Obesity, cardiovascular disease, and type 2 diabetes are major public health concerns worldwide. Fat, salt, and sugar levels in manufactured foods are being scrutinized due to concerns about their roles in these diseases. There are also government-sponsored campaigns targeted at increasing consumption of fruit, vegetables, and whole grain foods. As well as presenting challenges for food manufacturers, including cereal processors, there are opportunities to positively impact public health and to develop new health-promoting products. The rapid success of “free from” products, including gluten- and wheat-free products, is an example of how consumer health concerns can open the way to product innovation. If these products are to succeed in the market, however, they must have sensory attributes that make them desirable to consumers.

Sensory Characterization of Texture

Appearance and texture play important roles in consumer acceptance of products at point of sale and during handling and consumption. Food texture is a sensory property that combines several attributes that can be categorized into three main groups (12):

Mechanical—The response to applied stress in the mouth.
Geometrical—The arrangement of food components, generally sensed visually but also detectable in the mouth, including textural characteristics described by terms such as gritty, grainy, coarse, fibrous, cellular, or crystalline.
Mouthfeel—The perception of moisture and fat content, including textural characteristics such as oiliness and greasiness.

Of these textural characteristics, mechanical properties can be measured using instruments to determining the stress that develops as controlled strain is applied to a food sample. A wide range of instruments has been developed to measure the properties of specific food materials (13) (e.g., the Werner-Bratzler shear test for meat and the pea tenderometer). Methods intended to measure textural characteristics typically involve compression, reflecting the action of the human jaw, although unloading characteristics can also provide information about adhesiveness and elastic recovery. These mechanical properties can be characterized by five primary parameters (hardness, cohesiveness, viscosity, elasticity, and adhesiveness) and three dependent parameters (brittleness, chewiness, and gumminess).

Texture Profile Analysis

Texture profile analysis (TPA) is a widely used protocol based on double compression of a sample between two flat surfaces. The method was originally developed using the texturometer (5), in which a bite-sized sample is repeatedly compressed to 25% of its height against a plate, imitating the action of the human jaw. The method was later adapted by Bourne (3) for use with a universal testing machine (Instron) and employs a double compression protocol. A schematic of TPA trace is shown in Figure 1. Figure 2 describes the parameters defined by Bourne for analysis of TPA traces. The parameters are derived from those originally developed for the texturometer to correspond to the sensory mechanical properties classified by Szczesiak (12), with later modifications (14).
A wide range of texture measurement instruments equipped with a diverse selection of probes and attachments for alternative test protocols and applications is now available for food analysis. These types of instruments are derived from materials science applications, in which uniform samples are tested under well-defined loading geometries to measure fundamental material properties. Food materials generally have complex structures that are often fragile and difficult to cut precisely. To overcome these problems, empirical tests have been designed that replicate and correlate with the consumer experience of texture. Nevertheless, care is required to select the appropriate test conditions to achieve reliable and relevant results.

**Compressible Products**

**Testing Approaches.** For compressible food materials such as breads and cakes, loading between flat plates is a typical approach. The TPA protocol as originally implemented used 75% compression to represent the large compression that occurs in the mouth. To assess bread crumb firmness, a smaller compression is typically appropriate. Figure 3A shows a TPA force trace for double compression of a single 15 mm thick slice of bread compressed with a 25 mm diameter probe at a speed of 5 mm/sec to a strain of 35%. Figure 3B shows the equivalent stress-strain curve.

The stress-strain curves for bread can be interpreted using a general model for foams (6). During first loading, the cell walls of the foam demonstrate linear elasticity until they reach a critical stress and some cell walls buckle. This buckling softens the foam, as illustrated by the change in slope in Figure 3B. The load is removed at the same rate at which it was applied to the position at which the probe initially contacted the surface. The unloading stress response does not immediately drop off to zero and does not follow the loading response, exhibiting hysteresis due in part to the viscoelastic nature of the bread. After a short pause, the bread is reloaded. The stress is lower on the second compression, which indicates that the foam did not fully recover after initial compression. The model suggests that the firmness of the bread is determined by the thickness of the rod (cell wall thickness), the length of the rod (cell diameter), and the geometric arrangement of the rods as well as the mechanical properties of the bread crumb material (15).

