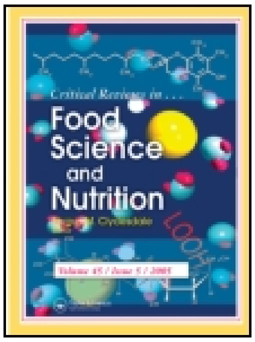

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Reduced Fat Food Emulsions: Physicochemical, Sensory, and Biological Aspects

CHERYL CHUNG,[1] GORDON SMITH,[2] BRIAN DEGNER,[2] and DAVID JULIAN McCLEMENTS[1]

[1]Department of Food Science, University of Massachusetts, Amherst, Massachusetts, USA
[2]ConAgra Foods, Six ConAgra Drive, Omaha, Nebraska, USA

Fat plays multiple important roles in imparting desirable sensory attributes to emulsion-based food products, such as sauces, dressings, soups, beverages, and desserts. However, there is concern that over consumption of fats leads to increased incidences of chronic diseases, such as obesity, coronary heart disease, and diabetes. Consequently, there is a need to develop reduced fat products with desirable sensory profiles that match those of their full-fat counterparts. The successful design of high quality reduced-fat products requires an understanding of the many roles that fat plays in determining the sensory attributes of food emulsions, and of appropriate strategies to replace some or all of these attributes. This paper reviews our current understanding of the influence of fat on the physicochemical and physiological attributes of food emulsions, and highlights some of the main approaches that can be used to create high quality emulsion-based food products with reduced fat contents.

Keywords Fats, textural perception, emulsion, instrumental analysis, sensory evaluation, reduced fat foods, satiety

INTRODUCTION

In general, the acceptability of food products depends on their appearance, texture, flavor, auditory characteristics, and satiability (Overbosch et al., 1991; Taylor, 1996; Bourne, 2002; Foster et al., 2011b; Costell et al., 2010). In this review, we focus on food products that can be considered to be oil-in-water emulsions, such as many sauces, dressings, dips, beverages, desserts, and soups (Friberg et al., 2004; McClements, 2005). Oil-in-water emulsions consist of small spherical oil droplets dispersed within an aqueous medium. The perceived quality of these products is strongly influenced by the characteristics of the fat droplets that they contain, e.g., particle concentration, size, charge, interfacial properties, physical state, and interactions (Druaux and Voilley, 1997; McClements, 2005; Talbot, 2011; Foster et al., 2011b). There is currently a great concern that over consumption of fat-rich products is leading to increased incidences of chronic human diseases, such as obesity, coronary heart disease, and diabetes. Consequently, the food industry is trying to develop reduced fat products with physicochemical and sensory properties that match those of their full-fat counterparts. This is often challenging because of the multiple roles that fat droplets play in determining the overall quality of food products (Bayarri et al., 2007; Bayarri et al., 2006; Benjamins et al., 2009a; Brauss et al., 1999; Malone and Appelqvist, 2003; McClements, 2005). For example, when fat droplets are reduced or removed the optical properties, texture, mouthfeel, flavor profile, and biological response (e.g., satiety and satiation) of the product are altered in a manner that is usually undesirable to consumers. The many roles that fat droplets play in determining food quality mean that it is usually difficult to identify a single fat replacement strategy that can be used to produce high quality low-fat products with the same desirable attributes as their full fat counterparts. Instead, a number of different strategies may need to be used in combination to mimic the optical, rheological, stability and flavor profile normally provided by fat droplets.

The rational development of high quality reduced fat food emulsions depends on a thorough understanding of the impact of fat droplets on their physicochemical and sensory attributes. This review therefore focuses on establishing the multiple roles that fat droplets play in determining the properties of food emulsions, particularly on mouthfeel attributes. We begin by providing an overview of emulsion characteristics, the

Address correspondence to David Julian McClements, Department of Food Science, University of Massachusetts, Amherst, MA 01003, USA. E-mail: mcclements@foodsci.umass.edu

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/bfsn factors influencing the rheological and textural properties of food emulsions, and analytical methods available to measure food rheology and texture. We then discuss the impact of fat droplets on the physiological responses of the body after meal intake, focusing on oral, gastrointestinal, and brain responses. A brief review of previous research on the influence of fats on the sensory perception of emulsion-based foods is given, and then we conclude with a discussion of effective strategies to formulate reduced-fat food emulsions.

EMULSION SYSTEMS

Emulsions in Food Science

The fats in many food products are present in an emulsified form, either in the final product or at some stage during the manufacturing process. Examples of emulsion-based food products include mayonnaise, dressings, condiments, sauces, milk, cream, cheese, yogurt, beverages, desserts, butter, and margarine (McClements, 2005; Le Reverend et al., 2010). An emulsion is a structurally heterogeneous material that consists of two immiscible liquids, such as oil and water, with one being dispersed in the other in the form of small spherical droplets (Figure 1). The droplets are stabilized by emulsifying agent(s) that exhibit good film forming properties, such as surfactants, phospholipids, proteins or polysaccharides. Typically, there are two categories of emulsions widely used in the food industry: oil-in-water (O/W) systems (e.g., milk, yogurt, sauces, dressings) or water-in-oil (W/O) systems (e.g., butter, margarine). An O/W emulsion is composed of oil droplets dispersed in a watery phase, whereas a W/O emulsion consists of water droplets dispersed in an oily phase (Figure 1) (Dickinson and Patino, 1999; McClements, 2005; 2010). The nature of the ingredients and processing operations used to produce an emulsion determine the properties of the droplets formed (e.g., concentration, size, charge, interfacial characteristics, and interactions). In turn, the droplet properties strongly influence oral processing and sensory perception of emulsion-based food products (Figure 2) (McClements, 2005; Foster et al., 2011b). In this paper, we focus on fat reduction of food products that can be considered to be oil-in-water emulsions, such as sauces, dressings, mayonnaise, deserts, beverages, and yogurts.

Droplet Characteristics

The sensory and bulk physicochemical properties of emulsions are highly dependent on the properties of the droplets they contain (McClements, 2005). Consequently, it is important to understand how the characteristics of droplets within emulsions may vary and how they can be controlled to obtain different functional attributes in a product. In this section, we highlight some of the most important characteristics of the droplets in O/W emulsions.

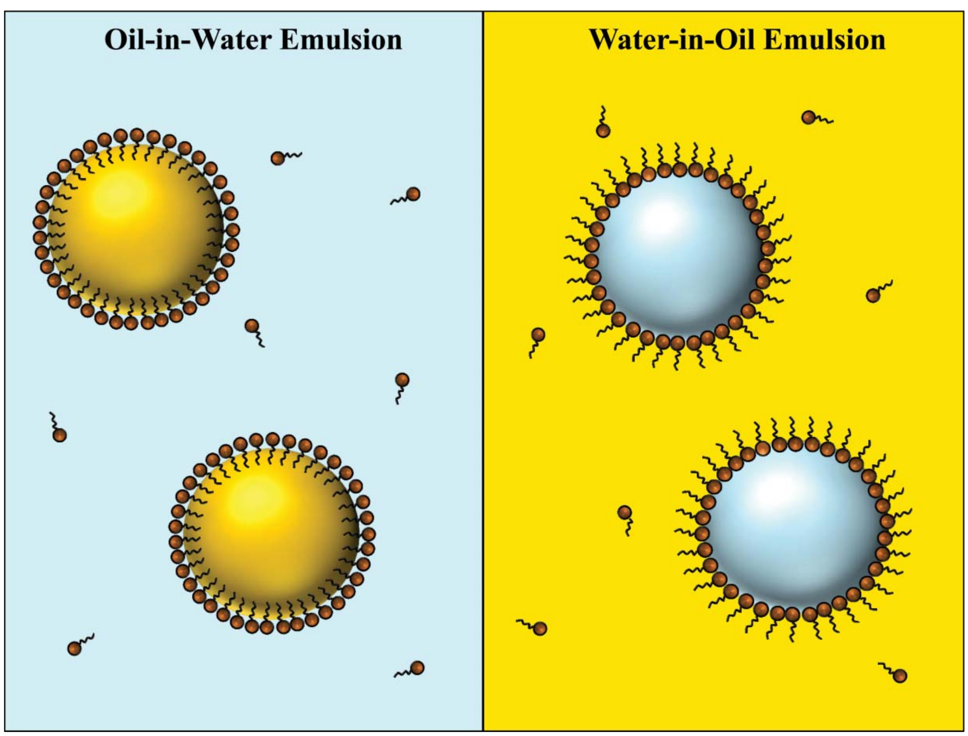

Figure 1 Schematic diagram of oil-in-water emulsion (left) and water-in-oil emulsion (right) consisting of emulsifier-coated droplets dispersed in the continuous phase.

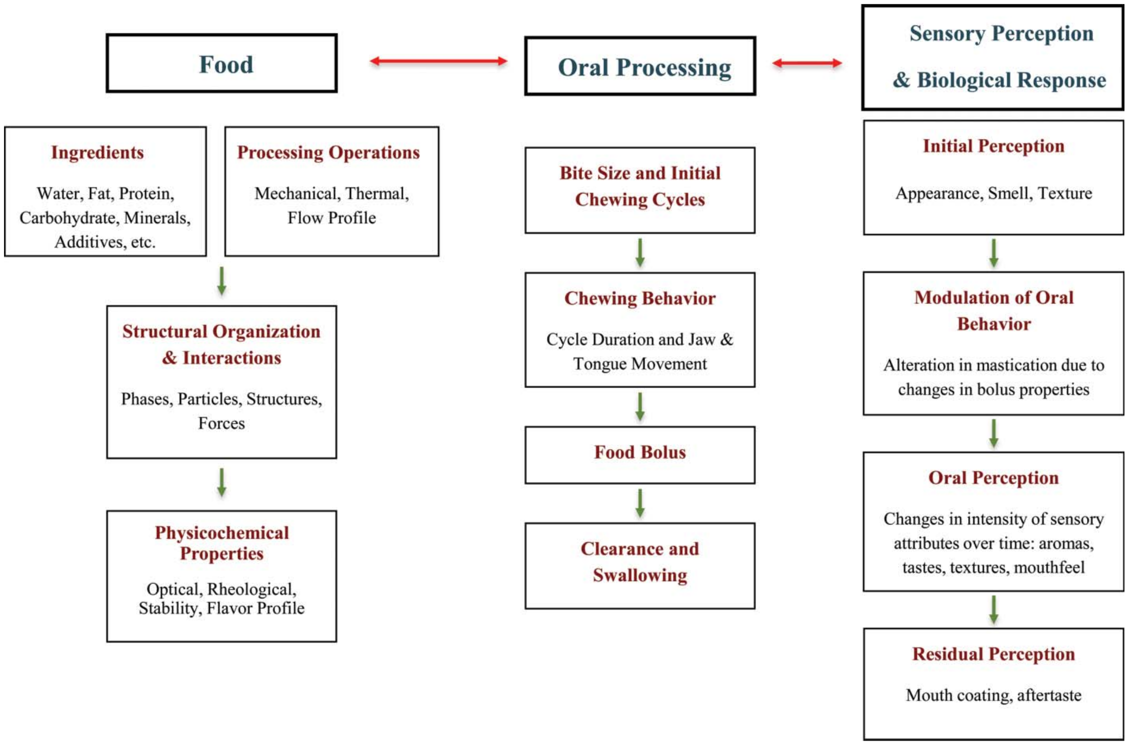

Figure 2 Overview of the relationship among food properties, oral processing, sensory perception, and biological response of food emulsions. Flow diagram is adapted from Foster et al. (2011) and McClements (2005).

Droplet Concentration

The droplet concentration in an O/W emulsion is expressed as the amount of fat droplets per unit amount of emulsion using appropriate concentration units (McClements, 2005). For example, the *disperse phase volume fraction* (ϕ) is the volume of fat droplets per unit volume of emulsion. The fat droplet concentration in a food emulsion is usually controlled by varying the initial proportions of aqueous phase and fat phase used to prepare it. Alternatively, an emulsion may be prepared with a particular fat droplet concentration and then be diluted (e.g., by adding aqueous phase) or concentrated (e.g., by gravitational separation, filtration, centrifugation, or evaporation). The overall concentration of fat droplets in an O/W emulsion plays a major role in determining its physicochemical, sensory, and physiological properties. For example, desirable sensory attributes (such as "creaminess," "thickness" or "richness") of emulsion-based food products usually increases as the fat droplet concentration increases.

Particle Size Distribution

The particle size distribution (PSD) of an emulsion represents the fraction of particles in different size classes (McClements, 2005). The initial PSD of an emulsion can usually be controlled by varying homogenization conditions (e.g., homogenizer design; intensity or duration of energy input) or system composition (e.g., emulsifier, oil, water, cosolvents and additives). Smaller droplets can usually be produced by increasing the intensity or duration of homogenization, by increasing the concentration of emulsifier used, or by optimizing the viscosities of the oil and aqueous phases (Walstra, 1993; Schubert and Engel, 2004). Overtime, the PSD may change due to various instability mechanisms (see below).

Droplet Charge

The electrical characteristics of the fat droplets in O/W emulsions are usually characterized in terms of the ζ-potential versus pH profile (Hunter, 1986). Fat droplet charge can be controlled by careful selection of emulsifier type and solution conditions (such as pH and ionic strength). Droplets stabilized by nonionic surfactants tend to have a low net charge (e.g., Tweens and Spans), those stabilized by anionic surfactants have a high negative charge (e.g., lecithin, DATEM, CITREM, fatty acids), those stabilized by polysaccharide emulsifiers tend to have a negative charge (e.g., gum arabic and modified starch), and those stabilized by proteins have a positive charge below their isoelectric point (pI) and negative charge above it (e.g., whey, casein, egg, and soy proteins). The electrical charge on the fat droplets may influence their physical and chemical stability within emulsion-based food products

(McClements, 2005), as well as their behavior within the human gastrointestinal tract. Fat droplet charge plays an important role in preventing droplet aggregation in electrostatically stabilized emulsions (such as those stabilized by proteins and ionic surfactants), and also determines how fat droplets behave in the mouth and gastrointestinal tract after ingestion.

Interfacial Characteristics

The fat droplets in food emulsions are normally coated by a layer of adsorbed species (emulsifiers) to protect them from aggregation. The properties of this interfacial region are determined by the type, concentration, and interactions of any surface-active species present in the system during homogenization, as well as by the events that occur before, during, and after emulsion formation, e.g., complexation, co-adsorption, competitive adsorption, or multilayer formation (Dickinson, 2003). Interfacial characteristics, such as chemical reactivity, surface energy, charge, thickness, permeability, rheology, and environmental responsiveness, can be controlled by altering system composition and/or processing conditions. Controlling the interfacial characteristics is one of the most powerful methods of designing food products with specific functional performances (Dickinson, 1992, 2003). In emulsion-based food products, the interfacial properties of the fat droplets play an important role in determining the overall rheology, stability, and mouthfeel.

Physical State

The fat droplets in O/W emulsions can be liquid, partially crystalline, or fully crystalline depending on the nature of the lipid phase used and the thermal history of the system (Walstra, 2003; Muller and Keck, 2004; Wissing et al., 2004; McClements, 2005). For example, the fat droplets in an O/W emulsion can be made to crystallize by reducing the temperature sufficiently below the melting point of the fat phase. The crystallization temperature of an emulsified fat is often substantially below that of a bulk fat because of supercooling effects (McClements, 2012). In addition, the nature of the crystals formed by an emulsified fat may be different from those formed by a bulk fat because of curvature effects and the limited volume present in an individual emulsion droplet, e.g., polymorphism, crystal shape, dimensions, and melting behavior (Rousseau, 2000; Muller and Keck, 2004; Wissing et al., 2004). The concentration, nature, and location of fat crystals within fat droplets can be controlled by careful selection of lipid type (e.g., solid fat content versus temperature profile, polymorphic forms, crystal habit), thermal history (e.g. temperature versus time profile), emulsifier type (e.g., protein, polysaccharide or surfactant), additives (e.g., crystallization inhibitors or promoters), and droplet size (Muller et al., 2000; Walstra, 2003; Muller and Keck, 2004). Information about the amount, type and location of crystals in fat droplets can be obtained using methods such as differential scanning calorimetry (DSC), nuclear magnetic resonance (NMR), X-ray diffraction, infrared spectroscopy, and microscopy (electron or optical) (McClements, 2005).

Controlling Droplet Characteristics for Improved Performance

Manipulation of the concentration, particle size distribution, interfacial properties, and physical state of the droplets can be carried out to create food emulsions with specific functional performances. Knowledge of how specific particle characteristics influence the physicochemical, sensory, and physiological properties of emulsions is essential for creating reduced fat products.

Physicochemical Properties of Emulsions

Some of the most important bulk physicochemical characteristics of emulsions are briefly outlined below. Particular emphasis is given to highlighting the role that fat droplets play in determining these properties, and in outlining potential strategies that can be used to replace fat droplets based on this knowledge.

Rheology

Emulsions exhibit a wide variety of different rheological behaviors depending on their composition, structure, and interactions: viscous liquids; viscoelastic liquids; viscoelastic solids; plastics; or elastic solids (Walstra, 2003; McClements, 2005; Genovese et al., 2007). Fat droplets play an important role in contributing to the desirable rheological properties of many types of emulsion-based food products, but various other ingredients may play an important role too, such as starch granules, hydrocolloids, air bubbles, and ice crystals.

