the flavor (tastants and aromas present or released during chewing).

2.1.2. Food structures and interactions. A fundamental understanding of the relationships between the manufacturing process, food structure and physical properties, the interaction with the processes occurring in the mouth, and sensory properties is required when designing foods for specific functionality in the mouth. It goes without saying that for food to be nutritionally beneficial it needs to be consumed; so it is required to be sensorially and hedonically appealing.

2.1.2.1. Meat and fish. Meat is a water-filled, fibrous composite. When raw, both the contractile fibers and the connective tissue are highly extensible, so the material requires large deformation before fracture. Human teeth are ill equipped to deal with this type of structure. Meat is a heat-sensitive composite: Actomyosin fibers heat set, rendering the contractile fibers stiffer. Connective tissue melts so that wet heating converts a rubber into a composite capable of being delaminated in the mouth. Complete fragmentation is not required, and the bolus is formed by reassembling bundles of fibers. Muscle tissue is high in water content, and in land mammals can contain stored fat. This provides the juiciness or succulence of this tissue.

2.1.2.2. Fruit and vegetables. There is an abundance of vegetable biomass that humans do not eat; because of their high cellulose content, they cannot be broken by chewing. They contain highly aligned cross-linked fibers, making the structures very resistant to both tensile and compressive failure. Edible vegetable tissue contains less cellulose, mostly within cell walls. In fresh tissue, the walls are prestressed by turgor pressure. Compression by the molars produces a high-speed fracture, which occurs with sound emission, and the texture is perceived as crisp and crunchy. Lubricating liquid is simultaneously released. Cooking does not always have a beneficial effect. The action of heat weakens the adhesion between cell walls. Turgor is lost, and cracks do not propagate as readily. Compression by the molars is sufficient to break the chewed piece, but fracture can occur by cell separation rather than cell wall fracture. No brittle fast fracture occurs, so crispness is lost. Little liquid is squeezed out in the first compression strokes, and it plays no useful part in bolus formation. The liquid remaining within cells is not detected, and the food may be described as dry.

2.1.2.3. Solid foams. Cereal grains provide a convenient method to store nutritional components, but the seeds are small and hard, and provide a dry floury texture given that the starchy components absorb saliva. Bakery employs a series of technologies to improve texture and nutritional value.

Milling breaks the seeds. The addition of excess water swells starch and protein, and if only an equal weight of water is added, forms a plastic mass or dough, which allows for the incorporation of gas bubbles. Heat performs several structuring actions. First, starch gelatinizes, proteins may heat set, and the combination forms a continuous matrix; however, the expansion of gas blows and lifts the structure. Provided the matrix sets before all gas escapes, a solid foam forms that is porous and does not collapse on cooling. Even unleavened bread has a porous structure, but the incorporation of carbon dioxide increases the phase volume of gas in the final product.

Baked foams are easily compressible, and the pores provide crack initiation points during chewing. The material properties of the foam walls are water dependent, so bread has a higher breaking strain than extruded dry snacks. The latter, when exposed to water in saliva, collapse and melt in the mouth. The physics of solid foams has been modeled extensively, and the behavior of edible foams is similar (Attenburrow et al. 1989).

2.1.2.4. Melting structures. Melting structures comprise materials structured by crystals or sugar glasses, and include sweets and confectionary, ice cream, and chocolate. Chocolate is a continuous network of fat crystals, in which are embedded the hard particles of sugar crystals and milk solids. The melting profile of cocoa butter means that chocolate is a brittle solid at room temperature; thus, it is easily fractured. All crystals melt at mouth temperature, and a cream emulsion forms with saliva.

Ice cream is a whipped cream in which the continuous water phase is frozen. Static freezing produces dendritic ice, so the product can be hard and crunchy. Modern technology controls the ice crystal size and shape by crystallizing under shear, to produce spherical ice crystals and reduced air cell size. The net effect is faster collapse of the structure in the mouth and a greater perception of creaminess. This is one of the first cases where understanding the requirements of mouth action has allowed the systematic design of a preferred structure.

2.1.3. In vivo techniques. Oral processing, and in vivo techniques for measuring it, has been reviewed previously (for example, Chen 2009, Spyropoulos et al. 2011). Researchers have measured mouthful size (Hiiemae et al. 1996), oral shear rates (Nicosia & Robbins 2001, Shama & Sherman 1973), force applied during mastication and number of chews (Bellisle et al. 2000, Ioakimidis et al. 2011), and bolus formation and swallowing; however, all vary from person to person and as a function of the food being consumed (its viscosity, mechanical strength, etc.). Videofluorography (Hiiemae & Palmer 1999, Mioche et al. 2002), ultrasound (de Wijk et al. 2006), and functional magnetic resonance imaging (fMRI) (Felton et al. 2007) have allowed the processes occurring during oral manipulation to be visualized, and video rate endoscopy can be used to consider the deposition behavior of foods (Adams et al. 2007, Pivk et al. 2008, Watson et al. 2002); however, studies on the normal population are rare, with the majority coming from medical research.

2.1.4. In vitro models. In vitro models offer several advantages over in vivo studies, mainly due to their reduced cost, lower requirements in terms of time and labor, and absence of ethical approval constraints. Although they can be relatively accurate and reproducible, in vitro models should not be regarded as replacements for in vivo studies, but rather as complementary techniques (Guerra et al. 2012).

Several authors have attempted to understand the processes that occur during oral processing of foods. Correlations between instrumental measurements and sensory perception can give a good indication of the sort of forces experienced in the mouth. For example, a correlation was observed by Friedman et al. (1963) between their double compression texture profile analysis and sensory perception of numerous texture attributes. Similarly, multiple authors, for example, Shama & Sherman (1973a,b), have correlated bulk rheology to the sensory perception of thickness, and Kokini (1987) correlated thin film rheology and measures of friction coefficient (often termed tribology) to perception of creaminess and thickness. Furthermore, Malone et al. (2003) investigated tribological and sensory data for a series of oil-in-water emulsions, indicating a good relationship between the instrumental data and sensory properties of fattiness and smoothness.

In their dynamic mouth process model, Hutchings & Lillford (1988) take account of the structure of the food (mechanical or rheological behavior), the degree of lubrication, and the effect that these properties of the food have on oral processing time until swallowing occurs.

Although these models of oral processing are simplistic and variations are observed between individuals and the structure of the food itself (shears experienced tend to be food specific, due to the variations in structure), they are moving in the right direction for understanding mastication. More complex models, taking account of the physical (e.g., size, shape, deformability, temperature) and chemical (e.g., salts, enzymes) environment of the mouth, and multiple methods of deformation (mimicking chewing, sliding of the tongue, etc.) might be appropriate ways to progress our understanding.

2.2. Food Structure Design for Functionality in the Stomach

In this section, we detail the anatomy of and the processes occurring in the stomach, the design of foods for functionality in the stomach, and the in vivo methods and in vitro models used to study and model, respectively, the processes occurring in this organ.