**Bread.** The firmness of bread and cake crumb increases over the shelf life of the product, and softness in such products is often associated with the perception of freshness. It has long been known that although crumb firmness is closely related to moisture content it cannot be explained exclusively by product drying. Moisture migration within the product and physicochemical changes in the macromolecular components of a product, particularly starch retrogradation, also contribute to firmness. Use of texture measurements represents a simple, relevant approach to quantifying crumb staling. AACC International Approved Method 74-09.01 for measuring bread firmness (1,2) is primarily designed to characterize bread staling. A 25 mm thick bread slice is compressed under a 36 mm probe at a speed of 1.7 mm/sec to 40% compression. Firmness is defined as the force at 25% compression. This corresponds to the elastic buckling region seen in Figure 3B (albeit for slightly different conditions). For a typical 800 g loaf, the clearance between the probe and the crust is sufficient to avoid interference; however, if the textures of loaves with different volumes are to be compared, it is advisable to cut a core (Fig. 4).

One application of texture analysis of bread is to assess the effects of fiber inclusion. Current dietary recommendations advise that complex carbohydrates (starches) should form the primary energy source for a healthy diet and that the amount of dietary fiber consumed by most of the population should be increased.
Bakery products provide a good opportunity for delivering dietary fiber, both through the use of brown and wholemeal flours and supplementation with cereal brans or other sources of fiber. However, inclusion of these types of ingredients can result in reduced loaf volume, dark color, bitter flavor, and firm crumb texture (7). The effects of several of these properties have been studied in a collaborative European project, DREAM.

As part of the project, a model bread product was developed to provide a common system for use by researchers and product developers to study the effects of fiber addition on product quality and nutritional properties. A common protocol was defined for crumb firmness that was suitable for use with the different texture instrument models employed in the participating laboratories. Cylindrical samples (50 mm in diameter) were cut from the center of a 30 mm thick slice (Fig. 4) and compressed with a 50 mm diameter cylindrical probe to 40% of their original thickness. Compression was held for 2 min, resulting in stress relaxation. The modulus in the initial elastic region, critical stress at the transition between the linear elastic and buckling regions, maximum stress, and stress after relaxation were measured. Stress after relaxation measures the hysteresis observed in the unloading phase of a TPA measurement (Fig. 3). One implication of the results obtained for relaxation is that the rate of loading and unloading should be taken into account when designing and comparing studies.

A collaborative trial was performed in four European laboratories, using the model bread product and three levels of wheat bran addition (0, 10, and 20% of flour mass). Although identical ingredients and similar mixers were used, considerable variation between laboratories was observed. This variation illustrates the challenge of controlling bread texture and possibly results from differences in processing equipment, environmental conditions, and measurement of texture using different instruments. Despite these variations, the addition of bran consistently resulted in reduced loaf volume and increased firmness. Approaches to control the effects of wheat bran on bread volume and texture include control of water distribution and particle size. Maximum stress was regarded as an indication of crumb firmness and showed a strong negative correlation between loaf specific volume and firmness (Fig. 5), which was consistent with previous studies (11).

**Gluten-free Cake.** Although firmness is of primary interest, springiness and cohesiveness (Fig. 2) of the crumb are also important. When products are reformulated to include bran or for the gluten-free market, firmness alone may not be an adequate measure of the textural quality of the product. At the Campden BRI laboratory, a TPA test is used to measure the texture of both breads and cakes. An example of the usefulness of the added information provided by the second compression test is provided by a recent study in the lab, which found that gluten-free cake formulated by replacing wheat flour with wheat or other starches and xanthan gum was softer throughout its shelf life than the control. However, the cake was less springy and more fragile than the control, which was measured as lower cohesiveness (Fig. 6) and springiness in a TPA test.