The rheology of fluid emulsions is usually characterized by their apparent *shear viscosity*. In general, the shear viscosity of an O/W emulsion is determined by the continuous phase viscosity (η_C), the fat droplet concentration (ϕ), and the nature of the droplet-droplet interactions (w): $\eta = \eta_C \times f(\phi,w)$ (McClements, 2005; Genovese et al., 2007). Normally, the viscosity of an O/W emulsion increases with increasing fat droplet concentration, gradually at first and then steeply as the droplets become more closely packed (Figure 3). Around and above the droplet concentration where close packing occurs (typically around 50–60% fat for a nonflocculated O/W emulsion), the emulsion exhibits solid-like characteristics, such as visco-elasticity and plasticity (McClements, 2005). The droplet concentration where this steep increase in emulsion viscosity is observed

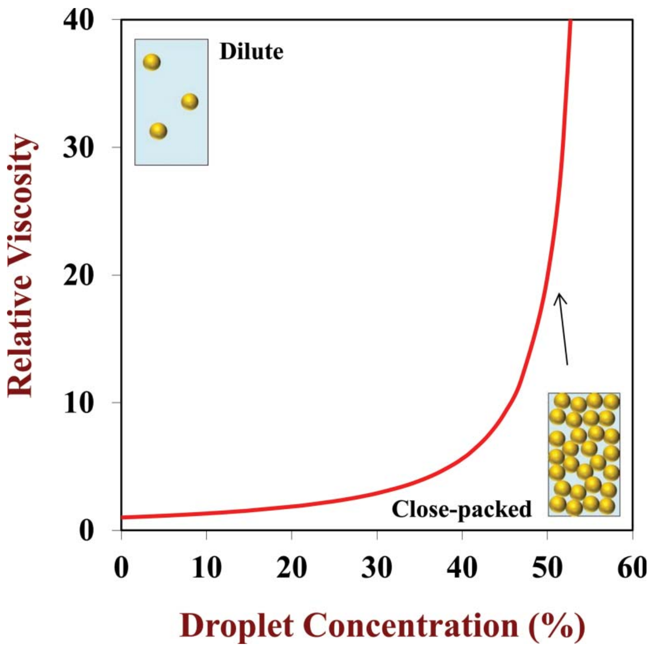

Figure 3 Calculated dependence of the relative viscosity (η/η_0) of an oil-in-water emulsion on fat droplet concentration. It is assumed that the droplets are nonflocculated, and that there are no thickening agents in the continuous phase.

depends on the nature of the fat droplet interactions in the system, decreasing for either strong attractive or strong repulsive interactions (McClements, 2005). The viscosity of an emulsion tends to increase when the droplets are flocculated because the effective particle concentration is increased due to the continuous phase trapped within the floc structure. In addition, shear-thinning behavior is observed in flocculated emulsions because of deformation and breakdown of the floc structure as shear stresses increase (Quemada and Berli, 2002).

The impact of droplet characteristics on emulsion rheology is usually one of the most important considerations when designing reduced fat versions of food products. When the fat droplets are removed from an emulsion there will be a decrease in viscosity or even a conversion from a highly viscous or gel-like product to a low viscosity product (Figure 3). For example, the desirable textural attributes of dressings and mayonnaises (e.g., "thickness," "spoonability") are lost when the fat content is reduced below a certain level, unless an effective fat replacement strategy is adopted. A number of strategies may be utilized to compensate for the loss of texture that occurs when the fat droplets are removed from full fat products. The overall viscosity of an O/W emulsion can be increased by adding *thickening agents* to the aqueous phase, such as starch granules or hydrocolloids. The viscosity can also be increased by adding *nonfat particles* that alter the flow profile of an emulsion in a similar manner to fat droplets, such as protein or polysaccharide microspheres, air bubbles, or some crystalline materials. In some cases it is possible to increase the viscosity of an emulsion by adding ingredients that promote fat droplet *flocculation* since these leads to the formation of a three-dimensional network with some elastic properties.

Optical Properties

Two of the most important optical properties of emulsion-based food products are their opacity and color, which can be quantitatively described using tristimulus color coordinates, such as the $L^*a^*b^*$ system (McClements, 2005). In this color system, L^* represents the lightness, and a^* and b^* are color coordinates: where $+a^*$ is the red direction, $-a^*$ is the green direction; $+b^*$ is the yellow direction, $-b^*$ is the blue direction; low L^* (0) is dark and high L^* (100) is light (Figure 4). The opacity of an emulsion can therefore be characterized by the lightness (L^*), while the color intensity can be characterized by the chroma: $C = (a^{*2} + b^{*2})^{1/2}$. The color intensity is usually inversely related to the lightness, which accounts for the reduction in color intensity which is observed when the droplet concentration in emulsions increases. In general, the optical properties of emulsions are determined by the relative refractive index, the droplet concentration, and the droplet size (McClements, 2002c, 2005). The lightness of an emulsion tends to increase with increasing refractive index contrast and increasing droplet concentration, and has a maximum value at a particular droplet diameter (typically around 500 nm). For O/W emulsions, the lightness increases steeply as the oil concentration increases from around 0 to 5 wt%, but then increases more gradually as the oil concentration is increased further (Figure 5). This has important implications for the production of reduced fat emulsion-based products. When the fat content is reduced there is a decrease in lightness, which may alter the consumer perception of product quality (e.g., the desirable "creamy" appearance).

Another important aspect of the appearance of many emulsion-based products is their surface gloss, which is determined by whether light reflection from the surface of the product is primarily specular ("glossy") or diffusive ("matt") (Lucca and Tepper, 1994; Chen, 2007). This effect will partly be

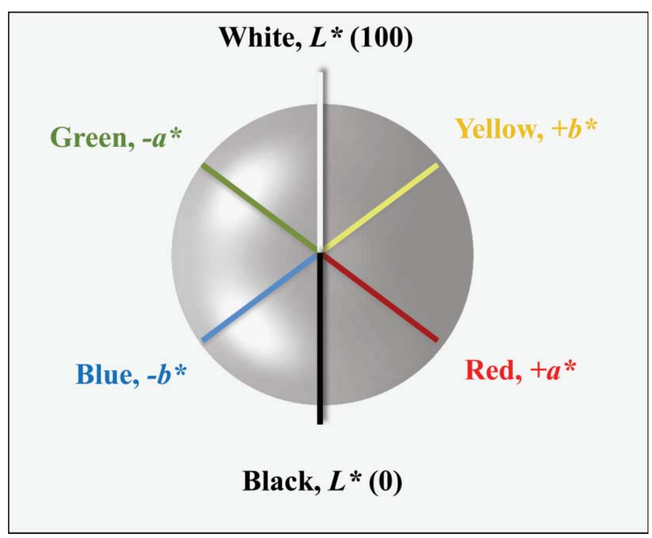

Figure 4 The color of a material can be represented in three-dimensional space using L^* a^* b^* tristimulus coordinates.

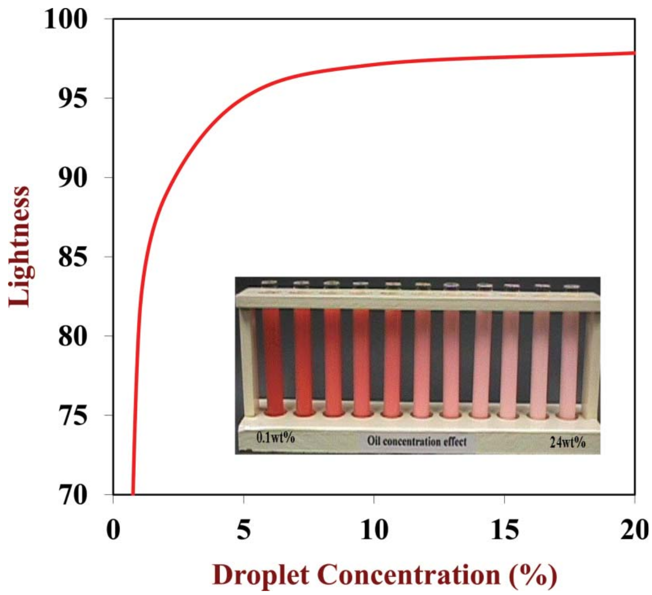

Figure 5 Dependence of the lightness of an O/W emulsion on fat droplet concentration. The photograph shows emulsions containing similar amounts of red dye, but different amounts of fat droplets. (Photograph from Chantraporrnchai et al., 2000.)

determined by the surface roughness of the product compared to the wavelength of light. In food products where the fat droplets are unstable to coalescence there may be a thin layer of fat visible on the surface of a product, which is often referred to as "oiling-off." In some products the appearance of this surface fat may be undesirable, but in other products it may be desirable (e.g., giving some soups and sauces a more authentic look). Fats may also contribute to the overall appearance of some foods due to their involvement in chemical reactions that occur at the products surface, e.g., surface browning in some foods leads to a characteristic "cooked" appearance.

The changes in the optical properties of emulsion-based foods when fat droplets are removed can be compensated for in a number of ways. First, it may be possible to alter the particle size distribution of the remaining fat droplets in a reduced-fat product so as to increase their light scattering efficiency (McClements, 2002a; 2002b). For example, if the product normally contained relatively large droplets that do not scatter light strongly, then it may be possible to produce a lower fat product that has the same lightness by homogenizing it to produce smaller fat droplets that scatter light more strongly. Second, it may be possible to incorporate nonfat particles that scatter light in a similar manner to fat droplets, thereby increasing the overall opacity of a reduced fat product, e.g., titanium dioxide (Chantrapornchai et al., 2000) or biopolymer particles (Matalanis et al., 2011). Third, the addition of certain types of hydrocolloids has been shown to replace the desirable surface sheen of emulsion-based products that is often lost when fat is removed (Sylvia, 1996; John et al., 2012; Ognean et al., 2006).

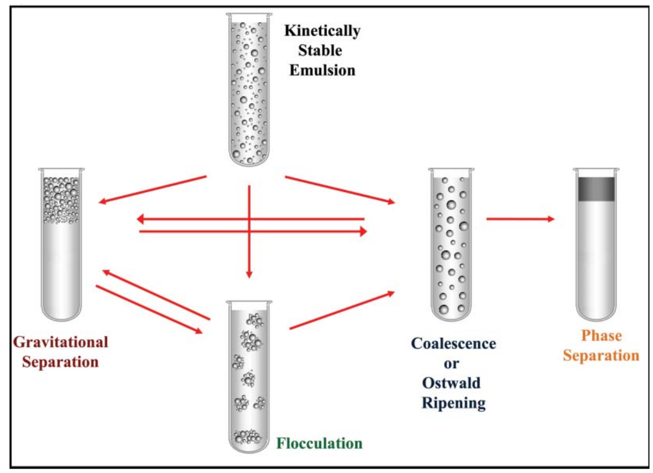

Figure 6 Schematic diagram of most common instability mechanisms that occur in food emulsions: creaming, sedimentation, flocculation, coalescence, Ostwald ripening, and phase inversion. (Adapted from McClements, 2005.)

Stability

Emulsions are thermodynamically unfavorable systems that tend to break down over time due to a variety of physicochemical mechanisms (Figure 6), including gravitational separation, flocculation, coalescence, and Ostwald ripening (Dickinson, 1992; Friberg et al., 2004; McClements, 2005). Gravitational separation is one of the most common forms of instability in food emulsions, and may take the form of either *creaming* or s*edimentation* depending on the relative densities of the dispersed and continuous phases. Creaming is the upward movement of droplets due to the fact that they have a lower density than the surrounding liquid, whereas sedimentation is the downward movement of droplets due to the fact that they have a higher density than the surrounding liquid. Liquid oils normally have lower densities than liquid water and so creaming is more prevalent in O/W emulsions. Nevertheless, this may not be the case in emulsions that contain fully or partially crystalline fat droplets because the density of lipids usually increases when crystallization occurs.

The creaming velocity within an oil-in-water emulsion tends to increase as the fat content decreases (Figure 7), which can be attributed to a reduction in the droplet–droplet interactions that inhibit fat droplet movement in concentrated systems (McClements, 2005). This phenomenon may have important implications for the formulation of stable reduced fat products (e.g., mayonnaise or dressings). When the fat droplets are removed from an emulsion-based food the rate of droplet creaming may increase, which would lead to a reduction in shelf life. Thus, it may be necessary to reformulate reduced fat products to prevent this phenomenon from occurring. There are a number of possible strategies available to reduce the creaming rate in O/W emulsions at low fat droplet concentrations: (i) adding thickening or gelling agents to increase the aqueous phase texture; (ii) decrease the droplet size to retard droplet movement; (iii) promote droplet flocculation to form

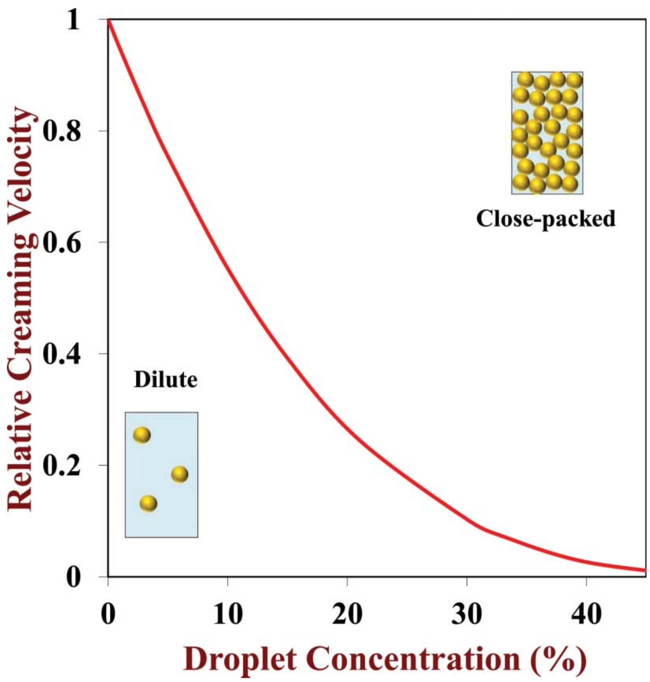

Figure 7 Calculated dependence of the creaming velocity of the fat droplets in an oil-in-water emulsion on droplet concentration.

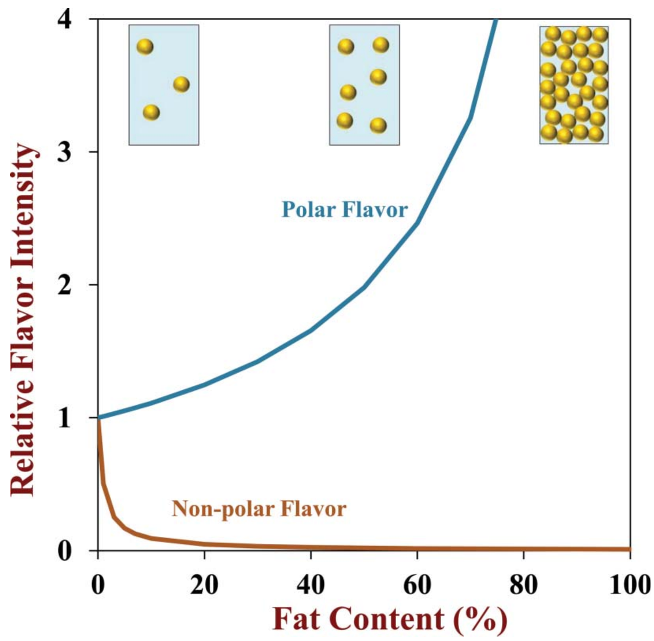

Figure 8 Schematic representation of flavor dependence of the creaming velocity of the fat droplets in an oil-in-water emulsion on droplet concentration. (Adapted from McClements, 2005.)

a three-dimensional network of aggregated droplets that extends throughout the system; (iv) decrease the density contrast (e.g., by using partially crystalline fats).

Molecular Distribution and Release Characteristics

The flavor profile of a food emulsion depends on the distribution of the various types of flavor molecules present in the different phases (e.g., oil, water, and gas phases), which is governed by their equilibrium partition coefficients and the kinetics of molecular motion (McClements, 2005; Frank et al., 2011a). Altering the fat content of a food alters the distribution of the various flavor molecules within the system between these different phases, as well as their release rates. In an emulsion, release is usually characterized in terms of the increase in concentration of the flavor compound in the aqueous phase (taste) or headspace (flavor) as a function of time (flavor intensity-time relationship). The influence of fat on the distribution and release of flavor molecules has an important impact on the development of reduced fat products, which is discussed in more detail in a later section. One indication of this effect is the change in the concentration of flavor molecules in the headspace above an emulsion as the fat content is increased (Figure 8). As the fat content gets higher, the concentration of nonpolar flavors in the headspace above an emulsion (and therefore their perceived flavor intensity) decreases, whereas the opposite is true for polar flavors. This phenomenon obviously has important consequences for the formation of reduced-fat emulsions, and means that the type and amount of the flavor components present in a reduced-fat system must be carefully reformulated to better mimic that of a full-fat product.

MIXED COLLOIDAL SYSTEMS

Many emulsion-based food products do not simply consist of oil droplets dispersed within an aqueous phase. Instead, they contain a variety of other kinds of polymers and particles dispersed within the aqueous phase, such as hydrocolloids, starch granules, protein particulates, ice crystals, and air bubbles. The presence of these nonfat particles and polymers may have a pronounced influence on the microstructure and physicochemical properties of emulsion-based food products. In these mixed systems, it is important to establish the physical characteristics of the nonfat particles or polymers in order to understand how they contribute to the overall properties of the system. For particles, the most important parameters to know are their composition, concentration, size, shape, charge, interfacial properties, physical state, interactions, and bulk physical properties (such as density, refractive index, and rheology). For polymers, the most important parameters to know are their molar mass, branching, conformation, hydrophobicity, and charge characteristics.

The nonfat particles or polymers in mixed emulsion-based food products contribute to the overall physicochemical, sensory, and nutritional properties. The presence of these substances will lead to an increase in the viscosity of the overall system due to their influence on fluid flow. The change in viscosity will depend on the concentration, size, conformation, and interactions of the particles or polymers present. They will also alter the optical properties of emulsions due to their ability to scatter light. The magnitude of this effect will depend on their refractive indices, concentrations, and sizes. Nonfat substances may also alter the flavor profile of an emulsion-based product due to their ability to alter the partitioning and mass transport of volatile and nonvolatile molecules between the oil, water, and gaseous phases, e.g., due to flavor binding or viscosity enhancement. Finally, the presence of nonfat particles and polymers may influence the stability of emulsion-based products to gravitational separation, flocculation, coalescence, and phase separation. For example, these substances may increase the aqueous phase viscosity or promote droplet network formation, which inhibits the movement of fat droplets within the system.