2.2.1. The processes occurring in the stomach. Following the mouth, the stomach is the next process that food encounters during human digestion (see **Figure 1**). The stomach functions as a storage vessel in which food that arrives from the mouth is further broken down and mixed with digestive juices, containing gastric acid, bile salts, and digestive enzymes, secreted by the gastric glands. The resulting mixture of food and gastric juices is called chyme, a slurry of varied rheological properties, consisting of aqueous solutions, lipid phases, and solid particulates (Widmaier et al. 2006). The stomach's storage function is aided by its flexibility: From an initially resting (fasted state) volume of 25 mL (Vertzoni et al. 2005), it can expand to accommodate large volumes of food (1.5–4.0 L) (Kong & Singh 2008). Anatomically, the stomach is divided into four major sections: fundus, body, antrum, and pylorus (Widmaier et al. 2006). The proximal part of the stomach, fundus and body, mainly acts as the reservoir for undigested material, whereas the function of the antrum (distal stomach) is as a grinder-mixer-siever-pump function.

Stomach motility during the fasting phase is characterized by a cyclic contractive pattern, whereas in the fed phase muscle contractions become continuous, moving (with propagation velocities that average 2.5 mm/s) food from the top to the pylorus, which contracts, causing the chyme to be propelled back into the stomach's main body via retropulsion (Kong & Singh 2008; Pal et al. 2007). Retropulsion is responsible for drastic mixing and emulsifying the food with gastric juices, causing grinding and rubbing between food particulates and/or the stomach wall. The current literature suggests that contraction forces range from 0.2 N (Camilleri & Prather 1994) to 1.89 N (Kamba et al. 2000, 2001), depending on the stomach's fasting or fed state.

Motility in the stomach is not only fundamental for mixing but also controls the passage of chyme into the intestine. The residence time of food inside the stomach depends on its composition and physical properties (Kong & Singh 2008): Liquids are located in the antrum, whereas solid particles and lipids are mainly placed in the body of the stomach (Schulze 2006); the stomach acts as a sieve where liquid and small particles leave more quickly than larger ones. In healthy individuals, the half-emptying time for non-nutrient liquids is approximately 20 minutes (Camilleri 2006). In contrast, solids are retained in the stomach for further processing and are only emptied through the pylorus when reduced to a particle size of $\leq$2 mm (Thomas 2006). Gastric emptying into the intestine is regulated in response to the nature of duodenal contents and is influenced by several factors including the volume, consistency, and fat content. Complete gastric emptying of solids usually takes place after 3–4 hours (Kong & Singh 2008).

2.2.2. Food structures and interactions. Structural design of foods for specific functionalities in the stomach has mainly been focusing on two areas: (*a*) encapsulation and release and (*b*) appetite control/satiety.

The main role of the encapsulating structure, with regards to the human stomach, is to protect its encapsulated material to deliver it further down the GI tract (McClements & Li 2010). Alginate is an excellent candidate as it will create gel networks that, under highly acidic conditions (pH $\sim$ 2 and lower), will tend to shrink, creating highly insoluble structures (George & Abraham 2006). Therefore, it is expected that under the pH conditions typically encountered in the stomach during digestion (pH $\sim$ 1.2), release from an alginate matrix will be inhibited (George & Abraham 2006), while the encapsulated material will be shielded from exposure to the potentially destructive stomach conditions (e.g., acidity). Subsequent transport of the acidic chyme to the small intestine, where neutralization of the previously low pH conditions occurs, will result in the breakdown of the alginate encapsulant and the eventual release of its content(s) (George & Abraham 2006).

The rheological properties of digested food within the GI tract are crucial in determining motility and transit time. Gastric emptying and nutrient absorption are strongly delayed when chyme viscosity is increased (e.g., soluble dietary fibers) (Schneeman 1998). Furthermore, some hydrocolloids can form acid gels (Dettmar et al. 2011, Norton et al. 2011). This might have beneficial effects for appetite regulation, as is discussed later in the review (see Section 3.2). As pH conditions in the stomach can vary, acid gelation can become problematic, so gelation through ionic cross-linking could be considered instead (Dettmar et al. 2011). However, food structures formulated with such types of hydrocolloids and in the presence of cross-linking ion(s) could be faced with almost unavoidable stability issues (gelation prior to consumption) during storage. An alternative novel approach would be to formulate foods containing fluid gel systems (concentrated dispersions of gel particles) that can help to avoid stability issues during storage and will further structure under acidic conditions.

2.2.3. In vivo techniques. Several different techniques have been developed to study digestive processes occurring in the stomach. These range from direct (invasive and noninvasive) to indirect methods, usually applied to measure or estimate food processing in the stomach, food structure disintegration during digestion, gastric motility, gastric emptying, and accommodation. Direct methods were developed to measure stomach motility and accommodation, but their invasive nature, besides causing a level of discomfort, has been argued to disrupt normal physiology (Choe et al. 2001, De Schepper et al. 2004). Noninvasive direct methods (Simonian et al. 2004) include MRI, which has been developed for the acquisition of rapid sequential scans and has been used to monitor gastric motility and emptying (see **Figure 2**), but also to estimate the size of food particulates in the stomach and the viscosity of stomach contents (Lobo et al. 2009, Marciani et al. 2001). However, MRI has several limitations, including expense and the supine positioning of the subjects during scanning that could interfere with the normal (upright seating positioning) digestive function (Jones et al. 2006). Finally, indirect methods, including blood and breath testing, have also been used for studying gastric emptying of digested foods (Marciani et al. 2001, Parkman et al. 2004).

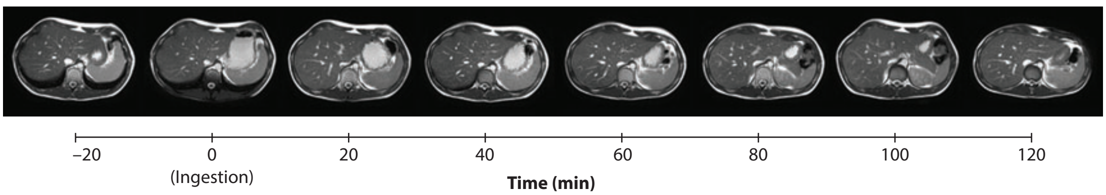

Figure 2

Sequential echo-planar magnetic resonance imaging scans (before and after ingestion of a drink) used to evaluate gastric emptying kinetics. Ingestion takes place at 0 min. Figure reprinted from Lobo et al. (2009), with permission from Elsevier, copyright 2009.

2.2.4. In vitro models. Current static in vitro models do not mimic digestive physical/physiological processes and do not take into consideration food microstructure or physicochemical characteristics. They have been mainly utilized to measure release of actives and nutrients under well-controlled (usually constant) conditions (e.g., pH, temperature) (see, e.g., Nagah & Seal 2005). Dynamic GI tract models include the TNO intestinal model (TIM) and the dynamic gastric model (DGM). The TIM has been used to study food disintegration and release of nutrients and/or actives from model food structures under various physiological GI conditions (Souliman et al. 2007, Yoo & Chen 2006). The DGM in vitro system has been used to investigate several different gastric phenomena and food structure-stomach interactions (Vardakou et al. 2011) and, more recently, the survival of commercial probiotic strains in the human upper GI tract (Lo Curto et al. 2011).