It is therefore particularly important to identify the different kinds of particles and polymers present within an emulsion-based product, characterize them, and establish their influence on the overall properties of the system. Recently, our laboratory has treated food sauces and dressings as multimodal particulate systems containing starch granules, fat droplets and hydrocolloids (Chung et al., 2012b, 2013). Before heating, the system consists of a mixture of native starch granules and fat droplets (Figure 9), which has a relatively low viscosity and is unstable to phase separation. After heating, the starch granules swell and take up a much bigger effective volume (Figure 9), which leads to a large increase in viscosity and an improved stability to phase separation. The rheology and appearance of these mixed colloidal systems depends strongly on the size, concentration, and interactions of the different types of particles and polymers present, and their rheological properties can be modeled using multicomponent mathematical theories. Our recent studies have found that the textural characteristics of these model sauces are highly sensitive to the aggregation state of the fat droplets in the spaces between the starch granules.

ASSESSMENT OF REDUCED FAT FOOD PROPERTIES

Analytical Measurements

As it is often costly, inconvenient, and time-consuming to conduct sensory evaluation of all food products during the product development process, various quantitative analytical measurements have been developed (Chen, 2009). These instruments are used to identify the main factors influencing the overall quality attributes of foods, as well as to provide quantitative information that predicts the sensory performance of foods. Analytical methods also have the advantage that they overcome many of the inherent variations in sensory analysis associated with differences in the physiology, perception, and descriptive capabilities of foods by individuals (Piggott et al., 1998; Taylor and Linforth, 2000). Analytical methods have been developed to measure the optical properties (appearance), flavor (aroma and taste), and rheology (texture) of foods, and to correlate them to their sensory equivalents.

Appearance

A consumers first sensory impression of a food product is usually the appearance, which is characterized by the color, opacity, surface gloss, and homogeneity (McClements, 2002c; Gonzalez-Tomas and Costell, 2006). This initial sensory impression has been shown to have a major impact on the subsequent in-mouth perception and overall acceptability of foods (Su et al., 2010), presumably by altering consumer expectations. The appearance of emulsion-based foods is therefore one of the most important factors influencing consumers' assessment of overall product quality (McClements, 2002c; 2005; Gonzalez-Tomas and Costell, 2006). The appearance of a food emulsion is influenced by light scattering from the fat droplets, which depends on their concentration and size. Typically, the opacity of an emulsion increases

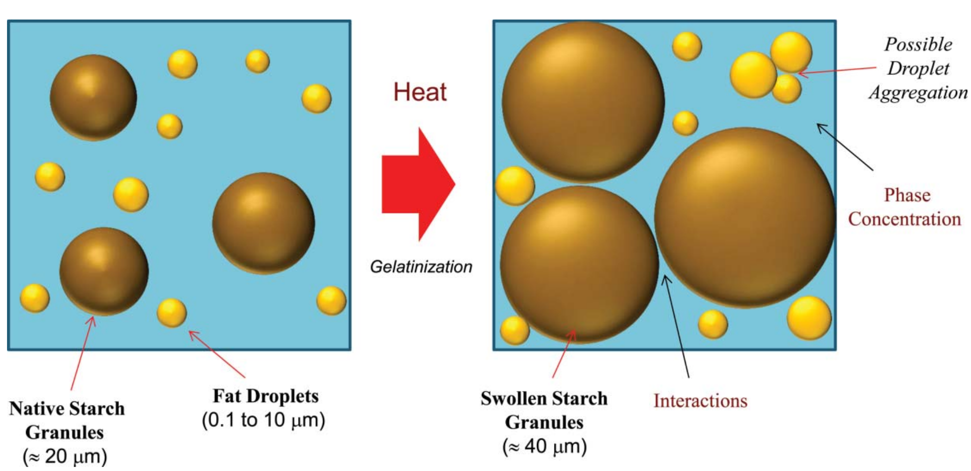

Figure 9 Sauces are multi-modal colloidal suspensions containing starch granules and fat droplets. Other ingredients may also play an important role, such as biopolymers, minerals, and surfactants.

with increasing droplet concentration (Figure 5), and has a maximum value at an intermediate droplet radius (around 500 nm).

The color of a food product can be quantified mathematically in terms of tristimulus coordinates (e.g., XYZ, L^* a^* b^* or Hunter-Lab coordinates) (Figure 4) and measured instrumentally using a colorimeter (Hutchings, 1999; McClements, 2002c; Gonzalez-Tomas and Costell, 2006). The most commonly used coordinate system to quantify and report the color of foods is the CIELAB developed by the Commission International de l'Eclairage (CIE). The surface gloss is a measure of whether light reflection from a food surface is primarily specular (glossy) or diffusive (matt), which depends on surface characteristics such as topology and heterogeneity. There are a variety of handheld and bench top colorimeters commercially available that can be used to measure the color, opacity, and surface gloss of food products, including emulsions.

AromaVolatile Compounds

Aroma is the result of interactions between volatile compounds released from a food or beverage and receptors located within the nasal cavity (Taylor, 1996; McClements, 2005). The release of volatile flavors can be quantified instrumentally by headspace analysis using a variety of methods depending on the information required (Taylor and Linforth, 2000; Dattatreya et al., 2002; Rabe et al., 2002; Frank et al., 2011b). These methods include static and dynamic headspace analysis methods. Static headspace analysis is used to determine the equilibrium partition coefficient of flavor compounds between a food and the headspace above it. Dynamic headspace analysis is used to measure flavor release rates, and may be carried out on the headspace collected above a food product or from the breath exhaled from a human during mastication. The composition of the flavor compounds in the headspace can be measured using a variety of methods, with the most common being gas chromatography (GC), high performance liquid chromatography (HPLC) and mass spectrometry (Taylor and Linforth, 2000; McClements, 2005). General information about the overall flavor profile above a food can also be obtained using analytical instruments called "electronic noses." These devices were developed to simulate the response of human sensory receptors to food flavor and can be used to monitor changes in the concentrations of one or more flavor compounds over time above a product (Linforth, 2000; Steinhart, Stephan and Bucking, 2000; Miettinen et al., 2002).

Taste–nonvolatile Compounds

The taste of a food is determined by specific types of nonvolatile molecules present or dissolved in the saliva during mastication (e.g., bitter, sweet, salty, or acidic components). In emulsions, the taste molecules partition between the oil and water phases, thus characterization of a taste in these systems involves measurements of the time-dependence of their concentrations in the water phase, which is influenced by their oil-water partition coefficients and oil-to-water mass transfer rates. The concentration of nonvolatile flavors in the water phase may be measured using static or dynamic approaches within a food product or within the mouth during mastication by collecting and analyzing saliva samples over time (McNulty and Karel, 1973; Rogacheva et al., 1999).

Texture and Mouthfeel

Fat droplets play an important role in determining the texture and mouthfeel of emulsion-based products, and this is known to be one of the most important factors influencing their overall sensory acceptance. There has been considerable interest in relating fundamental rheological properties that can be quantified instrumentally to perceived textural attributes of food emulsions, such as "thickness," "creaminess," "smoothness," or "sliminess" (Malone et al., 2003a; van Aken, 2007). The most commonly measured rheological properties of food emulsions are their viscosity and viscoelasticity (Malone et al., 2003a), and their fracture properties (van Vliet, 2002; van Aken, 2007). One of the major challenges in this area is developing test conditions in analytical instruments that simulate the complex processes that occur during the mastication within the mouth, such as product fracture, interactions with saliva, coating of the tongue and palate, and complicated stress/flow profiles (van der Bilt et al., 2006; de Wijk et al., 2011; Foegeding et al., 2011; Salles et al., 2011; Foster et al., 2011a).

Flow Behavior (Large Deformation)

The perceived texture of food emulsions may be judged prior to consumption (e.g., how they pour from a container, respond to stirring, or drip from a spoon) or during consumption (e.g., how they flow within the mouth or coat the tongue). Large deformation methods are usually the most suitable for mimicking processes that involve the flow or disruption of food emulsions (Foegeding et al., 2011). The flow behavior of food emulsions is typically measured using a viscometer or rheometer. The apparent viscosity of a sample is calculated as the shear stress divided by the rate of strain. Food emulsions often exhibit non-Newtonian behavior, i.e., their viscosity depends on strain rate (Malone et al., 2003a; McClements, 2005; Gonzalez-Tomas et al., 2008). The most common type of non-Newtonian behavior is *shear-thinning*, i.e., a decrease in viscosity with increasing strain rate. When trying to simulate the rheological behavior of food emulsions during mastication, it is therefore important to establish the strain rate that provides the best representation of the flow conditions within the mouth. Shama and Sherman (1973) measured the influence of strain rate on the rheological properties of semisolid foods and attempted to correlate the measured results to the sensory perception of food products during mastication. They proposed that shear rates of 10–50 s^{-1} to be the most suitable for mimicking oral conditions (Shama and Sherman, 1973). It should also be noted that food emulsions are diluted with saliva within the mouth and this will have a pronounced effect on their perceived textural properties during mastication. This is particularly important in food emulsions that contain starch granules, because the starch is rapidly degraded by amylase within the mouth (Chung et al., 2012a).

Many emulsion-based food products can be considered to have "plastic-like" behavior: they behave as elastic solids below a critical applied stress (the "yield stress"), but behave as viscous fluids above this value. These products are usually characterized in terms of their yield stress, consistency, and flow index.

Viscoelastic Properties (Small Deformation)

Small deformation rheology is commonly used in fundamental studies of material properties (Larson, 1999). The most commonly measured property of solids and gels is the *dynamic shear modulus* (G), which has as an elastic component G' (the storage modulus) and a viscous component G'' (the loss modulus). The dynamic shear modulus can also be reported as a complex modulus (G^*) and a phase angle (δ) (Tadros, 2004; Liu et al., 2007; Mun et al., 2009). As with large deformation methods, it is important to establish the most appropriate operating conditions for this type of measurement, e.g., the oscillation frequency. A frequency of 50 rad s^{-1} has been reported to give a good correlation with the perceived "thickness" of some foods (Bistany and Kokini, 1983; Richardson et al., 1989). Small deformation tests have been widely used to characterize the rheological properties of emulsions and emulsion-based food products. Nevertheless, the data obtained from these techniques may not correlate well with the results of sensory evaluations (Liu et al., 2007). A major drawback of small deformation methods is that they are not carried out under conditions that simulate the complex processes occurring within the mouth during mastication, e.g., sample disruption or dilution with saliva.

Tribology

The limitations of conventional rheological testing methods has led to considerable interest in developing alternative methods that more accurately model the complex processes occurring within the mouth. An important element of the mastication process that is not modeled well using conventional rheological methods is the fact that a food is present as a *thin lubricating film* between the tongue and palate. The importance of frictional forces and lubrication on texture perception was recognized many years ago (Kokini and Cussler, 1983). However, the widespread utilization of thin film rheology ("tribology") to simulate the oral behavior of food products and to correlate to sensory perception has only become popular fairly recently (Stokes et al., 2008; Le Reverend et al., 2010; Chen and Stokes, 2012). The thin film rheology of materials is measured using instruments referred to as tribometers. A simple tribometer consists of a ball and a disk between which the sample to be analyzed is placed. A normal load is applied to the system and the ball and disk are made to rotate at different speeds, leading to a relative strain rate between them. The instrument measures the *coefficient of friction* of the material as the strain rate is changed. The tribological properties of a material are usually described by a "Stribeck curve", which is divided into three regimes: (i) boundary friction; (ii) mixed friction; (iii) fluid friction. The Stribeck curve is a plot of the measured coefficient of friction versus strain rate.

A number of studies have shown that tribology measurements can provide information about food stuffs that cannot be deduced from conventional bulk rheology methods (Malone et al., 2003a; de Wijk and Prinz, 2005, 2006). Several authors have used tribology to study the friction, lubrication, and adhesion of model food systems (such as mayonnaise, chocolate, and desserts) and related them to in-mouth textural perception (Malone et al., 2003a; Lee et al., 2004; de Wijk and Prinz, 2005, 2006; Bellamy et al., 2009; Terpstra et al., 2009).

Extensional/elongational Flow Rheology

Initial studies of oral food texture largely focused on the importance of simulating the shear flow that occurred within the mouth (Shama and Sherman, 1973; Kokini et al., 1977). More recently it has been recognized that elongational flow also plays an important role during mastication (de Bruijne et al., 1993). When the tongue and palate move together during mastication the food material is squeezed out from between them, which had a strong elongational flow component. Hence, it has been proposed that rheological testing methods should include both elongational and shear flow to more accurately simulate oral food texture (Lillford, 2000; Le Reverend et al., 2010). A number of testing methods have therefore been developed that utilize elongational and sheared flow (Suwonsichon and Peleg, 1999; Campanella and Peleg, 2002; Terpstra et al., 2007). Some of the methods suitable for testing semisolid food products (such as many emulsion-based products) include tribology (see above), squeezing flow (Campanella and Peleg, 2002; Chatraei et al., 1981), "imperfect" squeezing flow (Suwonsichon and Peleg, 1999), pressure drop techniques (Macosko, 1994), and funnel techniques (Terpstra et al., 2007).

In the squeezing flow method (Chatraei et al., 1981; Campanella and Peleg, 2002; Engmann et al., 2005), the food sample is compressed between two parallel plates to induce biaxial elongational deformation. The compression between the two plates and the food is said to resemble that of the tongue and palate during mastication (Terpstra et al., 2007). In brief, the elongational properties of a material are measured by loading the sample on the lower plate followed by compression of the sample from an initial sample height to a final sample height by lowering the upper plate at a controlled rate. Next, the upper plate is halted at the final height to allow stress relaxation of the sample, followed by a decompression step (Suwonsichon and Peleg, 1999; Terpstra et al., 2007). The output of this test is in the form of force–height, force–time and/or height–time relationships, from which several rheological parameters can be derived, e.g., elongational flow curve (Suwonsichon and Peleg, 1999; Campanella and Peleg, 2002). Further information about the various squeezing flow techniques available can be found in the literature (e.g., (Suwonsichon and Peleg, 1999; Campanella and Peleg, 2002; Engmann et al., 2005; Terpstra et al., 2007)).

Recently, a combined squeezing flow–shear viscosity method has been developed to simulate the oral processes occurring during mastication (Chung et al., 2012a). The sample to be tested is placed between two horizontal parallel plates that undergo a series of compression-shear-decompression motions designed to simulate mastication. The normal and shear forces measured on the upper plate provide information about the rheological properties of the sample, including maximum peak force (related to consistency), maximum trough force (related to adhesiveness), residual stress (related to yield stress), and shear viscosity. The sample to be tested can be mixed with saliva prior to testing to more closely simulate oral conditions. Preliminary experiments indicate that this technique can be used to monitor the textural changes in starch-based food products during oral processing (Chung et al., 2012a). A schematic diagram of this new mastication simulation method and the typical data obtained is shown in Figure 10.

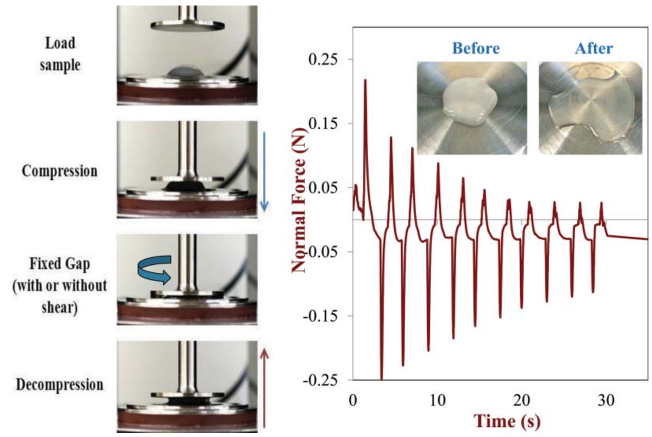

Figure 10 Diagram of an instrumental method designed to simulate oral mastication. The device measures normal and shear forces versus time when a sample is subjected to numerous compression-shear-decompression cycles.

Other Miscellaneous Tests

A number of other rheological and nonrheological tests have been used to better understand the influence of food behavior in the mouth on perceived textural perception. These tests include:

Wettability

The ability of a food material to spread out and coat the tongue is characterized by its wettability, which can be measured using contact angle techniques (Ranc et al., 2006; Ranc et al., 2006; van Aken, 2007; Dresselhuis et al., 2008).

Stickiness

The tendency of a food to give a sticky sensation when the tongue and palate are moved apart can be simulated by measuring the tensile force when two probes are moved apart (van Aken, 2007).

Spit-out Methods

A food material can be spat out after mastication, and then its microstructure and physicochemical properties can be measured using various analytical methods, such as microscopy, rheology, light scattering or ζ-potential (de Wijk et al., 2006; Prinz et al., 2006b).

Oral Microscopy

The structure of an ingested food can be visualized in vivo within the mouth using specially developed microscopy methods (Adams et al., 2007). The thickness of lipid layers deposited on the human tongue can also be measured (Pivk et al., 2008a).

Food Microstructure

The structural organization of the various components within an emulsion-based food product plays an important role in determining its physicochemical and sensory properties. A variety of analytical tools are available to provide information about the size, shape, aggregation state, and location of the various components in food emulsions.

Microscopy

The techniques that have been most commonly used to visualize microstructure of a food product include optical microscopy (McClements, 2005), confocal laser scanning microscopy (CLSM) (Loren et al., 2007), electron microscopy (McClements, 2005) and atomic force microscopy (AFM) (Morris, 2007). An example, of the use of optical and confocal fluorescence microscopy to study the distribution of fat droplets within a model food emulsion containing swollen starch granules and emulsified fat is shown in Figure 11.