Several computational models have been developed to simulate the stomach's motility patterns and the fluid dynamics of gastric contents, and to evaluate the stresses/forces experienced by foods, as well as other phenomena occurring during digestion (Pal et al. 2007, Schulze 2006). More recently a three-dimensional computational fluid dynamics model was developed and used to investigate the flow patterns occurring in the stomach as a function of the viscosity of gastric contents, the relationship between the disintegration rates of food structures, and the dynamics of gastric contents during digestion (Ferrua et al. 2011, Ferrua & Singh 2010).

2.3. Food Structure Design for Functionality in the Small and Large Intestines

In this section, the anatomy and processes occurring in both the small and large intestines are discussed, in addition to our current, if limited, knowledge of the interactions between food structures and the intestines. The in vivo and in vitro techniques used to study and understand the processes occurring in the intestines are also described.

2.3.1. The processes occurring in the intestines. As food exits the stomach it enters the duodenum (first section of the small intestine), where the chyme is mixed with bile and pancreatic secretions. It is then passed into the small jejunum (middle section of the small intestine), where many of the digestive reactions occur, such as the breakdown of proteins to amino acids and the breakdown of carbohydrates to oligo- and monosaccharides, followed by absorption of both macro- and micronutrients (see **Figure 1**). Only a small amount of digestion occurs in the stomach (approximately 10%), although there is a significant amount of structural breakdown; the state of the food exiting the stomach (e.g., structured/liquid state and viscosity) has an influence on the behavior in the small intestine.

The movement of the walls of the intestine is responsible for the mixing of chyme with secretions, and it allows molecules to move to the walls for absorption into the blood stream. There are two types of wall movement:

- Segmentation: This occurs when the tube becomes full. This is the mixing process that allows the nutrients to be released and absorbed.
- Peristalsis: This is responsible for movement along the tube. It is controlled by the mass of material in the system and a feedback signal to the brain that tells the system that the nutrients have been absorbed.

The food is then passed into the large intestine (bowel or colon). Here, the remaining water is absorbed, and the unusable food matter is passed through the body. Bacteria are key to what happens in the large intestine; they cause breakdown of materials that are nondigestible by the human process, and thus release key ingredients for the health of the host (for example short-chain fatty acids). Controlling the mircoflora is claimed to have beneficial effects on health.

2.3.2. Food structures and interactions. Little is known about the interaction between food structure and the digestive processes occurring in the intestine. A few studies have suggested that water-soluble fiber (such as guar, cellulose, or pectin) decreases the reabsorption of bile, and so lowers cholesterol, in addition to slowing down carbohydrate digestion. It is argued to be as a result of the viscosity of these fibers, which slows the mixing process. Similar results reported for the different fibers support this mechanism.

Water-insoluble fiber also collects water and binds/entraps other material to form exit (stool) mass. The effect of bran has been studied (McIntyre et al. 1997). The authors compared particle size effects by comparing as-obtained bran with grinding the bran into a powder. They also compared performance with plastic particles of the same size. This work has shown that not only is the binding of water important, but also the particle size is important in the mechanism of gut transit. The comparison with plastic particles suggests that secretion is caused by the presence of the particles, which increases the rate of transit. Furthermore, it has also been argued that particles clean up the large intestine, reducing the occurrence of problems caused by chemicals sitting in the system, for example iron ions that are linked to cancer (Williams et al. 2011).

Although hydrocolloid gels have been investigated for functionality in the stomach (see Section 2.2.2), their use for controlling absorption and transit in the intestine has received little, or no, attention. However, there have been investigations into the use of gels for controlled release of medication (Gourtsoyiannis et al. 2006). This could be used in the future to modify digestion and/or absorption of both macro- and micronutrients (see **Figure 3**).

2.3.3. In vivo techniques. In addition to visualizing processes occurring in the stomach, MRI has also been used to visualize transit of food through the intestines (Gourtsoyiannis et al. 2006). However, as yet, this technique does not have the time or spatial resolution to measure structural changes and molecular release in flow within the intestines. As the technique develops, this will become more likely in the future, resulting in a rapid increase in the understanding of the healthy intestine and of how food structures can be used to modulate food intake or nutrient absorption in the healthy population.

2.3.4. In vitro models. Several physical and mathematical models of the intestine have been developed. These are often for drug applications, but the principle of absorption can be translated to foods and food structures. Recently, work has been carried out in several groups to build a physical model of the human intestine (Nahar et al. 2012, Tharakan et al. 2010). However, these models use an inert membrane; thus, the extraction process is not realistic. It is highly likely that the next stage of model development will be to use living membranes. This should be achievable using pig intestine with the aqueous medium that is controlled to allow the cells to live for several hours.

2.4. Future Perspectives

There is a need to understand the processes occurring during digestion in more detail. A major scientific hurdle preventing advancement of this area is the lack of measurement techniques available. This means that the GI tract is often treated as a black box, with researchers measuring what goes in and what comes out and then trying to determine what has happened in between. As measurement techniques improve, it may become possible to measure structural changes to the food (e.g., kinetics of food microstructure disintegration) occurring during processing in the body. There is also a need for a multidisciplinary approach: learnings and methodologies used in medical/pharmaceutical, personal care, or agrochemical applications should be considered within the foods arena. Additionally, further research into in vitro/in vivo correlations using well-defined

Figure 3

Image of the small bowel along its entire length. Figure reprinted with permission from Gourtsoyiannis et al. (2006), with permission from Elsevier, copyright 2006.

model food structures is required, to improve the representative nature of existing in vitro models of the mouth, stomach, and intestines, as well as to develop new ones.

In the future, foods will be designed that provide specific performance in the GI tract, for example binding or targeted release. Mechanisms that foods will be required to address include (*a*) pressure-controlled structural breakdown/release, (*b*) time release structures (that match the breakdown rate for the transit time in the human GI tract), (*c*) osmotically controlled structures, (*d*) polysaccharide-based structures using nonstarch polysaccharides that are fermented so as to trigger breakdown and release, (*e*) bioadhesive systems for specific binding to parts of the intestinal wall, or even (*f*) structures with controlled swelling or dehydration properties to act as cleaning agents.

Furthermore, if we wish to fully develop and exploit this area, we need to understand, measure, or take account of the variability between individuals. Additionally, the challenge is to provide individually designed nutrition. This will require much more detail on genetics, which is currently a highly active research area within molecular biology. Finally, it cannot be forgotten that the foods being designed are intended to be consumed; thus, research is needed to establish consumers' attitudes toward novel functional foods designed for added benefits over and above traditional products (Norton 2013).

3. CASE STUDIES

In this section we focus on three examples of groups of consumers who have differing nutritional or health needs: elderly, obese, and athletes.

3.1. Elderly: Maximizing Sensory Perception and Overcoming Physiological Difficulties

As a result of the worldwide aging population (typically as a result of rising life expectancy) the number of elderly people is increasing; older adults have specific dietary needs that might be addressed with food formulation engineering.

The main nutritional concern for the elderly is the decline in food intake and loss of motivation to eat, which often result in weight loss or undernutrition (malnutrition), and may in turn result in poor overall health or the development of chronic diseases (Brownie 2006, Donini et al. 2003). There are numerous social (e.g., poverty or isolation), psychological (e.g., depression or dementia), and physiological (e.g., changes in chewing and swallowing behavior, sensory function, or GI tract function) reasons why the elderly might become malnourished. It is increasingly more important to consider how these factors, particularly the physical factors, might be addressed with changes to food structure.

Taste disorders commonly occur in the elderly, including hypogeusia (diminished sensitivity to taste) and dysgeusia (distortion of normal taste) (Schiffman 2008), possibly as a result of taste buds/papillae inactivity (altered functioning of ion channels) (Schiffman & Graham 2000). There are considerable differences between young and elderly subjects in the both sensory perception and pleasantness of food flavors (de Graaf et al. 1994). Taste is important for many reasons, including the ability to identify the safety of the food (toxic substances are often bitter), but it is also an indicator of nutritional value (learned associations between taste and post-ingestive effects, for example between sweetness and energy), which modulates meal size and energy intake.

Similarly, olfactory function (both detection and discrimination) declines in the elderly, often reducing intake of foods (Schiffman & Warwick 1993). Inability to taste or smell food is likely to reduce the pleasure associated with eating, reduce food intake or change the types of foods consumed, and possibly lead to malnutrition. As such, enhancing flavor within foods could have beneficial effects for the elderly (Schiffman & Warwick 1993). Additionally, having a burst of flavor (for example, by utilizing double emulsion technology or by encapsulating for controlled flavor release) could have beneficial effects.

Elderly people often have poor dentition or ill-fitting dentures, decreased masticatory performance (lower muscle activity per chew and more chewing cycles before swallowing) (Mioche et al. 2004), and altered salivary secretion (half the flow rate in 70 year olds than 30 year olds) (Chen 2009). In addition, it is common for the elderly to have dysphagia, the difficultly or inability to swallow, which can often lead to dehydration as fluid intake is reduced. Thickeners are often recommended to increase viscosity and facilitate swallowing as a more cohesive bolus is formed, which reduces the speed of the flow of the liquid through the GI tract (Forster et al. 2011). However, a decrease in perceived flavor intensity (of both odor and taste) is often seen with increasing viscosity (Christensen 1980, Hollowood et al. 2002, Kokini et al. 1982, Moskowitz & Arabie 1970, Pangborn & Szczesniak 1974). The effect on perception is dependent on the polysaccharide used to thicken the solution (Mälkki et al. 1993) and polymer concentration, where the most dramatic effect on flavor is observed above c^* (coil overlap concentration) (Baines & Morris 1987, Cook et al. 2002), possibly as a result of efficiency of mixing in the mouth (Ferry et al. 2006). The suppression of taste is very important when considering thickening solutions for the elderly as they are likely to already suffer from a loss of taste or olfactory function; thus, the type of thickener used, the concentration, and the combination of tastants and aroma compounds should be given consideration.

The elderly are typically less active and their metabolism also slows, meaning that their energy requirements decrease. A reduction in energy intake is also attributed to slower gastric emptying and altered hormonal responses. The release of hormones involved in feeding has been shown to change with age, including increased activity of cholecystokinin (increasing satiety and decreasing food intake), and some evidence of decreased activity of ghrelin (which stimulates feeding) and leptin (suppresses appetite and food intake) (Chapman 2004). Changes to the GI tract might also impact nutrient absorption and metabolism (either nutrient bioavailability or reduced enzymatic capacity for nutrient absorption) (Brownie 2006). As we become older, our bodies are less efficient at absorbing and utilizing nutrients, meaning that our nutrient requirements increase. As such, it is important that the elderly consume a nutrient-rich diet. Deficiencies in nutrient bioavailability could be overcome by encapsulation and controlled or targeted (within particular parts of the GI tract) release of nutrients or bioactives (see Section 2.2.2).

Foods for the elderly should be designed that take into account all these factors (reductions in taste or smell; difficulties chewing, swallowing, and digesting; and increased requirements of many macro- and micronutrients). To compensate for the lack of appetite or reduced intake, foods should be energy dense, provide adequate nutrients, and most importantly be palatable.

3.2. Obese: Nutrient Reduction and Increased Satiety

It is well known that the prevalence of overweight (BMI 25–30) and obesity (BMI 30+), and the related health issues, is increasing (as a result of overnutrition). Food products can be designed that are reduced in energy (for example, reductions in fat or sugar) or that have positive effects on appetite, by increasing within-meal satiation and postmeal satiety (and consequently having effects on energy regulation), both of which could have beneficial effects for weight reduction and the prevalence of obesity.

Different sensory and/or hedonic responses to taste and flavor might also exist between lean and obese people, which could have effects on the taste of foods formulated for this group. Hedonic responses to fat have been shown to be negatively correlated with the degree of overweight: obese individuals have been shown to prefer high-fat (>34% lipid) foods, whereas normal-weight people prefer foods containing ∼20% lipid (Bartoshuk et al. 2006, Drewnowski et al. 1985). Processing can be adapted in reduced-fat foods to change the textural properties, often resulting in products that are perceived as creamier (Kaufmann & Palzer 2011) (an attribute typically associated with high-fat products).

One well-known option for decreasing the energy density of foods is the use of emulsions, where part of the fat is substituted with water in the form of droplets. An extension of this is double emulsions, whereby the dispersed droplets contain smaller droplets, which are thought to be hidden from the consumer during oral processing. In addition to fat reduction, double emulsions could have added advantages, for example to delivering active compounds to the gut without being detected (for example, as bitter) in the mouth. The use of emulsions for fat reduction and prevention of obesity has been extensively reviewed previously (Norton et al. 2007, Norton & Norton 2010).

The nature of the emulsion can affect how it is broken down within the GI tract, affecting satiety signals, stomach emptying, and nutrient uptake. For example, emulsion droplet size, stability, and interfacial composition will affect the ability for lipase (the enzyme responsible for the breakdown of fats in food) to bind to the emulsion interface, in turn having an effect on lipid digestion (Golding

& Wooster 2010); there appears to be a relationship between droplet size, surface area, and degree of lipolysis and gastric emptying.

Foods can be formulated containing structures (e.g., certain hydrocolloids) known to bind with lipases and/or bile acids, reducing their concentration during digestion in the stomach and intestine (McClements & Li 2010). Consequently, the emulsification process of lipids in the stomach is less effective, leading to a lower interfacial area available for enzymatic activity and lipid digestion (Brownlee 2011, Guillon & Champ 2000, Harris & Smith 2006, Kahlon et al. 2005). Alternatively, coating lipid droplets can create an effective physical barrier against the action of lipases and/or bile acids (McClements & Li 2010). Coverage of lipids with protein-carbohydrate conjugates (Lesmes & McClements 2012), layer-by-layer structures (Mun et al. 2006), and encapsulation within core-shell structures (Hoad et al. 2011) are some of the approaches that have shown encouraging results in terms of delaying lipid digestion.