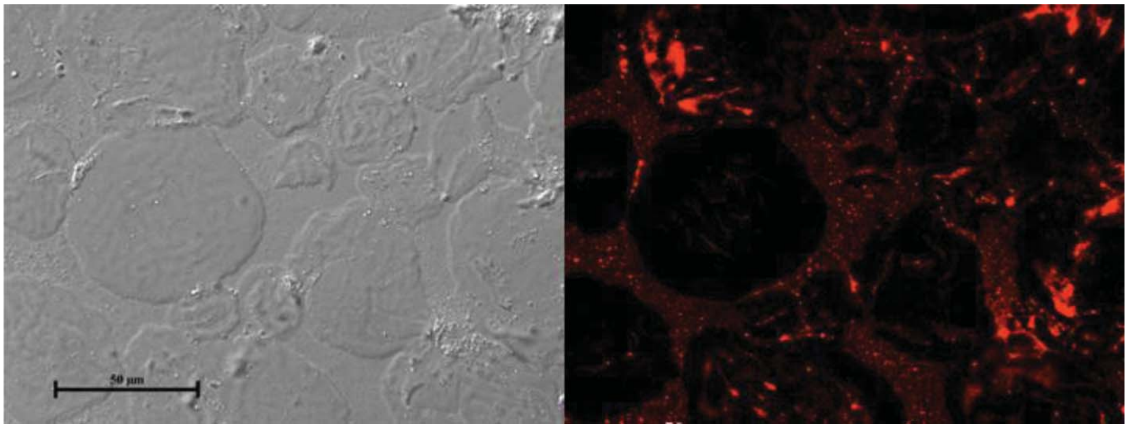

Figure 11 Optical microscopy (left) and confocal fluorescence microscopy (right) images of a model sauce containing starch granules and fat droplets. In the confocal image the swollen starch granules are the large black objects, while the fat droplets are the small red particles evenly dispersed throughout the intervening aqueous phase. Images kindly supplied by Bicheng Wu.

Particle Characteristics

Knowledge of particle characteristics, such as size and charge, are often critical for understanding the properties of emulsion-based food products (McClements, 2005, 2007). The most commonly used methods of measuring the particle size distribution of emulsion products are based on light scattering. Static light scattering (particles of 100 nm–1000 μm) and dynamic light scattering (3 nm–3 μm) instruments are suitable for analyzing emulsions containing relatively small fat droplets. The electrical charge (ζ-potential) of fat droplets is usually measured using particle electrophoresis (Hunter, 1986). This technique measures the direction and velocity of particle movement in a well-defined electric field and uses a mathematical model to determine the ζ-potential of the particles. Information about the physical state of fat droplets (e.g., solid versus liquid) can be determined using optical microscopy (crossed-polarizers), differential scanning calorimetry, nuclear magnetic resonance, or X-ray scattering.

Limitations of Tests

Ideally, food scientists would like to establish one or more rheological tests that can be used to reliably predict the sensory performance of foods. These tests could then be used to quantitatively screen the effects of factors such as product composition, manufacturing methods, and storage conditions on product quality. In reality, it has proved extremely difficult to identify objective rheological measurements that reliably correlate to the sensory performance of foods. This phenomenon can be attributed to the complexity of the physicochemical and physiological processes that occur during the mastication and sensory perception of foods. For this reason, sensory testing is still the most reliable method of testing the overall perceived quality of food products.

Sensory Evaluation

As mentioned previously, analytical tests and instruments may help to identify key factors that determine flavor perception, however, they cannot model the extreme complexity of the human sensory system. Moreover, the definitive test of the quality of a food product is its acceptance and liking by consumers. Hence, sensory analysis by human subjects is still a critical tool for assessing the overall flavor profile and acceptance of food products (Dijksterhuis and Piggott, 2000; Foster et al., 2011b). Besides that, the study of in-mouth sensory perception has a key role in elucidating the way food microstructures behave within the mouth (van Aken, 2007). This knowledge can then be used to redesign foods to have particular desirable sensory attributes.

A panel of people is commonly used to carry out sensory analysis in the food industry (Stone and Sidel, 2004). The individuals on the panel are selected based on their sensory sensitivity and are preferably not involved in the subject of research. A sensory panel may be an untrained or a trained group depending on the purpose of the test. It is more time consuming and expensive to use trained panels, but more detailed and precise information can often be obtained. The typical size for a sensory panel ranges between about 10 to 20 people (van Aken, 2007). The most commonly used sensory methods in the food industry can be divided into two categories: (i) *discriminative* tests and (ii) *descriptive* tests (Stone and Sidel, 1993; Piggott et al., 1998; Murray et al., 2001). In a discriminative test a panelist is asked to assess whether there is a detectable difference between some attribute(s) of different food samples. In a descriptive test a panelist is asked to score some predetermined attribute of a food product on a scale.

In traditional sensory analysis, a panel is provided with a sample and then asked to provide an overall evaluation of it. More recently, it has been recognized that the perceived flavor of a food changes before, during, and after mastication (Taylor and Linforth, 2000). Hence, a number of dynamic sensory analysis methods have been developed (Dijksterhuis and Piggott, 2000): (i) time-intensity analysis (de Wijk et al., 2003; McClements, 2005; van Aken, 2007); (ii) instructed tests (de Wijk et al., 2003; van Aken, 2007); and (iii) temporal dominance of sensation (TDS) tests (Kemp et al., 2009; Pineau et al., 2009; Foster et al., 2011b). In general, sensory evaluation should be treated as a dynamic multifaceted process that begins from the panelist's first visual impression of the product, followed by sensations of smell and touch during handling of the product, and then by sensations of aroma, taste, and mouthfeel during and after consumption of the product (Morris, 1995). Details of different sensory tests can be found in the references cited above and in the many textbooks and review articles on this important subject.

ORAL PHYSIOLOGY AND FAT PERCEPTION

Mastication

The initial amount, structure, composition, and geometry of a food product influence its oral processing and flavor perception (Figure 2). Mastication is a complex physiological and physicochemical process that leads to the break down and lubrication of ingested foods into a bolus suitable for swallowing (Chen, 2009; Foster et al., 2011b). Oral processing involves integrated movements of the upper and lower jaw, tongue, cheeks, and lips (Hiiemae et al., 1996), which are coordinated by the *motor program* activated in the brain stem central pattern generator (Dellow and Lund, 1971; Yamada et al., 2005). Sensory feedback from different types of receptors allows the motor program to adapt continuously throughout a chewing sequence to the properties of the bolus (Woda et al., 2006; Foster et al., 2011b). The oral processing of foods during mastication can be divided into a number of stages:

Stage I: The initial stage following ingestion of a food product involves squeezing small portions of the food into a thin gap and shearing them between the tongue and other oral surfaces (e.g., the teeth and palate) (Ranc, Servais, Chauvy, Debaud and Mischler, 2006; Foster et al., 2011b; van der Bilt, 2009). The behavior of emulsion-based food products during this stage depends on their initial structure and physical properties. Predominantly, fluid-like products (such as milk, dressings, or beverages) do not need to be broken down into smaller pieces within the mouth, whereas semisolid or solid-like products (such as some gelled deserts, butter, and margarine) need to be disrupted. The kinetics of product breakdown within the mouth and the nature of the fragments formed play an important role in determining the perceived texture of semisolid foods (Figure 12).

Stage II: The second stage in oral processing involves the conversion of the food into a *bolus* of suitable size, composition, and properties for swallowing and further processing within the gastrointestinal tract. This process involves rhythmical mouth movements that reduce the dimensions of the food and mix it with saliva (Pedersen et al., 2002; van der Bilt, 2009; Foster et al., 2011b). The number of chewing cycles required to prepare the bolus is related to the bite volume and consistency of the ingested food (Thexton and Hiiemae, 1997). Saliva contains a number of components that influence the oral processing and sensory perception of foods (Williams et al., 2005). Amylase in the saliva promotes the enzymatic degradation of any starch within a food product, which may play an important role in sensory perception. For example, the influence of starch degradation by amylase on changes in the textural properties of model sauces containing starch granules and fat droplets is shown in Figure 13. In the presence of amylase the shear viscosity of the sauces decreases more rapidly under simulated mastication conditions than in its absence, which can be attributed to starch degradation. The water in saliva moistens, dilutes, and lubricates food particles, while the mucins bind the masticated food components together and form a slippery bolus that can be more easily swallowed (Foster et al., 2011b; Pedersen et al., 2002). The

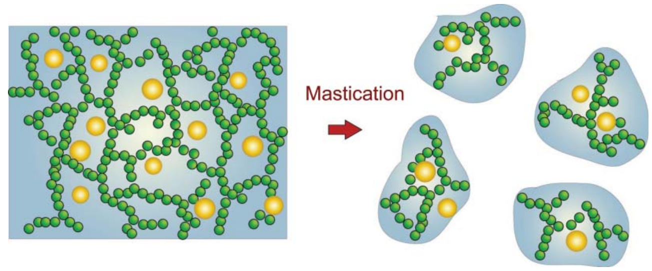

Figure 12 The breakdown of semisolid and solid foots in the mouth due to mastication plays an important role in determining their sensory perception.

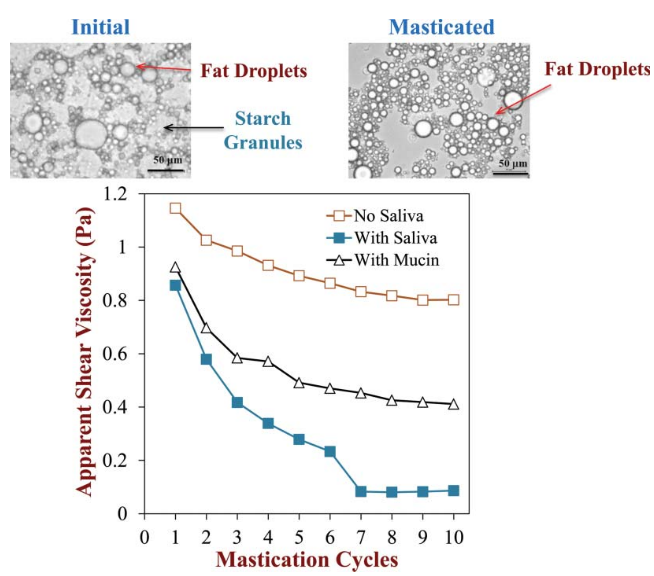

Figure 13 Influence of saliva on the microstructure and texture of mixed food emulsions containing fat droplets and starch granules during mastication: (i) No saliva; (ii) saliva (water, mucin, and amylase); (iii) mucin (water and mucin). Photos show model sauce before and after mastication with saliva.

secretion of saliva within the oral cavity is stimulated by various olfactory, visual, auditory, touch, and taste cues (Fischer et al., 1994; Totora and Grabowski, 1999).

Stage III: The third stage in the mastication process involves movement of the bolus to the back of the tongue prior to swallowing. It has been reported that the transport of the food in the mouth during this stage is mainly due to tongue-palate interactions (Hiiemae et al., 1996). When the slippery food bolus is ready to swallow, it is propelled backward into the oropharynx and then down into the esophagus (Pedersen et al., 2002; van der Bilt, 2009; Foster et al., 2011b).

FLAVOR PERCEPTION

A general introduction to flavor perception is given in this section, while the role of fat in flavor perception is discussed in the following section. It is useful to make a distinction between the terms "sensation" and "perception" when considering the sensory attributes of food products. *Sensation* can be defined as the response of a particular sensory receptor to some form of stimulation, whereas *perception* can be defined as awareness through the senses interpreted in the light of experience. Thus a *sensation* is a physiological response that can often be quantified using appropriate analytical methods, whereas a *perception* is usually an oral or written description reported by a person that depends on physiological, psychological, and cultural factors. In addition, the overall perception of a particular food attribute may come from one or more of the five human senses (touch, taste, smell, hearing, and sight). An individual's perception of a particular food product is the result of the way that it interacts with the different senses before, during, and after ingestion, as interpreted by the brain (van der Bilt, 2009). The process of mastication provides sensory feedback from which sensory perceptions are derived (Brown et al., 1998).

Flavor is defined as the combined perception of mouthfeel, texture, taste and aroma (British Standards Institute, 1975), and flavor perception during mastication usually involves integration of information from all of these senses (Small and Prescott, 2005; Gonzalez-Tomas et al., 2008). Thus, changing one flavor modality of a food may alter its overall flavor perception (Small and Prescott, 2005). The perceived flavor of an ingested food depends on its initial composition, structure, size, shape, and rheology, as well as its behavior in the mouth during mastication, e.g., due to dilution with saliva, oral motion, flow profiles, and surface phenomenon (Brown et al., 1998; Togashi et al., 2000; Ranc et al., 2006; Woda et al., 2006).

Flavor perception of foods occurs throughout the mastication process, which involves the first bite, subsequent oral processing, and post-swallowing when a thin coating of food remains on the oral surfaces (Ranc et al., 2006; van der Bilt, 2009; Foster et al., 2011b). Sensory inputs to the brain are a result of the interactions of volatile and nonvolatile compounds with odor, taste, trigeminal and tactile receptors in the nose and mouth before, during, and after mastication (Bell, 1996; Taylor, 1996; Brown et al., 1998). There are numerous types of receptors in the oral and nasal cavity that can respond to chemical and physical aspects of ingested foods, thereby leading to perceptions of aroma, taste, texture, and mouthfeel. The aroma of a food is a result of the interactions of volatile compounds with flavor receptors in the nose (olfactory epithelium) while the taste of a food is from the interactions of some nonvolatile compounds with receptors in the mouth (Taylor, 1996; Duran and Costell, 1999; Gilbertson et al., 2000). Most of the perceived sensations related to food texture occur during the manipulation, deformation, and movement of the food across the oral receptors (van der Bilt, 2009). Mouthfeel is primarily the result of interactions between the food and nonspecific receptors within taste buds that are sensitive to tactile stimuli (Smith and Margolskee, 2001). The flavor perceived from a food is determined by the type and concentration of flavor compounds present in the product and the ability of these compounds to reach the appropriate sensory receptors in the mouth and nose (Taylor and Linforth, 1996; Larsson and Larsson, 1997). The initial concentration, location within the food, and the ability of the flavor compounds to move from the food matrix to these receptors determines the characteristic flavor profile of a food product.

INFLUENCE OF FAT ON FLAVOR PERCEPTION

Fats influence the overall flavor perception of emulsion-based products through both direct and indirect mechanisms that influence mouthfeel, aroma, and taste. Different sources of fats and oils used to prepare food emulsions differ in the type and concentration of volatile compounds they contain. Thus, food products made from olive oil, corn oil, fish oil, and canola oil will all have different flavor profiles. The type and amount of fat present will also influence the perception of volatile and nonvolatile components by altering their partitioning between the oil, water, and gaseous phases (Figure 8) (McClements, 2005). The fat droplets will also alter the mouthfeel of emulsion-based products due to their influence on their rheological, coating and thermal properties (Chen, 2009; Chen and Eaton, 2012).

Influence of Fat on Flavor Partitioning and Release

Fats in food emulsion products can affect flavor perception in various ways. Fats can affect the aroma and taste by altering flavor partitioning and mass transport (de Roos, 2006). Fats can act as a reservoir for nonpolar volatile compounds (Bayarri et al., 2006; Doyen et al., 2001) and therefore mediate their rate and extent of release during mastication (Rabe et al., 2003). The perception of a flavor compound depends on its location within the food matrix, i.e., fat droplet interior, aqueous phase, oil-water interface, or headspace (Druaux and

Voilley, 1997; McClements, 2005; van Aken, 2007). Fats also have a significant effect on the texture and mouthfeel of emulsions by forming a coating on the oral tissue when fat droplets breakdown through coalescence and phase separation (Elmore et al., 1999; van Aken, 2004; Prinz et al., 2006a; Pivk et al., 2008; Pivk et al., 2008b). In the mouth, the coating formed by the fats on the oral surfaces may act as a reservoir for aroma compounds. Consequently, this may prolong the residence time of aroma compounds in the mouth and produce longer lingering effects of flavor, and the food product may be perceived as "rich" in comparison to a reduced fat product (Doyen et al., 2001; Malone et al., 2003b; de Roos, 2006). The presence of fat droplets in O/W emulsions has been found to influence both the instrumental flavor profile (flavor concentration versus time) and the dynamic sensory perception (perceived flavor versus time) of food products (Shamil et al., 1991; Malone and Appelqvist, 2003).