The ingestion of hydrocolloids, or the increase of viscosity of the stomach contents, could also have benefits for appetite, increasing gastric distention (Hoad et al. 2004), reducing energy intake (Paxman et al. 2008, Pelkman et al. 2007), and decreasing hunger and increasing fullness (Hoad et al. 2004, Peters et al. 2011, Solah et al. 2010). Acid gelation (see Section 2.2.2) could be used to affect hormone signaling, slow gastric emptying, increased feelings of fullness, and with controlled energy release could influence satiety, and as such be beneficial for tackling obesity (Norton et al. 2011).

Foods that have reduced energy density, retard lipid digestion, or slow gastric emptying, while tasting creamy, are likely to have a positive effect on this group.

3.3. Athletes: Cognitive and Physical Performance

Dietary carbohydrates play a critical role in the provision of energy and in the maintenance of normal blood sugar (glucose) concentrations, the latter being an important determinant of cognitive and physical performance (Blaak et al. 2012, Burke et al. 2011). Nonetheless, the act of consuming carbohydrates, which results in increases in blood glucose concentrations, represents a considerable challenge to the maintenance of normal blood glucose levels (Wasserman 2009). Tighter glycemic control, characterized by a reduced, but more sustained, postprandial glucose response to carbohydrate ingestion, may be beneficial for aspects of cognitive function (Blaak et al. 2012, Nilsson et al. 2009). Furthermore, pre-exercise ingestion of high-glycemic-index carbohydrates has been considered to compromise exercise performance due to a rebound effect on blood glucose levels, where glucose levels switch from very high concentrations to below normal, thus compromising blood energy levels (a phenomenon known as rebound hypoglycemia) (Jeukendrup & Killer 2010). Thus, methods that control carbohydrate release from foods and minimize changes in blood glucose may be beneficial for cognitive function and athletic performance optimization (Burke et al. 2011, Jeukendrup & Killer 2010, Nilsson et al. 2009).

The delivery of ingested carbohydrates to the circulation ultimately requires transit through and digestion in the mouth, stomach, and small intestine prior to absorption of component monosaccharides in the small intestine (see **Figure 1**). Carbohydrate digestion is under enzymatic control [salivary and pancreatic α-amylase (mouth/stomach and duodenum, respectively); various disaccharidases (small intestine)], and therefore protection from, or slowing of, enzyme action could delay digestion, absorption, and energy delivery. For example, the enzymatic conversion of the disaccharide sucrose to isomaltulose, a commercially available functional carbohydrate, reduces digestion, absorption, and subsequent glycemic and insulinemic responses (Goda & Hosoya 1983, Lina et al. 2002, van Can et al. 2009). Furthermore, the encapsulation of active ingredients within the core of nano- or microcapsules or within different layers of multi-shell capsules formed from food-grade hydrocolloids can be used to control the release of nutrients and bioactives in food formulations (Augustin & Hemar 2009). In the case of carbohydrates, such an approach may delay exposure of starch or sugars to digestives enzymes, and thus slow energy release.

As mentioned in Section 2.2.2, another promising area of research is acid-gelation or self-structuring of biopolymers, which in addition to delaying gastric emptying, could also delay energy release. In this respect, focus has been placed on the efficacy of alginates, which undergo gel formation through acidification or divalent ion bonding (Georg Jensen et al. 2012). Furthermore, our preliminary work indicates that the acid (and ion)-sensitive hydrocolloid gellan gum may be a viable approach to control glucose release from ingested nutritional products (J.E. Norton, T.B. Mills & G.A. Wallis, unpublished observations; see **Figure 4**). Such approaches, which can be used to create relatively low viscosity formulations, are particularly suited to sport and energy products, where most frequently sugars (such as glucose or sucrose) are provided in beverage format, and therefore technologies that are compatible with liquid or soft-food delivery systems are preferable.

The efficacy of such technologies should be evaluated in the context of their proposed use. For example, for athletes prolonged energy release may be most appropriate for pre-event fueling in situations where exogenous energy sources are not freely available during the event itself (Burke et al. 2011). Nonetheless, approaches that can minimize glycemic perturbations from carbohydrate ingestion and provide a sustained release of energy to the body certainly have the potential to positively impact aspects of cognitive and physical performance.

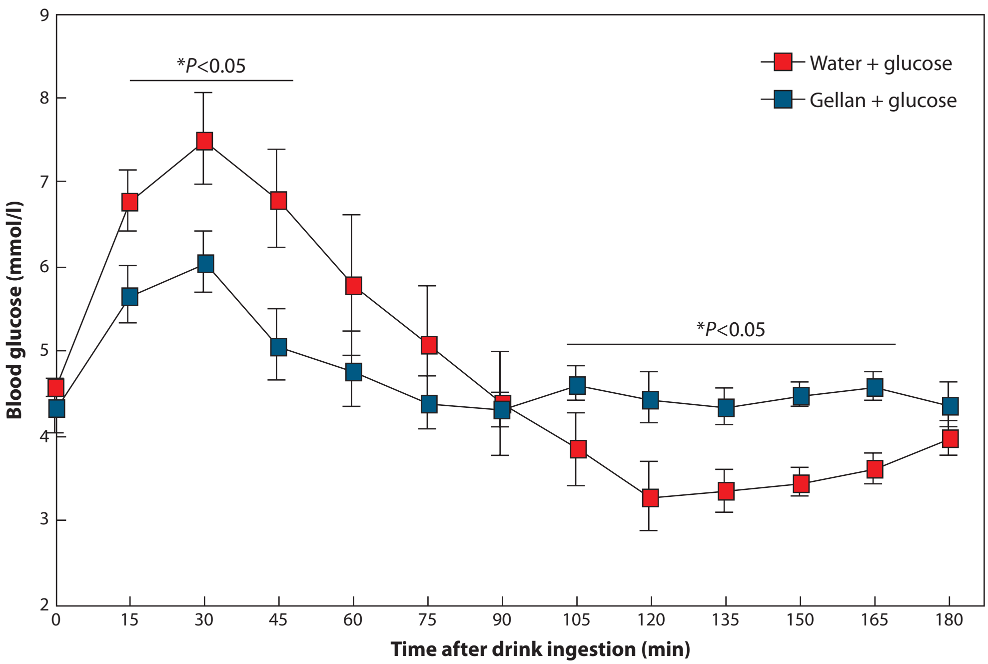

Figure 4

Mean (± standard error mean) blood glucose responses to consuming 25% glucose versus 25% glucose + 0.5% gellan gum beverages [$n = 8$ (healthy men aged 20–35 years)]. Note statistically significant blunting of postprandial surges in blood glucose and near absence of rebound drops in blood glucose levels with the gellan-containing drink.

4. CONCLUSIONS AND FUTURE OUTLOOK

Foods are no longer likely to be designed exclusively to provide specific flavors, tastes, or textures but are also designed to provide specific functionalities within the human body, over and above simple nutrition. By transferring the knowledge outlined above, it will be possible to provide more nutritious food that has additional functionality within particular parts of the GI tract. As such, there is a need to more fully understand the processes occurring in the body (specifically the mouth, stomach, and intestines) during digestion and the interaction between food structure and these processes. Understanding will expand with progress in both in vivo techniques and in vitro models but will require shared learnings from multiple disciplines. Being aware of the nutritional needs of individual (or groups of) consumers (as a result of age, health concerns, or amount of physical activity being undertaken, for example) when designing food structures is also likely to become increasingly more important. Eating is a pleasurable process, but foods of the future will be required to provide much more, in terms of functionality for health and nutrition.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

LITERATURE CITED

Adams S, Singleton S, Juskaitis R, Wilson T. 2007. In-vivo visualisation of mouth–material interactions by video rate endoscopy. *Food Hydrocoll.* 21:986–95

Atkins A. 2009. *The Science and Engineering of Cutting*. Oxford: Butterworth-Heinemann

Attenburrow GE, Goodband RM, Taylor LJ, Lillford PJ. 1989. Structure, mechanics and texture of a food sponge. *J. Cereal Sci.* 29:61–70

Augustin MA, Hemar Y. 2009. Nano- and micro-structured assemblies for encapsulation of food ingredients. *Chem. Soc. Rev.* 38:902–12

Baines ZV, Morris ER. 1987. Flavour/taste perception in thickened systems: the effect of guar gum above and below c^*. *Food Hydrocoll.* 1:197–205

Bartoshuk LM, Duffy VB, Hayes JE, Moskowitz HR, Snyder DJ. 2006. Psychophysics of sweet and fat perception in obesity: problems, solutions and new perspectives. *Philos. Trans. R. Soc. B.* 361:1137–48

Bellisle F, Guy-Grand B, Le Magnen J. 2000. Chewing and swallowing as indices of the stimulation to eat during meals in humans: effects revealed by the edogram method and video recordings. *Neurosci. Biobehav. Rev.* 24:223–28

Blaak EE, Antoine JM, Benton D, Bjorck I, Bozzetto L, et al. 2012. Impact of postprandial glycemia on health and prevention of disease. *Obes. Rev.* 13:923–84

Brownie S. 2006. Why are elderly individuals at risk of nutritional deficiency? *Int. J. Nurs. Pract.* 12:110–18

Brownlee IA. 2011. The physiological roles of dietary fibre. *Food Hydrocoll.* 25:238–50

Burke LM, Hawley JA, Wong SH, Jeukendrup AE. 2011. Carbohydrates for training and competition. *J. Sports Sci.* 27:S17–27

Camilleri M. 2006. Integrated upper gastrointestinal response to food intake. *Gastroenterology* 131:640–58

Camilleri M, Prather CM. 1994. Axial forces during gastric emptying in health and models of disease. *Dig. Dis. Sci.* 39:14S–17S

Chapman IM. 2004. Endocrinology of anorexia of ageing. *Best Pract. Res. Clin. Endocrinol. Metab.* 18:437–52

Chen J. 2009. Food oral processing—a review. *Food Hydrocoll.* 23:1–25

Choe SY, Neudeck BL, Welage LS, Amidon G, Barnett JL, Amidon GL. 2001. Novel method to assess gastric emptying in humans: the pellet gastric emptying test. *Eur. J. Pharm. Sci.* 14:347–53

Christensen C. 1980. Effects of solution viscosity on perceived saltiness and sweetness. *Percept. Psychophys.* 28:347–53

Cook DJ, Hollowood TA, Linforth RST, Taylor AJ. 2002. Perception of taste intensity in solutions of random-coil polysaccharides above and below *c**. *Food Qual. Prefer.* 13:473–80
de Graaf C, Polet P, van Staveren WA. 1994. Sensory perception and pleasantness of food flavors in elderly subjects. *J. Gerontol.* 49:P93–99
De Schepper HU, Cremonini F, Chitkara D, Camilleri M. 2004. Assessment of gastric accommodation: overview and evaluation of current methods. *Neurogastroenterol. Motil.* 16:275–85
de Wijk RA, Wulfert F, Prinz JF. 2006. Oral processing assessed by M-mode ultrasound imaging varies with food attribute. *Physiol. Behav.* 89:15–21
Dettmar PW, Strugala V, Richardson JC. 2011. The key role alginates play in health. *Food Hydrocoll.* 25:263–66
Donini LM, Savina C, Cannella C. 2003. Eating habits and appetite control in the elderly: the anorexia of aging. *Int. Psychogeriatr.* 15:73–87
Drewnowski A, Brunzell JD, Sande K, Iverius PH, Greenwood MRC. 1985. Sweet tooth reconsidered: taste responsiveness in human obesity. *Physiol. Behav.* 35:617–22
Felton SM, Gaige TA, Reese TG, Wedeen VJ, Gilbert RJ. 2007. Mechanical basis for lingual deformation during the propulsive phase of swallowing as determined by phase-contrast magnetic resonance imaging. *J. Appl. Physiol.* 103:255–65
Ferrua MJ, Kong F, Singh RP. 2011. Computational modeling of gastric digestion and the role of food material properties. *Trends Food Sci. Technol.* 22:480–91
Ferrua MJ, Singh RP. 2010. Modeling the fluid dynamics in a human stomach to gain insight of food digestion. *J. Food Sci.* 75:R151–62
Ferry AL, Hort J, Mitchell JR, Cook DJ, Lagarrigue S, Valles Pamies B. 2006. Viscosity and flavour perception: Why is starch different from hydrocolloids? *Food Hydrocoll.* 20:855–62
Forster A, Samaras N, Gold G, Samaras D. 2011. Oropharyngeal dysphagia in older adults: a review. *Eur. Geriatr. Med.* 2:356–62
Friedman HH, Whitney JE, Szczesniak AS. 1963. The texturometer—a new instrument for objective texture measurement. *J. Food Sci.* 28:390–96
Georg Jensen M, Pedersen C, Kristensen M, Frost G, Astrup A. 2012. Review: efficacy of alginate supplementation in relation to appetite regulation and metabolic risk factors: evidence from animal and human studies. *Obes. Rev.* 14:129–44
George M, Abraham TE. 2006. Polyionic hydrocolloids for the intestinal delivery of protein drugs: alginate and chitosan—a review. *J. Control. Release* 114:1–14
Goda T, Hosoya N. 1983. Hydrolysis of palatinose by rat intestinal sucrase isomaltase complex. *Food Nutr. (Roma)* 36:169–73
Golding M, Wooster TJ. 2010. The influence of emulsion structure and stability on lipid digestion. *Curr. Opin. Colloid Interface Sci.* 15:90–101
Gourtsoyiannis NC, Papanikolaou N, Karantanas A. 2006. Magnetic resonance imaging evaluation of small intestinal Crohn's disease. *Best Pract. Res. Clin. Gastroenterol.* 20:137–56
Guerra A, Etienne-Mesmin L, Livrelli V, Denis S, Blanquet-Diot S, Alric M. 2012. Relevance and challenges in modeling human gastric and small intestinal digestion. *Trends Biotechnol.* 30:591–600
Guillon F, Champ M. 2000. Structural and physical properties of dietary fibres, and consequences of processing on human physiology. *Food Res. Int.* 33:233–45
Harris PJ, Smith BG. 2006. Plant cell walls and cell-wall polysaccharides: structures, properties and uses in food products. *Int. J. Food Sci. Technol.* 41:129–43
Hiiemae K, Heath MR, Heath G, Kazazoglu E, Murray J, et al. 1996. Natural bites, food consistency and feeding behaviour in man. *Arch. Oral Biol.* 41:175–89
Hiiemae KM, Palmer JB. 1999. Food transport and bolus formation during complete feeding sequences on foods of different initial consistency. *Dysphagia* 14:31–42
Hoad C, Rayment P, Risse V, Cox E, Ciampi E, et al. 2011. Encapsulation of lipid by alginate beads reduces bio-accessibility: an in vivo 13C breath test and MRI study. *Food Hydrocoll.* 25:1190–200
Hoad CL, Rayment P, Spiller RC, Marciani L, de Celis Alonso B, et al. 2004. In vivo imaging of intragastric gelation and its effect on satiety in humans. *J. Nutr.* 134:2293–300
Hollowood TA, Linforth RST, Taylor AJ. 2002. The effect of viscosity on the perception of flavour. *Chem. Senses* 27:583–91