The amount of fat droplets in an emulsion-based product influences the partitioning and release of flavor molecules, thereby altering its perceived flavor profile. The flavor profiles of emulsion-based food products can therefore become imbalanced when the fat concentration is reduced (Figure 14). In full fat products the flavor intensity remains moderately high over prolonged periods ("sustained release"), whereas in reduced fat products there is an initial high intensity spike of flavor immediately after consumption, followed by low flavor intensity at longer times ("burst release") (Malone and Appelqvist, 2003; Frank et al., 2011a; Frank et al., 2012). The reason for this initial flavor burst in reduced fat emulsions is because an appreciable fraction of the nonpolar flavor molecules are initially present in the water phase rather than the oil phase (Malone and Appelqvist, 2003). This effect is particular

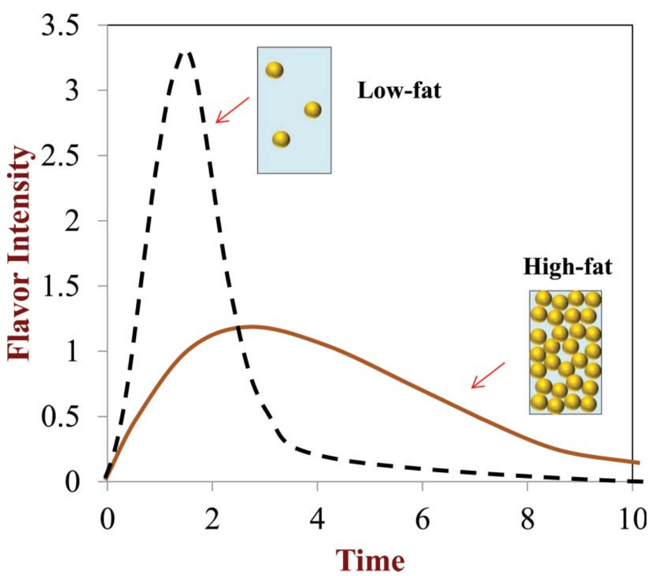

Figure 14 Highly schematic diagram of differences in flavor release profiles of low fat and high fat emulsion-based foods. A nonpolar flavor molecule will give a burst release in a low-fat product, but a more sustained release in a high fat product.

important for nonpolar flavor compounds, such as the buttery and creamy flavors present in many emulsion-based products. A major challenge in creating reduced fat products is therefore to match their flavor release profiles to those of equivalent full fat products. This can be achieved by reformulating the type and concentration of flavor components in a reduced fat product and/or by using novel encapsulation technologies that modulate the release profile of specific flavors (Malone et al., 2000; Malone and Appelqvist, 2003; Foster et al., 2011a). Enhancement of other nonfat flavors can also be done to change the overall flavor profile to compensate for the effects of fat reduction, e.g., by adding herbs, seasonings or spices, by increasing sodium or savory levels, or by adjusting pH or acidity. Food scientists can also change the relative proportion of different components in reduced fat meals, e.g., by keeping the composition of an emulsion-based sauce the same but reducing the amount of it in the meal.

The kinetics of flavor release also depends on droplet size for nonpolar flavors since they must diffuse out of the fat droplets before being released into the aqueous phase and headspace above the emulsion (Miettinen et al., 2002). When the fat droplets are above a certain size (a few micrometers) there may be a delayed release of nonpolar flavor molecules within the mouth during mastication. On the other hand, for smaller droplets the particle size may not have a strong influence on flavor release kinetics since molecular diffusion occurs so rapidly. Changing the concentration, size, or structural organization of the fat droplets within emulsions may also indirectly influence aroma and taste perception (Malone et al., 2003b; Bayarri et al., 2007). For example, products with different viscoelastic properties may trigger different *trigeminal* sensations and so modify the signals from the taste and aroma receptors during neural processing, or they may alter the mass transport of flavor and aroma molecules through the food matrix during mastication. Fats may also coat the surface of the oral cavity during mastication thereby physically interfering with the ability of taste molecules reaching the taste receptors (Lynch et al., 1993).

Influence of Fat on Mouthfeel and Texture

The "mouthfeel" of food products plays an important role in determining their overall perceived flavor. "Mouthfeel" can be defined as the sensations arising from the interactions of an ingested food (mixed with saliva) with the receptors in the mouth that respond to tactile stimuli during mastication (Smith and Margolskee, 2001). Visual and auditory cues may also contribute to the perceived mouthfeel of foods (Chen and Eaton, 2012; McClements, 2005; Su et al., 2010; Foster et al., 2011b).

A number of descriptors have been developed to describe the mouthfeel characteristics of food emulsions including "creaminess," "firmness," "hardness," "thickness," "thinness," "smoothness," "richness," "sliminess," "watery," and "astringency" (Mela et al., 1994; Guinard and Mazzucchelli, 1996; Malone et al., 2003a, 2003b; Chen and Eaton, 2012). An important contributor to the perceived mouthfeel of a food product is its bulk and thin film rheological behavior (Guinard and Mazzucchelli, 1996; Malone et al., 2003a; van Aken, 2004). Certain aspects of the mouthfeel of a product may persist in the mouth after food consumption (e.g., mouth coating and astringency), which is usually referred to as "afterfeel," in the same way as the term "aftertaste" is used to refer to residual taste sensations (Guinard and Mazzucchelli, 1996).

For food emulsions, the perceived mouthfeel is greatly influenced by the type, concentration, and interactions of the fat droplets present (Roland et al., 1999; Frost et al., 2001; Kilcast and Clegg, 2002). For example, the perceived "fattiness," "creaminess," and "thickness" of oil-in-water emulsions has been shown to increase with increasing oil droplet concentration and size (Mela et al., 1994; Moore et al., 1998; Kilcast and Clegg, 2002; Clegg et al., 2003; Frost and Janhoj, 2007; Chojnicka-Paszun et al., 2012; Ciron et al., 2012). However, other studies found no influence of droplet size on perceived "creaminess" (Akhtar et al., 2005). Thus, it may be deduced that fats can influence the sensory properties of different food products in product-specific different manners. A study also found that there was a critical fat level (between 22 and 33%) below which fat was not perceived by textural cues (Bellamy et al., 2009). Ingested W/O emulsions (such as butter and margarine) undergo phase inversion (O/W to W/O) in the mouth due, which can lead to the formation of free oil that can lubricate the oral surfaces (Reich and Urbanski, 2004; Tieu and Kosasih, 2007).

Mathematical models have been developed in an attempt to relate the perception of creaminess (related to fat content) with other sensory attributes, in particular "thickness" (related to rheological properties), "smoothness" (related to particle size in colloidal systems) and "slipperiness" (related to tribological properties) (Kokini and Cussler, 1983; Kokini, 1987, 1995).

A study done by de Wijk and Prinz (2005) found that with increasing fat content in vanilla custard desserts and mayonnaises there was: (i) lower sensations of roughness; (ii) higher sensations of creaminess; and, (iii) lower measured friction. For the mayonnaises, the size of the fat droplets influenced the measured friction, with friction increasing with increasing fat droplet size, especially for larger droplets ($d > 4\ \mu$m). The authors explained that smaller droplets might be less deformable than larger ones, which resulted in a smaller contact area and consequently reduced friction. Large droplets may also be more prone to in-mouth coalescence, leading to greater lubrication and coating of the tongue. The authors suggested that lubrication is an important mechanism by which fat affects the perceived texture of low fat foods within the mouth. In another part of the study, the authors reported that low fat foods mixed with saliva had lower friction compared to similar custards mixed with only water. They postulated that starch breakdown by salivary amylase resulted in reduced friction, possibly through the liberation of fat from the starch food matrix. The liberated fat may have migrated to the surface of the bolus via convection currents where it became available for lubrication between the bolus and the oral tissue. In another study, the same authors (de Wijk and Prinz, 2007) assessed the perceived fattiness, creaminess and other texture and flavor attributes of a group of vanilla custard desserts, white sauces, and mayonnaises of different fat content (0 to 72%), ingredients, and consumption temperatures. Instrumental methods were used to measure the lubrication behavior, infrared reflectance, and turbidity of rinse water of the foods. Their results revealed that the fat content of custards, sauces, and mayonnaises was (i) strongly related to perceived fattiness–fatty mouthfeel, fatty after-feel, and oily/fatty flavor and (ii) weakly but significantly correlated with creamy mouthfeel and after-feel. The results obtained from instrumental measurements for friction and infrared reflectance revealed that properties of the surface of the oral food bolus were important for fat-related attributes via mechanisms like lubrication.

Some studies strongly suggest that the friction sensed between the tongue and palate play a major role in determining the overall fat perception of ingested food products (Malone et al., 2003a; Dresselhuis et al., 2007). Tribological properties such as friction and lubrication may contribute to oral texture perception of fat-containing foods (de Wijk and Prinz, 2005; Dresselhuis et al., 2008), particularly mouth-coating phenomenon such as the formation of thin coatings of food remaining on oral surfaces after swallowing (Bellamy et al., 2009). Thus, objective instrumental measurements of the coefficient of friction of food products may provide information that is associated with fat-related textural sensory attributes, ranging from roughness to creaminess (de Wijk and Prinz, 2005; Dresselhuis et al., 2007; Dresselhuis et al., 2008).

The physical state and phase transitions of the fat phase within the mouth may also play an important role in contributing to the overall sensory perception of some fatty foods. The crystal structure and melting point of the fat phase in emulsion-based food products can be manipulated by product developers to alter their perceived textural attributes, which may be an important consideration when developing effective reduced fat strategies (Gioielli et al., 2003; van Aken et al., 2011). The melting of solidified fats within the mouth may contribute to the perceived mouthfeel of some food emulsions because it leads to a cooling sensation due to the endothermic enthalpy changes associated with crystal melting (Walstra, 1987).

The presence of biopolymers (polysaccharides or proteins) can also influence the perceived texture and mouthfeel of emulsion-based food products. The type, concentration, and interactions of biopolymers present within a food will influence the microstructure, rheology, and stability of emulsions in the mouth (Dickinson, 1992; Malone et al., 2003a). Creamy mouthfeel has also been observed to be effected by the type of emulsifier used to stabilize the oils, which could be due to the differences in the impact of emulsifiers on droplet flocculation, emulsion viscosity, and interactions with the oral surfaces (Moore et al., 1998; van Aken, 2004, 2007; van Aken et al., 2011).

Influence of Fat on Oral Coating

In the mouth, oil droplet coalescence can be (i) shear-induced, (ii) surface-induced, (iii) air-induced, and/or (iv) saliva-induced (Dresselhuis et al., 2008; Vingerhoeds et al., 2008; van Aken, 2010). Shearing can increase the frequency of droplets colliding with each other, which enhances the sensitivity of droplets to coalescence (McClements, 2005). Surface-induced coalescence occurs due to spreading of oil droplets on the oral mucosa (Dresselhuis et al., 2008; Benjamins et al., 2009b). Air-induced coalescence occurs due to the spreading of fat droplets on the surfaces of the air bubbles formed in the mouth during mastication (Hotrum et al., 2005). Saliva-induced coalescence would occur in emulsions stabilized by starch-based emulsifiers due to the enzymatic activity of amylase present in saliva. In general, the occurrence of in-mouth coalescence is influenced by emulsion characteristics (e.g., emulsifier type and concentration, oil type and concentration, droplet size, and droplet charge), the shear applied during mastication, saliva composition and properties, and the characteristics of the oral mucosa.

A study demonstrated that emulsions that were most sensitive to in-mouth coalescence gave rise to the highest reported levels of creamy, fatty, and oily sensations in sensory analysis (Dresselhuis et al., 2008). In this study, the authors investigated the relationship between the sensitivity of emulsions to in-mouth coalescence and the sensory perception of fat-related attributes (e.g., creaminess), as well as the relationship between in vivo perceived and ex vivo measured friction. Emulsions with varying sensitivities toward in-mouth coalescence were produced using different types of emulsifier, and then their sensory perception was evaluated by trained panelists. The author's reported that the emulsions that were most sensitive to in-mouth coalescence had the highest "creamy," "fatty," and "oily" taste sensations. Combining friction force measurements with sensory analyses revealed that the occurrence of coalescence gave rise to an enhanced fat perception and also lowered the orally perceived and experimentally measured friction. It has been reported that perception of fat-related attributes (e.g., creaminess) correlates with friction forces sensed between the tongue and palate (Malone et al., 2003a; de Wijk and Prinz, 2005). Coalesced oil droplets may form a fatty coating on the oral mucosa, which reduces the perceived friction force. Coalescence may also influence fat perception by affecting aroma release, as it is suggested that aroma perception correlates with creaminess perception (Yackinous and Guinard, 2000; Frost et al., 2001).

Benjamins et al. (2009a) evaluated the role of partial coalescence of whey protein-stabilized emulsions on sensory perception. They found that various fat-related sensory attributes (e.g., "creamy," "fatty," and "after-feel coating") were correlated to an increase in viscosity and partial coalescence within the mouth. Moreover, they found that in-mouth aeration induced extra coalescence, which increased the perception of fat-related sensory attributes.

In another study, it was found that adhesion and spreading of emulsion droplets on solid surfaces lowers the measured friction (Dresselhuis et al., 2008). The authors proposed that sensory perception of fat is related to orally perceived in-mouth friction. This study used a flow cell in combination with light microscopy and video imaging to distinguish between adhered and spread emulsion droplets. They postulated that electrostatic, steric, and hydrophobic interactions of the fat droplets with solid surfaces determined the adhesion and the subsequent spreading of fat droplets. The hydrophobic interaction between fat droplets and solid surfaces was shown to be particularly important for droplet adhesion and spreading. The authors further found that saliva was of minor importance for adhesion and spreading. This study suggested that it is may be a useful strategy to develop emulsions that are stable during their shelf life, but that breakdown in the mouth and spread onto oral surfaces thereby lowering oral friction and enhancing fat perception (Dresselhuis et al., 2008).

Influence of Fat on Thermal Conductivity and Temperature

Recently, it has been suggested that heat transfer between a food and the oral surface may also be an important cue for fat perception (Weenen et al., 2003; Prinz et al., 2007). Weenen et al. (2003) observed that high fat products were perceived as warmer than low fat products. In a further study, Prinz et al. (2007) highlighted that thermal conductivity may be an important parameter contributing to the perceived quality of fatty foods. This study found that the lips and tongue are able to detect small differences in the temperature of an ingested food. The researchers also suggested that the amount of flavor released from food products with different fat contents may be different due to differences in their temperature profiles within the mouth (Engelen et al., 2002; Prinz et al., 2007).

BIOLOGICAL RESPONSES: HUNGER, SATIETY AND SATIATION

Hunger consists of a range of physiological and psychological responses that drive individuals to eat and sustain eating, such as mental urges and cravings to consume food (Blundell et al., 2010; Halford and Harrold, 2012). In general, eating behavior is influenced by a combination of physiological oral, gastric, intestinal, and metabolic processes (French and Cecil, 2001; Havel, 2001). The ingestion of a food reduces hunger and stimulates various biochemical feedback mechanisms that initially decrease appetite and eventually suppress it, thereby stopping the inclination to consume more and thereby bringing a meal to an end. The various physiological and psychological processes associated with the decreased desire to consume more at the end of a meal are collectively known as *satiation*. The satiation response determines the total amount of food consumed during a meal, as well as the overall duration and rate of consumption of the meal. *Satiety* is the feeling of fullness that one experiences after the consumption of a meal. This feeling contributes to the length of time before a person starts to feel hungry again, and therefore helps prevent further consumption between meals. The satiation and satiety responses are both induced by ingested food components through mechanical stimulation and the release of specific peptides in the gastrointestinal tract (GIT) that modulate food intake. Satiation and satiety are influenced by food properties, such as its total mass, texture, composition, energy-density, internal structure, and sensory impact (Blundell et al., 2001; Del Prete et al., 2012; Halford and Harrold, 2012; Rego Costa et al., 2012).

Information about physiological and metabolic processes occurring in the GIT is received by the central nervous system (CNS). The CNS receives signals that contribute to the regulation of food intake, energy expenditure, and food storage by stimulating or inhibiting food consumption and regulating body fat stores (Blundell et al., 2001; Del Prete et al., 2012; Karhunen et al., 2008; Kim and Park, 2011; Schwartz et al., 2000). Overall, the cycle of eating in humans can be divided into three major stages: (i) meal initiation; (ii) within-meal satiety; and, (iii) across-meal satiety (Figure 15) (Moran, 2009; Del Prete et al., 2012).

HUNGER–MEAL INITIATION (PREPRANDIAL)

Immediately after consuming a meal a person normally has a feeling of fullness, but sometime after the meal has been consumed the levels of a hormone (*ghrelin*) that is produced within the stomach start to increase. Elevated levels of ghrelin have been associated with the feeling of hunger, which leads to an increase in appetite and the tendency to consume food. Ghrelin is a peptide expressed in the GIT that has been found to be a regulator of energy homeostasis and body weight (Cummings et al., 2002; Muccioli et al., 2002; van der Lely et al., 2004). Ghrelin peptides are also produced in other sites within the human body including the small intestine, lungs, pancreatic islets, placenta, kidney, and brain (Kojima et al., 1999; Hosoda et al., 2000; Karhunen et al., 2008; Del Prete et al., 2012). Ghrelin receptors are located widely in the brain and peripheral tissues, including the pituitary, stomach, intestine, pancreas, thymus, gonads, thyroid and heart (Cummings, 2006). Ghrelin has also been shown to have other biological actions, including modulating gastrointestinal motility, insulin secretion, pancreatic exocrine secretion, cardiovascular function, immunity, and inflammation (van der Lely et al., 2004; Drazen et al., 2006). The level of circulating ghrelin rises just before a meal and falls shortly after ingestion (Drazen et al., 2006). Ghrelin stimulates food intake by crossing the blood-brain barrier (BBB) and acting on reward centers in the brain (Karhunen et al., 2008) by stimulating synthesis of neuropeptide Y (NPY) and agouti-related protein (AgPR) in neurons within the hypothalamus (Figure 15) (Gil-Campos et al., 2006).

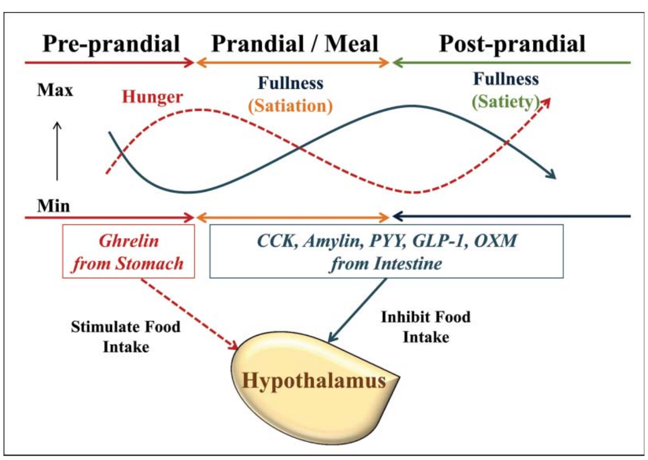

Figure 15 Highly schematic representation of changes in hunger, satiety and satiation responses before, during and after consumption of a meal. The various peptides associated with these responses, and the interactions between hypothalamus and digestive tract in controlling food intake are also shown. Figure adapted from Del Prete et al. (2012); Halford and Harrold (2012).