Hutchings JR, Lillford PJ. 1988. The perception of food texture. *J. Texture Stud.* 19:105–9

Ioakimidis I, Zandian M, Eriksson-Marklund L, Bergh C, Grigoriadis A, Södersten P. 2011. Description of chewing and food intake over the course of a meal. *Physiol. Behav.* 104:761–69

Jeukendrup AE, Killer SC. 2010. The myths surrounding pre-exercise carbohydrate feeding. *Ann. Nutr. Metab.* 57:18–25

Jones KL, O'Donovan DG, Hausken T, Russo A, Lei Y, Horowitz M. 2006. Effects of posture on gastric emptying, transpyloric flow and hunger after a glucose drink in healthy humans. *Dig. Dis. Sci.* 51:1331–38

Kahlon TS, Smith GE, Shao Q. 2005. In vitro binding of bile acids by kidney bean (*Phaseolus vulgaris*), black gram (*Vigna mungo*), bengal gram (*Cicer arietinum*) and moth bean (*Phaseolus aconitifolins*). *Food Chem.* 90:241–46

Kamba M, Seta Y, Kusai A, Ikeda M, Nishimura K. 2000. A unique dosage form to evaluate the mechanical destructive force in the gastrointestinal tract. *Int. J. Pharm.* 208:61–70

Kamba M, Seta Y, Kusai A, Nishimura K. 2001. Evaluation of the mechanical destructive force in the stomach of dog. *Int. J. Pharm.* 228:209–17

Kaufmann SFM, Palzer S. 2011. Food structure engineering for nutrition, health and wellness. *Proced. Food Sci.* 1:1479–86

Kokini JL. 1987. The physical basis of liquid food texture and texture-taste interactions. *J. Food Eng.* 6:51–81

Kokini JL, Bistany K, Poole M, Stier E. 1982. Use of mass transfer theory to predict viscosity-sweetness interactions of fructose and sucrose solutions containing tomato solids. *J. Texture Stud.* 13:187–200

Kong F, Singh RP. 2008. Disintegration of solid foods in human stomach. *J. Food Sci.* 73:R67–80

Lesmes U, McClements DJ. 2012. Controlling lipid digestibility: response of lipid droplets coated by β-lactoglobulin-dextran Maillard conjugates to simulated gastrointestinal conditions. *Food Hydrocoll.* 26:221–30

Lillford PJ. 2013. The physics of eating. See Norton et al. 2013, pp. 107–35

Lina BA, Jonke F, Kozsanowski G. 2002. Isomaltulose (Palatinose): a review of biological and toxicological studies. *Food Chem. Toxicol.* 40:375–81

Lo Curto A, Pitino I, Mandalari G, Dainty JR, Faulks RM, Wickham MSJ. 2011. Survival of probiotic lactobacilli in the upper gastrointestinal tract using an *in vitro* gastric model of digestion. *Food Microbiol.* 28:1359–66

Lobo DN, Hendry PO, Rodrigues G, Marciani L, Totman JJ, et al. 2009. Gastric emptying of three liquid oral preoperative metabolic preconditioning regimens measured by magnetic resonance imaging in healthy adult volunteers: a randomised double-blind, crossover study. *Clin. Nutr.* 28:636–41

Mälkki Y, Heiniö RL, Autio K. 1993. Influence of oat gum, guar gum and carboxymethyl cellulose on the perception of sweetness and flavour. *Food Hydrocolloids* 6:525–32

Malone ME, Appelqvist IAM, Norton IT. 2003. Oral behaviour of food hydrocolloids and emulsions. Part 1. Lubrication and deposition considerations. *Food Hydrocoll.* 17:763–73

Marciani L, Gowland PA, Fillery-Travis A, Manoj P, Wright J, et al. 2001. Assessment of antral grinding of a model solid meal with echo-planar imaging. *Am. J. Physiol.* 280:G844–49

McClements DJ, Li Y. 2010. Structured emulsion-based delivery systems: controlling the digestion and release of lipophilic food components. *Adv. Colloid Interface Sci.* 159:213–28

McIntyre A, Vincent RM, Perkins AC, Spiller RC. 1997. Effect of bran, ispaghula, and inert plastic particles on gastric emptying and small bowel transit in humans: the role of physical factors. *Gut* 40:223–37

Mioche L, Bourdiol P, Monier S, Martin J-F, Cormier D. 2004. Changes in jaw muscles activity with age: effects on food bolus properties. *Physiol. Behav.* 82:621–27

Mioche L, Hiiemae KM, Palmer JB. 2002. A postero-anterior videofluorographic study of the intra-oral management of food in man. *Arch. Oral Biol.* 47:267–80

Moskowitz HR, Arabie P. 1970. Taste intensity as a function of stimulus concentration and solvent viscosity. *J. Texture Stud.* 1:502–10

Mun S, Decker E, Park Y, Weiss J, McClements DJ. 2006. Influence of interfacial composition on digestibility of emulsified lipids: potential mechanism for Chitosan's ability to inhibit fat digestion. *Food Biophys.* 1:21–29

Nagah AM, Seal CJ. 2005. In vitro procedure to predict apparent antioxidant release from wholegrain foods measured using three different analytical methods. *J. Sci. Food Agric.* 85:1177–85