WITHIN-MEAL SATIETY (PRANDIAL)

After ingestion, food products are broken up in the mouth through mastication, and then move into the stomach and small intestine where they are broken up further by mechanical action, acids, enzymes, and other digestive components. As a result various digestion products are produced such as peptides/amino acids (from proteins), free fatty acids/monoacylglycerols (from fats), and oligosaccharides/monosaccharides (from carbohydrates). Various gastrointestinal and pancreatic peptides are released in response to the mechanical forces (e.g., stomach extension) and digestion products arising from food consumption. The release of these peptides modulates digestive processes, generates short-term satiety signals, and regulates blood glucose levels (Karhunen et al., 2008; Del Prete et al., 2012; Halford and Harrold, 2012). The circulating ghrelin stimulates gastric motility however its level is suppressed by meal intake, and is particularly sensitive to foods that have high-energetic and high osmotic loads. For example, ingestion of carbohydrates can delay gastric emptying and sustain fullness, thereby contributing to satiation and early post-meal satiety (Blundell et al., 2001).

Some of the peptides released after ingestion include cholecystokinin (CCK), pancreatic glucagon, and amylin (Figure 15) (Blundell et al., 2001; Del Prete et al., 2012; Karhunen et al., 2008; Kim and Park, 2011; Halford and Harrold, 2012). Cholecystokinin (CCK) is mostly produced in the duodenal and jejunal mucosa of the small intestine and circulates widely within the GIT (Del Prete et al., 2012). CCK is also found in the enteric nervous systems and CNS, where it serves as a neurotransmitter (Rehfeld and Hansen, 1986). CCK peptides are rapidly released into the surrounding tissues in response to nutrients, particularly meals rich in fats and proteins (Del Prete et al., 2012). The main actions of CCK include delaying gastric emptying ("duodenal brake"), and stimulating pancreatic enzyme secretion and gall bladder contraction. Thus, it promotes effective digestion of fat and protein in the small intestine through bile and digestive enzyme release, and inhibits food intake by reducing meal size, duration, and appetite (Kissileff et al., 1981; Lieverse et al., 1995; Little et al., 2005). Altogether, CCK has an important role in the feeling of satiation and therefore meal termination (Karhunen et al., 2008). A study found that the satiating effect is mediated through activation of mechanosensitive fibers in the stomach and duodenum (Kissileff et al., 2003). Moreover, gastric distension due to ingestion of foods and beverages enhances the effect of CCK. Endogenous amylin and pancreatic glucagon also play a role in meal cessation by inhibiting gastric emptying (Reda et al., 2002).

ACROSS-MEAL SATIETY (POST-PRANDIAL)

Some peptides are triggered during the consumption of a meal but their actions only come into effect after meal termination, such as tyrosine-tyrosine (PYY), glucagon-like peptide 1 (GLP-1), and oxyntomodulin (OXM) (Figure 15). These peptides are synthesized and released from endocrine cells in the distal intestine, i.e., ileum, colon, and rectum (Adrian et al, 1985; Batterham et al., 2002; Del Prete et al., 2012). Although these peptides are secreted during the consumption of a meal, their concentration in the body only reaches a peak sometime after meal termination and remains relatively high for a few hours afterward (Essah et al., 2007; Del Prete et al., 2012).

PPY is a member of the pancreatic polypeptide-fold (PP-fold) family (Cox, 2007). It has been suggested to play a role as a satiety signal by inhibiting appetite, slowing GIT transit, reducing gastric motility and emptying, and promoting nutrient digestion and absorption (Pironi et al., 1993; Essah et al., 2007). The other peptides that play a role in inducing satiety include GLP-1 and OXM, which are released in the distal intestine, pancreas, and CNS (Chaudhri et al., 2008; Suzuki et al., 2010). GLP-1 is proposed to play a role in the *ileal-brake mechanism* that regulates the flow of nutrients from the stomach to the small intestine (Nauck et al., 1997) and in reducing gastric emptying (Burcelin and Dejager, 2010). Other functions of GLP-1 include inhibition of both gastric acid secretion and gastric motility (Del Prete et al., 2012), stimulation of the secretion of glucose-induced insulin, and enhanced glucose sensitivity of resistant pancreatic beta-cells (Burcelin and Dejager, 2010). GLP-1 is thought to have only a short-term effect due to its rapid degradation within the body. OXM peptides inhibit motility and stimulate secretion of pancreatic enzyme and intestinal glucose uptake (Cohen et al., 2003). The satiety feeling produced by both OXM and GLP-1 could be due to their effects on the CNS (Del Prete et al., 2012). Pancreatic polypeptide (PP) hormones are secreted within the pancreas (Taborsky, 2001) as well as other sites, including the colon and rectum. PP has also been shown to affect energy balance by suppressing food intake and gastric emptying (Katsuura et al., 2002). Some other peptides that are not directly involved in meal initiation or termination but in maintaining metabolism or homeostasis include gastric inhibitory polypeptide (GIP), insulin, and leptin (Karhunen et al., 2008). Details of these peptides can be found in the literature: GIP (Eckel et al., 1979; Nauck et al., 1993; Meier et al., 2004); insulin (Newgard and McGarry, 1995; Havel, 2001; Porte et al., 2002).

CONTROLLING SATIATION AND SATIETY

The study of the biochemical mechanisms occurring before, during, and after the consumption of food is a rapidly growing area. A better understanding of the relationship between food composition (such as the type and amount of fat, protein, and lipid present) and the satiation and satiety responses may lead to the development of reduced calorie food products that leave consumers feeling less hungry and more full, and therefore to consume less and be more satisfied by what they consume. For example, foods could be fortified with those components known to induce satiation and satiety.

The structural organization of the components within a food and how they change during passage through the GIT may also play an important role in determining the satiety response. For example, it has been shown that the stability of emulsified lipids within the stomach may influence the satiety response (Figure 16). If an emulsion remains stable within the acid environment of the stomach, then the rate of gastric emptying is delayed and the satiety response is increased when compared to an unstable emulsion (Marciani et al., 2006; Marciani et al., 2006, 2007; Marciani et al., 2009). This effect has been attributed to the amount of calories passing into the small intestine from the stomach per unit time. If the fat droplets move to the top of the stomach due to "creaming" or "oiling off," then there are less calories passing into the small intestine, and the body wants to consume more. On the other hand,

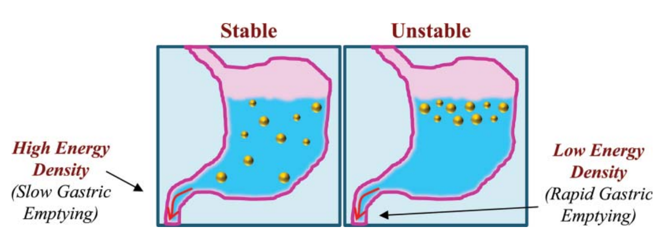

Figure 16 The stability of fat droplets to sedimentation and creaming may alter gastric emptying because the body detects the energy density of the food leaving the stomach. This mechanism has been proposed as a means of controlling satiety.

if the fat droplets are evenly distributed throughout the stomach, then the rate of calories passing into the small intestine will be higher, and therefore the body wants to slow down gastric emptying (so all food components can be efficiently digested) and one feels fuller (since the body is detecting calories). Food manufacturers may therefore be able to control the structural organization of food products to increase the feelings of fullness they induce during consumption, thereby reducing the total amount of calories consumed per meal and increasing the length of time between food intakes.

DEVELOPMENT OF REDUCED FAT PRODUCTS

Challenges of Reduced Fat Products

In recent years, there has been a steep increase in the promotion and awareness of a healthy-eating lifestyle. As a result, there is increasing demand for healthier food products, particularly for foods with reduced fats and/or calories (Malone et al., 2003b; Grunert, 2006; Bayarri et al., 2007; Liu et al., 2007; Gonzalez-Tomas et al., 2008; Aranceta et al., 2009; Mun et al., 2009; Hoefkens et al., 2011). Over-consumption of high-fat foods may lead to obesity and an excessive accumulation of fat in the adipose tissue (Halford and Harrold, 2012; Rego Costa et al., 2012). The richest source of calories in a diet is fat as it produces 9 kcal/g compared to 4 kcal/g for protein and carbohydrate (Akoh, 1995). Reducing the fat content of foods is therefore the most effective way of reducing their calorie density (Smith et al., 1994). However, even though it is important to formulate products with reduced- or low-fats (Bayarri et al., 2007), it is also important to produce foods that have desirable sensory properties, as consumers primarily make selections based on 'eating quality' and balanced food flavor (Malone et al., 2003b; Halford and Harrold, 2012). Therefore, it is a challenge to produce "healthy foods" that are low in fats yet possess highly desirable sensory properties. As discussed in previous sections, fats have a major influence on the physicochemical properties, sensory perception, and physiological response of ingested foods (Overbosch et al., 1991; Doyen et al., 2001; Rabe et al., 2003; Bayarri et al., 2006; Liu et al., 2007). Hence, reduction of the fat content of a food product may alter its desirable quality attributes, e.g., appearance, texture, stability, flavor profile, and satiety response (Doyen et al., 2001; Malone et al., 2003b; Bayarri et al., 2007).

Many different types of reduced- or low-fat food products are commercially available. Nevertheless, the overall quality attributes of these products rarely match their full-fat counterparts. Removing the fat from a food has a detrimental effect on its overall flavor profile and may lead to a product with an 'unbalanced' or 'uneven' flavor release profile (Malone et al., 2003b; Shamil et al., 1991; Shojaei et al., Taylor, 2006). Removing the fat may also have detrimental effects on the perceived mouthfeel of food products (Bellamy et al., 2009; Le Reverend et al., 2010). Consequently, it is important to develop effective strategies that can overcome the various challenges that occur when fat is removed.

Approaches for Fat Reduction in Foods

A variety of approaches have been developed in an attempt to produce reduced fat products with comparable flavor, taste, texture, and mouthfeel as full-fat products. These approaches include the use of *ingredients* designed to mimic certain desirable characteristics of fat droplets, such as fat mimetics (e.g., Olestra® and SALATRIM), hydrocolloid thickening agents (e.g., proteins and gums), and particulates (e.g., starch granules, hydrogel beads, protein microspheres, and air bubbles). Other approaches include the utilization of innovative *processing methods* (such as microfluidization) and *food structuring* techniques (such as controlled phase separation and network formation). A summary of some of the major approaches that have been used to develop effective fat replacement strategies is given below.

Fat Mimetics

Olestra® was specifically designed to be a fat substitute to replace digestible fats (triglyceride oils) in products such as fried foods, snacks, breads, and fillings (Bimal and Zhang, 2006; Prince and Welschenbach, 1998). From a chemical point of view, Olestra® is a sucrose polyester, made of a mixture of hexa-, hepta-, and octa-esters of sucrose and long-chain fatty acids from edible fats, such as soybean, corn, or cottonseed (Bimal and Zhang, 2006; Fouad et al., 2001; Prince and Welschenbach, 1998). The ester bonds in Olestra® are not hydrolyzed by the digestive enzymes (lipase) in the human gastrointestinal tract because of steric hindrance effects. Consequently, Olestra® is not absorbed by the body and can be considered to be a zero-calorie fat substitute. Nevertheless, it has many of the physicochemical, organoleptic, and functional attributes as conventional fats and oils. However, it was found that Olestra® may retard the absorption of fat-soluble vitamins and may be associated with undesirable gastrointestinal tract symptoms, such as cramping and anal leakage. Hence, the FDA limits the amount of Olestra® that can be used and the type of foods that it can be incorporated into (Prince and Welschenbach, 1998; Bimal and Zhang, 2006).

SALATRIM is another fat mimetic that is used to reduce the calorie content of some foods. Chemically, SALATRIM can be considered to be a group of structured triacylglycerols that have physicochemical, organoleptic, and functional properties similar to those of conventional fats, but that provide approximately half of the calories (Smith, Finley and Leveille, 1994). The triacylglycerols in SALATRIM are mixtures of short-chain fatty acids (acetic, propionic and/or butyric) and long-chain saturated fatty acids (mostly stearic) esterified to a glycerol backbone. SALATRIM has been used as a fat mimetic in reduced-calorie food products for many years (Smith et al., 1994; Softly et al., 1994). More recently it has been proposed that SALATRIM may also be an effective fat replacer due to its ability to suppress hunger and increase fullness, since there is a great concentration of undigested fat within the lower GIT (Sorensen et al., 2008).

Controlling Fat Composition

Several studies have shown that the chemical composition of a fat can affect its digestion rate and absorption, as well as its satiating ability (Small, 1991; Flint et al., 2003; French and Robinson, 2003; Rego Costa et al., 2012). For example, meals rich in diacylglycerols instead of triacylglycerols were shown to have beneficial effects on lipid metabolism and energy balance (Kamphuis et al., 2003). Healthy volunteers fed diacylglycerols had lower feelings of hunger, appetite, and food intake than those fed with triacylglycerols.

The characteristics of the fatty acids (chain length and degree of unsaturation) present within the lipid phase of a meal have also been found to be important in determining their biological response. Consumption of medium-chain triglycerides (MCTs) has been shown to be more satiating than long-chain triglycerides (LCTs) (Bremer, 1983; van Wymelbeke et al., 1998; Kahler et al., 1999; French and Robinson, 2003; St-Onge et al., 2003; Rego Costa et al., 2012). A possible explanation for these differences in satiating effect is related to differences in lipid metabolism. Typically, MCTs contain three saturated fatty acids with eight to twelve carbon atoms on each chain. MCT molecules are rapidly converted to free fatty acids and monoacylglycerols by lipase in the small intestine. These digestion products are then absorbed by the intestinal cells, and pass into the portal blood system without being re-esterified. The free fatty acids from MCTs are then transported to the liver and metabolized by β-oxidation. The increased oxidation of fatty acids in the liver is a proposed mechanism for their higher satiety signals. In addition to their faster metabolism and lower storage in adipocytes, MCTs are also found to promote higher energy expenditure in individuals (Flatt et al., 1985; St-Onge et al., 2003) and increased diet-induced thermogenesis (DIT) (Himms-Hagen, 1984). Long-chain triglycerides (LCTs) are also converted to free fatty acids and monoacylglycerols in the small intestine. They are then absorbed by the epithelium cells where they are re-esterified into triacylglycerols, packaged intro chylomicrons, and then transported into the lymphatic system before reaching the bloodstream. In the bloodstream, the LCTs are hydrolyzed by lipases into smaller molecules, or captured by tissues, e.g., muscle tissues where they undergo oxidation or adipose tissues where they are stored (Hyson et al., 2003; Rego Costa et al., 2012; St-Onge and Jones, 2002). LCTs therefore induced a different physiological response than MCTs when consumed as part of a meal.

Studies have also found that the degree of saturation of the fatty acids may influence their ability to induce satiation. A study showed that oils with high linoleic acid contents infused in the upper small intestine of humans significantly reduced food intake compared to oleic and stearic-acid containing oils (French et al., 2000). The effect of conjugated linoleic acid (CLA) supplementation on measures of obesity has also been studied, where it was shown that the daily intake of CLA can reduce total body fat and abdominal fat (Riserus et al., 2001; Kim and Park, 2011; Dilzer and Park, 2012).

These studies suggest that utilization of novel fat sources (such as MCT or CLA) may be useful for creating functional foods designed to regulate food intake and body mass (Kim and Park, 2011; Rego Costa et al., 2012).

Controlled Fat Droplet Aggregation

The rheological characteristics of emulsion-based products can be altered considerably by inducing droplet flocculation (Figure 17). Typically, there is a large increase in shear viscosity and shear thinning behavior when the fat droplets in an emulsion flocculate (McClements, 2005; Dickinson, 2006). At sufficiently high droplet concentrations, flocculation may even lead to the formation of gel-like or paste-like characteristics in a product due to the formation of a network of aggregated fat droplets (Dickinson, 2012). Droplet flocculation may be induced in oil-in-water emulsions using a variety of different approaches depending on the nature of the system.

Reduction in Electrostatic Repulsion: Flocculation can be promoted in electrostatically stabilized emulsions by reducing the electrostatic repulsion between the droplets. This can be achieved by altering the pH to reduce the charge on the droplets or by adding salts to screen the charges (Demetriades et al., 1997a; McClements, 2004).

Increase in Depletion Attraction: Flocculation can be promoted in various kinds of emulsions by increasing the depletion attraction between the droplets by adding nonadsorbing polymers or colloidal particles that increase the osmotic pressure (Dickinson, 2003, 2010).

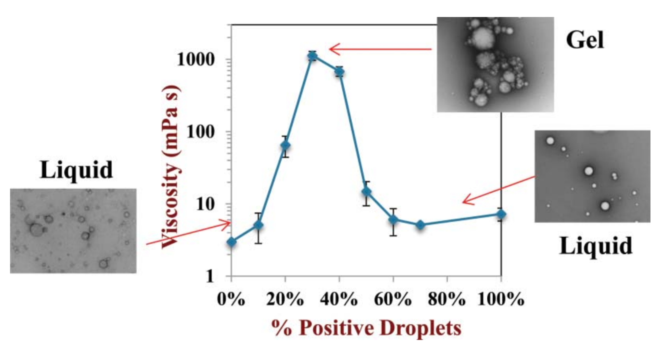

Figure 17 Emulsions containing mixtures of positive (LF-coated) and negative (β-Lg-coated) droplets are highly viscous at intermediate particle ratios due to heteroaggregation. (Adapted from Mao and McClements, 2012.)

Increase in Hydrophobic Attraction: Flocculation can be promoted in globular-protein stabilized emulsions by increasing the hydrophobic attraction between droplets. This can be achieved by heating the emulsions above the thermal denaturation temperature of the adsorbed proteins since this causes an increase in surface hydrophobicity (Demetriades et al., 1997b; Kim et al., 2002a, 2002b).

Bridging Flocculation: Flocculation can be promoted in emulsions containing charged droplets by adding oppositely charged polymers to form ionic bridges between different droplets (Guzey and McClements, 2006, 2007; Cho and McClements, 2009; Dickinson, 2010).

Heteroaggregation: Flocculation can be promoted by mixing positively and negatively charged droplets together—the oppositely charged droplets tend to associate with each other and form clusters (Mao and McClements, 2012a, 2012b, 2012c). This is usually achieved by preparing two emulsions using emulsifiers with different electrical characteristics, e.g., proteins with different isoelectric points (Figure 17).

Flocculation leads to an increase in the overall viscosity of an emulsion because the effective volume occupied by the particles increases due to the presence of water trapped within the floc structure (McClements, 2005). The viscosity of flocculated emulsions typically decreases appreciably when the system is sheared ("shear thinning") because of the progressive deformation and fragmentation of the floc structure. At sufficiently high droplet concentrations a three-dimensional network of aggregated droplets forms, which gives some solid-like characteristics to the system. These semisolid systems can often be characterized as nonideal plastics, with a yield stress, consistency, and flow index (McClements, 2005). The change in the rheological properties of an emulsion due to flocculation depends on the nature of the flocs formed, such as their concentration, size, shape, internal structure, and bond strength. In turn, floc characteristics depend on droplet properties (such as particle size distribution, concentration, charge, and hydrophobicity), colloidal interactions (e.g., sign, strength, and range) and solution conditions (e.g., pH and ionic strength). Food manufacturers may therefore be able to reduce the concentration of fat droplets in an emulsion-based food product by promoting droplet flocculation in the system so as to maintain a high viscosity when some of the fat droplets are removed. Nevertheless, one must also be careful that no adverse effects are introduced due to droplet flocculation, such as decreased creaming stability or changes in appearance.

Hydrocolloid Polymers

The incorporation of hydrocolloid polymers into reduced-fat products is one of the most widely used approaches for replacing some of the desirable characteristics of fat droplets. Typically, hydrocolloid polymers consist of relatively large hydrophilic molecules that have an extended structure when dispersed in aqueous solutions, such as some proteins (e.g., gelatin) and many polysaccharides (e.g., alginate, carrageenan, xanthan, locust bean gum, agar, etc.). These molecules occupy an effective volume in solution that is appreciably larger than the volume occupied by the polymer chain itself, due to their ability to trap water molecules (McClements, 2000). The most common reason for using hydrocolloid polymers as fat replacers is their ability to greatly increase the viscosity of aqueous solutions due to their large effective molecular volumes. Typically, only relatively small amounts of a hydrocolloid polymer have to be added to an emulsion-based food product to greatly increase its viscosity. Hydrocolloids may also alter the structural and physicochemical properties of food systems in other ways that may be beneficial to the production of reduced-fat products, e.g., they may increase opacity, improve stability, alter the flavor release profile, or modulate the satiety responses. An additional advantage of many polysaccharide-based hydrocolloids is that they are dietary fibers that are not digested in the upper GIT and therefore have relatively low calorie contents.

The potential of various types of hydrocolloid polymers at mimicking the functional properties of fat droplets in emulsion-based foods has been investigated, and a number of representative studies are summarized in Table 1. In general, polymers may be used in isolation or in combination to create desirable physicochemical and sensory properties in foods. In the remainder of this section, we provide a brief overview of selected studies that illustrate the potential use of hydrocolloid polymers in the development of reduced fat products.

The utilization of pectin and/or whey protein isolate (WPI) as fat mimetics in mayonnaise has been investigated (Liu et al., 2007). This study suggested that weakly gelled pectin had good potential for use as a fat mimetic. A reduced fat mayonnaise that contained a weak pectin gel in the aqueous phase was reported to have similar textural properties (firmness, consistency, cohesiveness, and viscosity) and sensory properties (appearance, color, odor, texture, taste, and acceptability) as a full fat mayonnaise. Presumably the pectin gel provided some of the desirable textural and stability attributes normally supplied by the fat droplets in a full-fat mayonnaise. The texture and sensory attributes of reduced fat mayonnaises containing microparticulated pectin or WPI-pectin complexes were less similar to those of full-fat mayonnaises. A variety of other hydrocolloids have also been investigated for their potential to fabricate reduced fat mayonnaises, including xanthan gum, citrus fiber, and guar gum (Su et al., 2010). The rheological properties and sensory scores of reduced fat mayonnaises containing certain combinations of these hydrocolloids were shown to be similar to that of full fat mayonnaises, e.g., xanthan gum and guar gum. The potential of enzyme-modified starch with or without xanthan gum addition as a fat mimetic in reduced fat mayonnaise has also been examined (Mun et al., 2009). Certain combinations of enzyme-modified starch and xanthan gum were able to produce reduced fat mayonnaises with similar rheological properties and appearances as full fat mayonnaises. It was proposed that the starch and xanthan

Table 1 Examples of published studies that have used food biopolymers as fat replacers in reduced-fat foods

Food type	Biopolymer type	Reference
Mayonnaise	Propylene glycol alginate and guar gum	(Wendin et al., 1997)
	Microparticulated pectin gel, pectin weak-gel, and microparticulated whey protein isolate–pectin	(Liu et al., 2007)
	Xanthan gum and enzyme-modified rice starch	(Mun et al., 2009)
	Xanthan gum, citrus fiber, and guar gum	(Su et al., 2010)
	Beta-glucan	(Marinescu et al., 2011)
	Oat dextrin	(Shen et al., 2011)
Yogurt	Amylomaltase-treated starch	(Alting et al., 2009)
	Inulin	(Modzelewska-Kapitula and Klebukowska, 2009)
Ice cream	Whey protein isolate and inulin	(Akalin et al., 2008)
Dairy beverages/desserts	λ-Carrageenan and short- and long-chain inulin	(Bayarri et al., 2010; Arancibia et al., 2011)
Dairy desserts	κ-Carrageenan and medium crosslinked modified tapioca starch	(Gonzalez-Tomas et al., 2008)
	Short- and long-chain inulin	(Arcia et al., 2011)
Cheese	Whey protein concentrate	(Lobato-Calleros et al., 2007)

could have contributed to structure formation in the reduced fat mayonnaise, thereby providing some of the textural characteristics normally supplied by fat droplets.

Gonzalez-Tomas et al. (2008) studied the influence of two hydrocolloid thickening agents (starch and κ-carrageenan) on the rheology and flavor of strawberry flavored dairy desserts. They found that the addition of κ-carrageenan and starch raised the apparent viscosity and shear modulus of the desserts, but decreased the amount of shear thinning. The polymers were not reported to influence the release of volatile flavor compounds from the products. Sensory analysis of the products indicated that there was a significant difference in perceived “thickness” between samples but not in strawberry flavor intensity.

Particulates

Various kinds of nonfat particulates are available for utilization in foods to replace some of the desirable sensory attributes normally provided by fat droplets, including inorganic particles, starch granules, protein microspheres, hydrogel particles, crystals, and gas bubbles. These particulates may be mixed with the fat droplets, or in some cases the fat droplets may be trapped inside the particulates (Figure 18). Particulates may simulate the properties of the fat droplets in emulsion-based products in a variety of different ways. First, particulates may increase the viscosity or modulus of aqueous solutions and therefore compensate for some of the changes in rheology that occur when fat droplets are removed. Second, particulates may scatter light and therefore contribute to the desirable creamy appearance of emulsion-based products. Third, particulates may simulate some of the mouthfeel characteristics normally associated with the interaction of fat droplets with the tongue in the oral cavity. Fourth, particulates may help prevent the creaming or sedimentation of fat droplets and other ingredients in foods due to their ability to increase the rheology of the aqueous phase.

In this section, we discuss a few examples of the use of protein microspheres as potential fat replacers in foods. Protein microspheres with well-defined dimensions (around a micrometer) can be formed through the controlled aggregation of globular proteins after thermal denaturation. Commercial, food ingredients have been developed based on this process, such as Simplesse^{R}, which is a microparticulated whey protein. The influence of adding protein microspheres to the milk used to prepare reduced fat cheeses has been examined (Schenkel et al., 2011). Fluorescence microscopy showed that

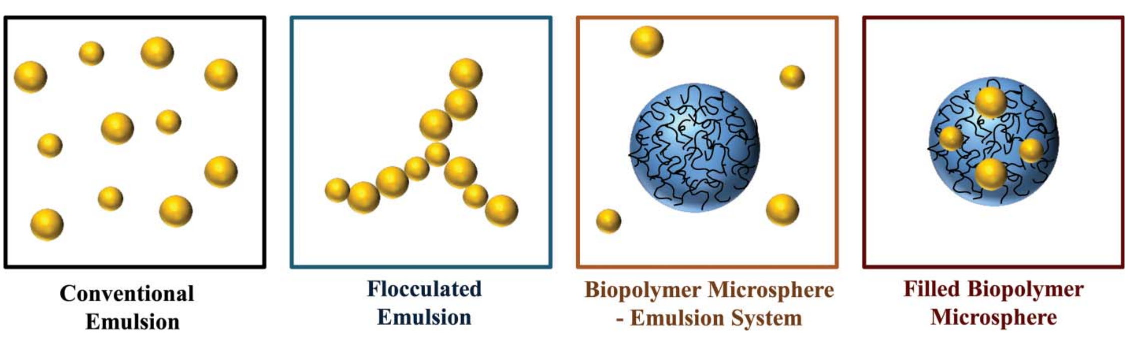

Figure 18 Structural design principles may be used to create reduced fat emulsion-based products with similar physicochemical attributes as conventional products.

the protein microspheres were embedded within the protein matrix of the final cheese products. The protein microspheres were found to influence the formation and texture of the cheese products. The possibility of using whey protein microspheres as fat replacers in yogurts has also been investigated (Sandoval-Castilla et al., 2004). The protein microspheres were found to alter the microstructure and rheological properties of the reduced-fat yogurts thereby providing some of the attributes normally provided by fat droplets. Protein microspheres have been used in the development of a variety of reduced fat products, including yogurts, ice creams, and cheeses (Yilsay et al., 2006; Aykan et al., 2008; Sahan et al., 2008; Karaca et al., 2009).

Another commercially available particulate material that is widely used in the food industry is titanium dioxide, which is mainly used to increase the opacity ("whiteness") of foods (Weir et al., 2012). Titanium dioxide particles have a relatively high refractive index and therefore scatter light strongly, which makes them highly effective lightening agents. Thus titanium dioxide can be used to replace some of the desirable creamy appearance of a product when the fat droplet content is reduced (Chantrapornchai et al., 2000). Many food manufacturers would like to have "clean" labels, and would therefore like to replace titanium dioxide with other forms of lightening agents. Protein microspheres or other particulate materials may prove to be useful natural alternatives.

Novel Processing Methods

The physicochemical and sensory properties of reduced fat foods can often be made to simulate those of higher fat products by altering the processing conditions normally used during production. Studies have examined the effect of various processing treatments on the properties of reduced fat foods, including high pressure processing (Penna et al., 2006), high pressure homogenization (Serra et al., 2007), thermo-sonication (Riener et al., 2009) and microfluidization (Augustin et al., 2008; Ciron et al., 2010, 2011). For example, the influence of treating nonfat (0% fat) and low-fat (1.5% fat) yogurts with a homogenization device (microfluidizer) that is capable of generating much stronger disruptive forces than conventional high pressure valve homogenizers (HPVH) on their microstructure, rheology, and sensory properties has been investigated (Ciron et al., 2010, 2011). Homogenization of milk at 150 MPa using the microfluidizer produced smaller fat droplets than homogenization at 5 or 20 MPa using the HPVH. The microfluidizer also caused appreciable changes in the microstructure of the yogurts formed from the homogenized milk, which was attributed to the reduction in fat droplet size and disintegration of casein micelles. The authors also reported appreciable changes in the rheological properties of the yogurts, with the microfluidized yogurt leading to a higher viscosity and yield stress than the conventionally homogenized yogurt. Microfluidization also affected the sensory properties of the yogurt, with the effect being highly dependent on fat content. For nonfat yogurts, microfluidization enhanced the perception of buttermilk and soft cheese flavors, and natural yogurt aroma and flavor but also increased the intensity of undesirable mouthfeel characteristics (i.e., chalkiness, dryness, and astringency). For the low-fat yogurts, microfluidized products had higher creaminess and more desirable texture characteristics (i.e., smoothness, cohesiveness, thickness, and oral and spoon viscosity) than conventionally homogenized products, which was attributed to changes in particle size and microstructure. Overall these studies suggested that microfluidization had the potential for producing high quality reduced-fat yogurts (Ciron et al., 2010, 2011).

Structural Design Approaches

In recent years, there has been a focus on the use of structural design approaches to create specific structures within foods that mimic some of the desirable attributes normally provided by fat droplets (Le Reverend et al., 2010): filled hydrogel particles (Malone et al., 2000; Malone and Appelqvist, 2003); controlled phase separation (Kasapis et al., 1993; Kasapis et al., 1993; Le Reverend et al., 2010); multiple emulsions (Muschiolik, 2007; Lobato-Calleros et al., 2008; Charcosset, 2009; Lobato-Calleros et al., 2009; Dickinson, 2011); air bubble-filled emulsions (Tchuenbou-Magaia et al., 2009; Tchuenbou-Magaia et al., 2011; Tchuenbou-Magaia and Cox, 2011); and controlled flocculation systems (Mao and McClements, 2012a, 2012b, 2012c).

Filled Hydrogel Particles

Filled hydrogel particles consist of oil droplets dispersed within a hydrogel particle (Figure 18). The hydrogel particles are typically made from proteins and/or polysaccharides that are capable of gelling under controlled conditions (such as heating, cooling, addition of specific ions, or enzyme addition). These kinds of particles can be formed using a variety of different preparation methods, including injection methods, molding methods, gel disruption, and controlled biopolymer phase separation (Matalanis et al., 2011). Filled hydrogel particles have been used to control the release of lipophilic aroma compounds so as to address flavor issues in reduced- or low-fat products (Malone and Appelqvist, 2003; Malone et al., 2003b). The fact that the oil droplets are trapped within a hydrogel particle means that they are surrounded by a static diffusion layer. This increases the path-length through which the aroma molecules must diffuse before they can be released from the product during mastication. As a result, they can make the flavor release profile of a reduced-fat product more similar to that of a high-fat product, by preventing a burst release and ensuring a more sustained release (Figure 14).

Multiple Emulsions

A multiple emulsion contains coexisting water-in-oil and oil-in-water morphologies within the same system (Dickinson, 2011). There are two major types of multiple emulsions that can be used in foods: water-in-oil-in-water (W/O/W) or oil-in-water-in-oil (O/W/O). Multiple emulsions of the W/O/W type are the most suitable for application in the formulation of reduced-fat food products with an aqueous continuous phase (Figure 19). Multiple emulsions can be prepared using many of the same mechanical devices as used to prepare conventional emulsions, such as high shear mixers, high pressure homogenizers, sonicators, and membrane homogenizers (Muschiolik, 2007; Charcosset, 2009; Dickinson, 2011). W/O/W emulsions are normally produced using a two-stage process: (i) a W/O emulsion is formed by homogenizing water and oil together in the presence of an oil-soluble surfactant; (ii) the W/O/W emulsion is formed by homogenizing the W/O emulsion with water in the presence of a water-soluble surfactant (Figure 19). Usually, the second homogenization stage has to be less intense than the first otherwise the system may breakdown. W/O/W emulsions are particularly suitable for reducing the fat content of products that normally exist as O/W emulsions because some of the fat within the droplets is replaced by water. In principle, W/O/W emulsions can be designed to have similar appearances, textures, and mouthfeel as O/W emulsions that have higher fat contents, however, there are often problems with ensuring that the multiple emulsions have sufficient stability for commercial applications.

Multiple emulsions (W/O/W) have been investigated as a means of reducing the fat content in white fresh cheese (Lobato-Calleros et al., 2006; Lobato-Calleros et al., 2008). The multiple emulsions were stabilized with amidated low-methoxyl pectin (LMP), carboxymethylcellulose (CMC), gum arabic (GA), and blends of these hydrocolloids. The structure and texture of the reduced fat cheeses were affected by the type of hydrocolloids used as emulsifying/stabilizing agents in the multiple emulsions. This study concluded that reduced-fat cheese-like products manufactured from skim milk and multiple emulsions (W/O/W) stabilized by hydrocolloids could closely simulate some of the important textural characteristics of full milk-fat cheeses. W/O/W emulsions may also be useful to reduce the fat content of products such as sauces, dressings, and mayonnaise that normally have a relatively high fat content, provided they can be made commercially viable.