Nahar S, Jeelani SAK, Windhab EJ. 2012. Peristaltic flow characterization of a shear thinning fluid through an elastic tube by UVP. *Appl. Rheol.* 22:43941–49

Nicosia MA, Robbins J. 2001. The fluid mechanics of bolus ejection from the oral cavity. *J. Biomech.* 34:1537–44

Nilsson A, Radeborg K, Bjork I. 2009. Effects of differences in postprandial glycemia on cognitive functions in healthy middle-aged subjects. *Eur. J. Clin. Nutr.* 63:113–20

Norton AB, Cox PW, Spyropoulos F. 2011. Acid gelation of low acyl gellan gum relevant to self-structuring in the human stomach. *Food Hydrocoll.* 25:1105–11

Norton I, Moore S, Fryer P. 2007. Understanding food structuring and breakdown: engineering approaches to obesity. *Obes. Rev.* 8:83–88

Norton JE. 2013. Design of food structures for consumer acceptability. See Norton et al. 2013, pp. 253–80

Norton JE, Fryer PJ, Norton IT, eds. 2013. *Formulation Engineering of Foods.* Weinheim, Ger.: Wiley

Norton JE, Norton IT. 2010. Designer colloids—towards healthy everyday foods? *Soft Matter* 6:3735–42

Pal A, Brasseur J, Abrahamsson B. 2007. A stomach road or "Magenstrasse" for gastric emptying. *J. Biomech.* 40:1202–10

Pangborn RM, Szczesniak AS. 1974. Effect of hydrocolloids and viscosity on flavor and odour intensities of aromatic flavor compounds. *J. Texture Stud.* 4:467–82

Parkman HP, Hasler WL, Fisher RS. 2004. American Gastroenterological Association technical review on the diagnosis and treatment of gastroparesis. *Gastroenterology* 127:1592–622

Paxman JR, Richardson JC, Dettmar PW, Corfe BM. 2008. Daily ingestion of alginate reduces energy intake in free-living subjects. *Appetite* 51:713–19

Pelkman C, Navia JL, Miller AE, Pohle RJ. 2007. Novel calcium-gelled, alginate-pectin beverage reduced energy intake in nondieting overweight and obese women: interactions with dietary restraint status. *Am. J. Clin. Nutr.* 86:1595–602

Peters HPF, Koppert RJ, Boers HM, Strom A, Melnikov SM, et al. 2011. Dose-dependent suppression of hunger by a specific alginate in a low-viscosity drink formulation. *Obesity* 19:1171–76

Pivk U, Godinot N, Keller C, Antille N, Juillerat MA, Raspor P. 2008. Lipid deposition on the tongue after oral processing of medium-chain triglycerides and impact on the perception of mouthfeel. *J. Agric. Food Chem.* 56:1058–64

Schiffman SS. 2008. 4.27—The aging gustatory system. In *The Senses: A Comprehensive Reference*, Vol. 4: *Olfaction & Taste*, ed. IB Allan, K Akimichi, MS Gordon, G Westheimer, TD Albright, et al. pp. 479–98. New York: Academic

Schiffman SS, Graham BG. 2000. Taste and smell perception affect appetite and immunity in the elderly. *Eur. J. Clin. Nutr.* 54:S54–63

Schiffman SS, Warwick ZS. 1993. Effect of flavor enhancement of foods for the elderly on nutritional status: food intake, biochemical indices, and anthropometric measures. *Physiol. Behav.* 53:395–402

Schneeman BO. 1998. Dietary fiber and gastrointestinal function. *Nutr. Res.* 18:625–32

Schulze K. 2006. Imaging and modeling of digestion in the stomach and the duodenum. *Neurogastroenterol. Motil.* 18:172–83

Shama F, Sherman P. 1973a. Identification of the stimuli controlling the sensory evaluation of viscosity. *J. Texture Stud.* 4:111–18

Shama F, Sherman P. 1973b. Variation in stimuli associated with oral evaluation of the viscosities of glucose solutions. *J. Texture Stud.* 4:254–62

Simonian HP, Maurer AH, Knight LC, Kantor S, Kontos D, et al. 2004. Simultaneous assessment of gastric accommodation and emptying: studies with liquid and solid meals. *J. Nucl. Med.* 45:1155–60

Solah VA, Kerr DA, Adikara CD, Meng X, Binns CW, et al. 2010. Differences in satiety effects of alginate- and whey protein-based drinks. *Appetite* 54:485–91

Souliman S, Beyssac E, Cardot JM, Denis S, Alric M. 2007. Investigation of the biopharmaceutical behaviour of theophylline hydrophilic matrix tablets using USP methods and an artificial digestive system. *Drug Dev. Ind. Pharm.* 33:475–83

Spyropoulos FK, Heuer EA, Mills TB, Bakalis S. 2011. Protein-stabilised emulsions and rheological aspects of structure and mouthfeel. In *Practical Food Rheology: An Interpretive Approach*, ed. IT Norton, F Spyropoulos, P Cox, pp. 193–218. Oxford, UK: Wiley

Tharakan A, Norton IT, Fryer PJ, Bakalis S. 2010. Mass transfer and nutrient absorption in a simulated model of small intestine. *J. Food Sci.* 75:E339–46

Thomas A. 2006. Gut motility, sphincters and reflex control. *Anaesth. Intensive Care Med.* 7:57–58

Topping DL, Clifton PM. 2001. Short-chain fatty acids and human colonic function: roles of resistant starch and nonstarch polysaccharides. *Physiol. Rev.* 61:1031–63

van Can JGP, Ijzeman TH, van Loon LJ, Brouns F, Blaak EE. 2009. Reduced glycaemic and insulinaemic responses following isomaltulose ingestion: implications for postprandial substrate use. *Br. J. Nutr.* 102:1408–13

Vardakou M, Mercuri A, Barker SA, Craig DQ, Faulks RM, Wickham MSJ. 2011. Achieving antral grinding forces in biorelevant in vitro models: comparing the USP dissolution apparatus II and the dynamic gastric model with human in vivo data. *AAPS PharmSciTech.* 12:620–26

Vertzoni M, Dressman J, Butler J, Hempenstall J, Reppas C. 2005. Simulation of fasting gastric conditions and its importance for the in vivo dissolution of lipophilic compounds. *Eur. J. Pharm. Biopharm.* 60:413–17

Wasserman DH. 2009. Four grams of glucose. *Am. J. Physiol.* 296:E11–21

Watson TF, Neil MA, Juskaitis R, Cook RJ, Wilson T. 2002. Video-rate confocal endoscopy. *J. Microsc.* 207:37–42

Widmaier EP, Raff H, Strang KT. 2006. *Human Physiology. The Mechanisms of Body Function*. Boston: McGraw-Hill

Williams I, Iqbal T, Webber M, Tselepis C. 2011. A mechanism for the effect of alginate on the gut microflora. *Gut* 60:A76

Yoo MJY, Chen XD. 2006. GIT physicochemical modeling—a critical review. *Int. J. Food Eng.* 2:1–10