Air-bubble Filled Emulsions

Air-bubble filled emulsions have been investigated as a novel approach for fat replacement in foods (Tchuenbou-Magaia et al., 2009; Le Reverend et al., 2010; Tchuenbou-Magaia and Cox, 2011). In this approach, a significant amount of the fat phase is replaced by stable air bubbles. These bubbles were originally produced using a novel group of proteins (hydrophobins) that assemble at the air/water interface to give gel-like structures. Hydrophobins are naturally occurring proteins, produced by a fungus (*Trichoderma reesei*), and have been found to have the ability to stabilize micron-sized air cells (1–100 μm) (Tchuenbou-Magaia et al., 2009; Basheva et al., 2011; Tchuenbou-Magaia et al., 2011; Tchuenbou-Magaia and Cox, 2011). The high surface elasticity of the protein film around the air bubbles helps prevent disproportionation (i.e., bubble growth due to the diffusion of air molecules from small to large bubbles through the intervening water phase). The interfacial film surrounding the air bubbles has been shown to be relatively robust and capable of surviving various processing steps that commercial products might experience in the

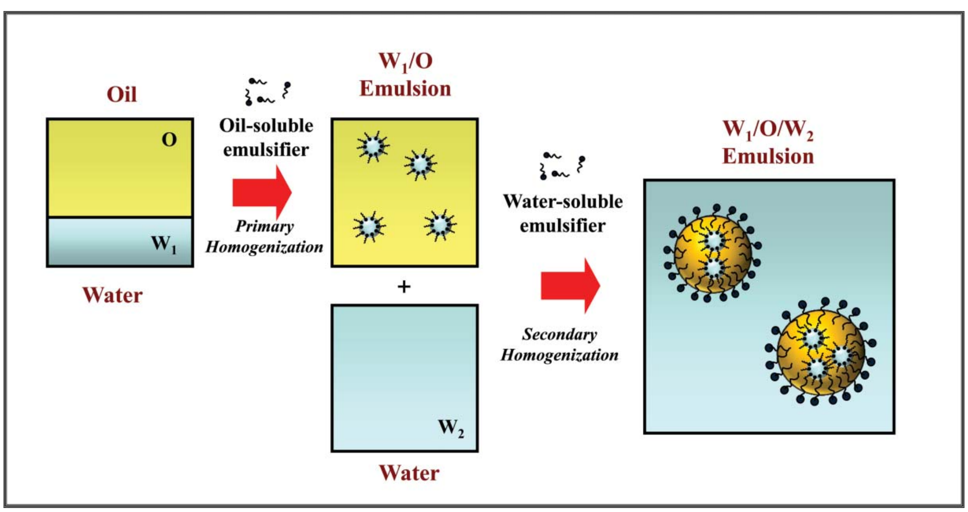

Figure 19 Multiple emulsions (W/O/W) are usually produced using a two-step procedure: (i) *Primary Homogenization*: An oil and aqueous phase are homogenized together in the presence of an oil-soluble emulsifier to form a W/O emulsion; (ii) *Secondary Homogenization*: The W/O emulsion is homogenized with a water phase in the presence of a water-soluble emulsifier to form a W/O/W emulsion. Adapted from McClements (2005).

food industry. Air-bubble filled emulsions showed little change in individual air bubble size when they were stored for up to 4 months at room temperature (Tchuenbou-Magaia et al., 2009). Tchuenbou-Magaia and others (2009) produced air-bubble filled emulsions using a sonication process. The authors were able to create tri-phasic systems (oil-water-air) with similar rheological properties to bi-phasic systems (oil-water) but at much lower fat contents.

Identifying alternative ingredients to stabilize air bubbles would be advantageous for their widespread commercial application as hydrophobins are currently expensive (Le Reverend et al., 2010). Tchhuenbou-Magaia et al. (2011) showed that cysteine-rich proteins (such as bovine serum albumin and egg albumin) could also be used to form stable air bubbles using a sonochemical method. The majority of the air bubbles formed by these proteins had diameters between 1 and 10 μm. This study also found a dependence of air bubble size and stability on the processing conditions and system composition. The interfacial films formed around the air cells by these proteins were found to be as robust as those formed by hydrophobins (Tchuenbou-Magaia et al., 2011). These studies therefore suggest that it may be possible to replace fat droplets with air bubbles in some reduced fat products, which would be highly advantageous because they would have few calories.

Controlled Droplet Flocculation

As mentioned earlier, the textural characteristics of emulsion-based products can be modulated by controlling fat droplet flocculation. Droplet flocculation leads to the formation of a three-dimensional network of aggregated fat droplets that provides high viscosity and gel-like characteristics. Various approaches can be used to induce droplet flocculation in emulsions. Normally, the droplets in emulsions are prevented from aggregation by ensuring that the magnitude of the repulsive forces is stronger than that of the attractive forces. Aggregation can therefore be induced by reducing the repulsive forces or increasing the attractive forces. The repulsive forces between protein-coated droplets can be reduced by altering the pH to close to the isoelectric point of the proteins (to reduce droplet charge) or by adding salts (to screen electrostatic interactions or bind to droplet surfaces) (Demetriades et al., 1997a). The attractive forces between fat droplets coated by globular proteins can be increased by heating them above their thermal denaturation temperature so as to increase the droplet surface hydrophobicity (Demetriades et al., 1997b). The attractive forces between fat droplets can also be increased by adding absorbing or nonabsorbing polymers to induce bridging or depletion flocculation (Cho and McClements, 2009; Dickinson, 2003, 2010). Finally, recent studies have shown that reduced fat products with high viscosities or paste-like textures can be produced by mixing positive droplets with negative droplets to induce hetero-aggregation (Mao and McClements, 2012a, 2012b, 2012c).

Monoglyceride Gels

Monoglycerides form gels under a particular set of compositions (oil-water-surfactant) and environmental conditions (temperature). Monoglyceride gels have been investigated for their potential in controlling the viscoelastic properties and sensory perception of certain foods, e.g., low-fat yogurts (Aguirre-Mandujano et al., 2009). The authors stated that a "simple alternative way for formulating reduced-fat yogurts is to create physical building blocks (structural elements) within the continuous phase that may substitute the functionality of the removed milk-fat." In their study, monoglyceride gels (MG gels) were prepared by blending monopalmitin and monostearin with an anionic co-surfactant. When low-fat yogurts containing these mixtures were cooled below the Krafft temperature they formed an α-gel phase, which led to a change in microstructure and rheological behavior. The reduced fat yogurts containing MG gels had comparable or improved rheological properties when compared to full fat yogurts. The rheological properties of the reduced fat yogurts could be controlled by varying the ratio of monopalmitin to monostearin used in the formulations. It was proposed that the MG gels reinforced the protein network, which provided desirable rheological properties and reduced syneresis.

Controlled Biopolymer Phase Separation

Many food systems contain mixtures of different types of biopolymers (e.g., proteins and polysaccharides) dissolved in aqueous solutions. Under certain conditions, these biopolymer mixtures may spontaneously phase separate into a number of different regions that have different compositions and physicochemical properties (Schmitt et al., 1998; Norton and Foster, 2002; Ye, 2008; McClements et al., 2009; Norton and Norton, 2010; Schmitt and Turgeon, 2011; Garrec et al., 2012; Garrec and Norton, 2012). The structural organization of these different regions can often be controlled by manipulating ingredient composition and processing conditions. This can lead to the production of materials that have novel optical, rheological, and flavor release characteristics that may be suitable for producing reduced fat food products. In general, phase separation can be induced by either aggregation-based or segregation-based processes (Figure 20). Aggregation-based processes occur when there is a strong attraction between the two different types of biopolymers, and leads to regions that are rich in both biopolymers and other regions that are depleted in both biopolymers (Schmitt and Turgeon, 2011). The most common form of aggregation-based separation used in the food industry is *complex coacervation* between a protein and an oppositely charged polysaccharide. For example, an anionic polysaccharide will form an electrostatic complex with a protein at pH values around and below its isoelectric point, leading to a two-phase biopolymer mixture that is highly viscous. Segregation-based separation occurs due to the *thermodynamic incompatibility* of two

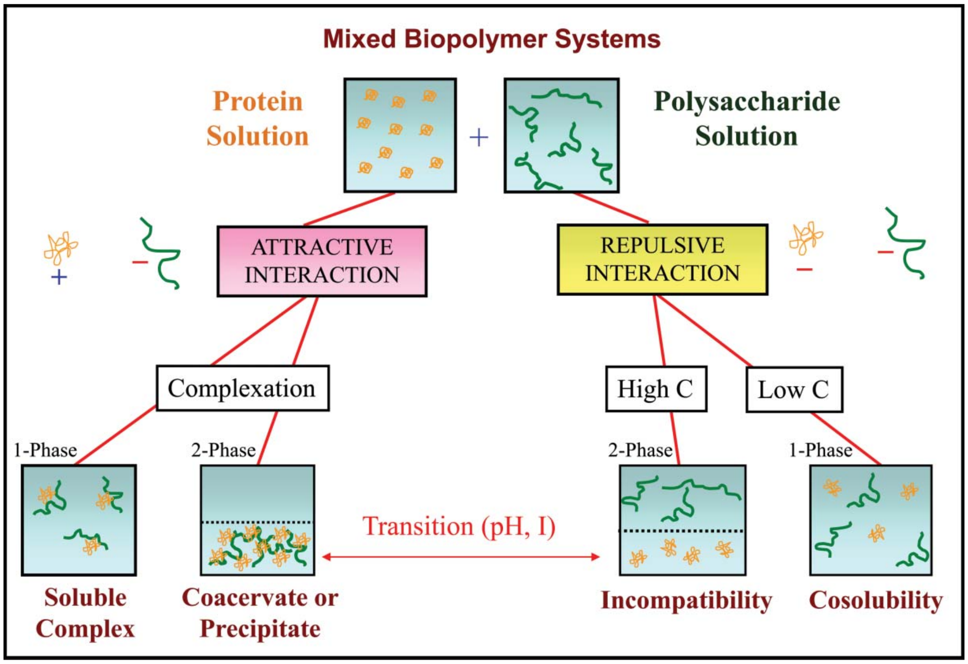

Figure 20 Mixed biopolymer solutions may phase separate under conditions where there are either attractive or repulsive interactions between the biopolymer molecules. Adapted from Matalanis et al. (2011).

biopolymers in solution (Norton and Foster, 2002). This kind of phase separation usually occurs when there is a repulsive interaction between the two different kinds of biopolymers. At low concentrations, the two biopolymers form a one-phase solution that contains an intimate mixture of the different kinds of biopolymer molecules (Figure 20). Above a critical concentration, the mixed system separates into two biopolymer phases with different compositions: one phase is rich in one type of biopolymer and depleted in the other, and vice versa.

Controlled phase separation can lead to mixed systems with structural organizations of the different phases that give novel textural, stability, optical, and release characteristics that may be suitable for producing reduced fat products (Norton and Foster, 2002; Norton and Norton, 2010). An example of a phase separated system formed by mixing fat droplets, protein (caseinate) and polysaccharide (pectin) together is shown in Figure 21. These systems are highly viscous gel-like and opaque materials that consist of fat droplets trapped within casein-rich microspheres that are themselves dispersed within a pectin-rich continuous phase.

Flavor and Mouthfeel Design

As mentioned previously, the partitioning and release rate of flavor molecules within an emulsion is altered appreciably when the fat content is changed (Figures 8 and 14). It is therefore usually necessary to reformulate the flavor blend used within a reduced-fat version of a food product in order to obtain a similar perceived flavor profile as the full-fat version (Meynier et al., 2003; Martuscelli et al., 2008). The intensity of the nonpolar flavor molecules in the headspace above an emulsion increases as the fat content decreases, and therefore it may be necessary to reduce their concentration in a reduced-fat product (Figure 8). Conversely, the intensity of polar flavor molecules decreases as the fat content decreases, and therefore it may be necessary to increase their concentration in a reduced-fat product. The flavor blends used to formulate most food products are highly complex mixtures containing aroma molecules with a wide range of different oil-water partition coefficients. Consequently, it may be necessary to carefully readjust the relative concentrations of all the different components in a flavor blend designed for a reduced-fat product. In addition, the overall flavor profile of a reduced fat product may be redesigned to compensate for the loss of desirable sensory attributes normally contributed by fat, e.g., food manufacturers may increase the intensity of salty or spicy flavors in a reduced-fat product.

The release profile of the flavors within a reduced-fat product may be controlled by encapsulation of some or all of them. There are a variety of different strategies available to encapsulate different kinds of polar and nonpolar flavor molecules (Gibbs et al., 1999; Augustin et al., 2001; Malone and Appelqvist, 2003; Madene et al., 2006; Burey et al., 2008; Given, 2009; Marques, 2010; Murugesan and Orsat, 2012). Encapsulation methods that are suitable for utilization in the food industry include molecular complexes, micelles, liposomes, emulsions, solid lipid particles, coacervates, hydrogel beads, and microencapsulates (spray drying). The selection of an appropriate encapsulation technology depends on the desired flavor profile, the nature of the food matrix, the expected physicochemical properties of the food (e.g.,

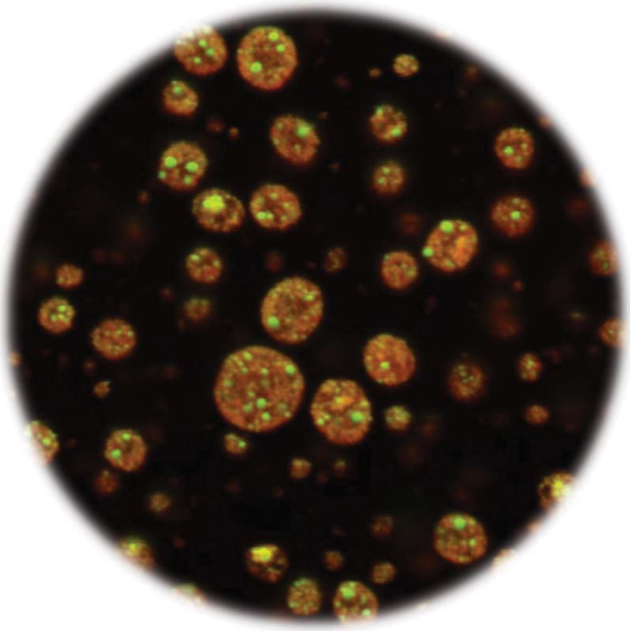

Figure 21 Confocal fluorescence microscopy image of a mixed system formed by controlled phase separation of fat droplets, casein, and pectin. Image provided by Matalanis et al. (2011).

appearance, rheology, stability), and the environmental conditions that the food experiences during its lifetime (e.g., heating, chilling, freezing, dilution, and mechanical stress).

The mouthfeel of reduced fat products may be modulated by changing the way that the fat droplets interact with the tongue and oral cavity, e.g., whether they cling to the tongue, or whether they coalesce and spread on the tongue (van Aken, 2007, 2010; van Aken et al., 2011). If a layer of fat droplet remains within the mouth after swallowing of a food, then the flavor release may be extended, which is desirable for many types of food products. It is possible to control the attachment of droplets to the oral cavity, as well as their tendency to coalesce and spread within the mouth, by changing the nature of the emulsifier used to stabilize them (Dresselhuis et al., 2008; Dresselhuis et al., 2008; Dresselhuis et al., 2008).

Combined Approaches

Due to the fact that fat droplets play so many different roles in determining the appearance, texture, stability, and flavor of emulsion-based food products it is often necessary to use a combination of different fat-replacement strategies to obtain a desirable outcome. For example, it may be necessary to use one strategy to mimic the desirable optical attributes of a product (e.g., particles that scatter light), another strategy to mimic the textural and mouthfeel properties (e.g., hydrocolloids or particulates that increase viscosity), and another strategy to mimic the desirable flavor profile (e.g., a reformulated flavor blend or an encapsulation technology that controls flavor release). Ingredient manufacturers already produce fat replacement systems that are preblended combinations of various ingredients designed to mimic specific fat attributes in select products. Nevertheless, further work is clearly needed in this area for specific types of food products.

FOOD MANUFACTURER PERSPECTIVES

As already mentioned, there is no single strategy that can be universally applied to create reduced-fat food products. Each category of emulsion-based food products has its own unique challenges, which depend on the composition, physicochemical properties, and sensory attributes anticipated by the consumer for that type of product. Hence, food products with different expected appearances, textures, and flavor profiles (such as dressings, sauces, soups, beverages, desserts, and yogurts) may require different fat reduction strategies. A food manufacturer must therefore identify the most appropriate strategy to use for their particular product. In addition to the physicochemical and physiological factors discussed earlier, a number of other factors will also contribute to this decision including:

Cost-in-Use: The additional costs associated with any changes in ingredients or processing operations required to produce reduced fat products plays a major role in determining their commercial viability.

Ease-of-Use: Food manufacturers typically have large capital investments in existing equipment and processing plants. In addition, the managers and operators working within these processing plants may be resistant to changes in well-established tried-and-tested current practices. It is therefore important that any changes in ingredients or processing conditions used to formulate a food product can easily be implemented without large changes in equipment or processes.

Robustness: It is important that any newly developed commercial product is able to maintain its desirable quality attributes throughout manufacturing, transport, and utilization. Technologies developed under the controlled conditions of a research and development laboratory, may not have the required robustness to resist the relatively harsh conditions that many commercial food products experience.

Label-Friendliness: There is an increasing trend within the food industry toward developing products with consumer-friendly labels, e.g., Kosher, vegetarian, vegan, or natural. In addition, there are concerns about listing the presence of undesirable components within foods, e.g., allergens, and genetically modified ingredients. Labeling concerns may limit the type of ingredients that can be utilized to develop successful reduced-fat strategies.

These factors should be considered during the initial stages of identifying a suitable strategy to reduce the fat content of specific emulsion-based products, otherwise considerable time and resources may be wasted during the research and development process (McClements, 2002c; Le Reverend et al., 2010).

CONCLUSIONS

The fat droplets in emulsion-based food products play a variety of critical roles in determining the overall appearance, aroma, taste, texture, mouthfeel, and biological response. Consequently, it is extremely challenging to produce high quality reduced-fat products with similar physicochemical, sensory, and physiological properties as their high fat counterparts. A number of different ingredient and processing strategies have been developed in an attempt to achieve this goal. The strategy adopted for a particular food product is highly system specific, and depends on consumer expectations for product appearance, texture, and taste, as well as manufacturers concerns about cost, production, and labeling. In this paper we provided an overview of the multiple roles that fat droplets contribute to the properties of emulsion-based foods, and then highlighted some of the strategies that could be used to compensate for the loss of desirable properties when fat is removed. The information provided in this review paper should prove useful for the rational design of high quality reduced fat products with improved physicochemical and sensory properties. Finally, it should be noted that we mainly relied on research published in the scientific literature on reduced fat emulsion-based products in this review, but that there is also a great deal of additional information in the patent literature.

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