**Salt Reduction.** Texture measurements are only tools to assess product quality; the goal is always to control texture to ensure that products consistently meet consumer expectations. Concerns over sodium levels in the diet have led to salt levels in U.K. breads being reduced by 38% since the 1980s, according to information provided by members of the Federation of Bakers. Salt does play a role in bread quality, however. Studies in the Campden BRI laboratories found that, although the effects of salt were relatively small compared with those of other factors such as flour quality and water addition, the effects of salt on dough handling and the fermentation rate of yeast do impact bread quality, including texture.

Campden BRI recently evaluated the need to take the general reduction of salt in bread into account in the evaluation of wheat quality (this study will be reported in a future article). Although not specifically part of the experimental design, the study also provided some insights into the effects of different test baking approaches. Sixteen wheat cultivars of varying breadmaking quality were tested at three salt levels: a control (1.5%), the amount specified for an extensograph test (2%), and a reduced level (1.1%). Our standard procedure is to use a standard quantity of yeast and to proof the bread to a standard height. As expected, loaf volume varied considerably between varieties, and there was a general negative correlation between specific volume and firmness (Fig. 7). At the highest salt level, firmness was lower for a corresponding specific volume. To test whether this was due to the effect of salt on yeast activity, the yeast level was adjusted using data from earlier studies to produce comparable proof times for each salt level. The control bread was proofed to height, and this time was used as the proof time for the experiment. Yeast adjustment greatly reduced the effect of salt on bread texture.
Brittle Products

Texture measurements are not only relevant for evaluating soft, compressible products. Many baked products have a hard or brittle texture, typically described by terms such as hard, crispy, or crunchy. The mechanical properties of such products are typically characterized by elastic deformation with high modulus followed by fracture. Under load, elastic strain energy is stored in the material. Discontinuities in the structure result in a concentration of stress. Above a critical level, the energy is released by crack extension, resulting in a decrease in applied force measured and, in some cases, a release of sound energy, which contributes to the sensory perception of product texture. Depending on the structure of the product and the loading mode, fracture may occur as a single event or multiple events.

Testing Approaches. Typical instrumental testing approaches include three point bending (Fig. 8A) and penetrometry with rod- (Fig. 8B), cone-, or tooth-shaped indenters. Figure 9 shows examples of force and sound emission measurements for tortilla chip and cheese puff products tested using three point bending and penetrometry geometries. Failure events are characterized by a sudden decrease in force, which is normally accompanied by a sound impulse.

Three point bending geometry tests the mechanical properties of a product as it is snapped. The loading geometry results in a bending moment that is maximum at the center. This encourages failure at that point in a controlled manner, typically with a single or small number of fracture events. Relevant parameters include the stiffness of the product, which is characterized by the gradient of the curve (from which elastic modulus can be calculated by modeling the product as an elastic beam); the force at the point of failure; and the energy of failure measured as the area under the force-deflection curve.

For the cheese puff example, multiple fracture events occurred due to successive fracture of individual walls within the structure and arresting of cracks by pores. Multiple fracture events such as these are characteristic of a crunchy texture. The area under the force-distance curve represents the energy of penetration and provides information on the firmness of the product. The number and relative height of force peaks and the sound energy provide information related to other sensory attributes such as crunchiness. A parameter recently developed at Campden BRI that is based on combined measurements of sound and force was able to discriminate between different commercial cracker products and was correlated with sensory scores for crispiness.

Biscuits. A major class of brittle baked products is known as biscuits in the European market and cookies in North America. These products include crackers, semisweet sheeted dough products, short rotary molded dough products, and cookies such as ginger snaps and encompass a wide range of textures, nutritional profiles, and variations in sugar, fat, and fiber contents. Moisture has an important influence on the texture of biscuits and many other brittle food products. Data from Saleem et al. (9) are used in Figure 10 to show force traces resulting from three point bending of semisweet biscuits with varying moisture contents prepared by equili-
biration at different relative humidities. At low moisture, brittle fracture is seen. Increasing moisture results in reduced stiffness, lower failure stress, and a more ductile failure mode at a greater failure strain, typically described as soft texture. Softening of texture due to moisture gain from the atmosphere or from higher water activity components within a composite product is one of the factors that limits the shelf life of biscuit and snack products. Texture measurement using methods such as three point bending geometry is useful, therefore, for shelf-life trials.

The brittle texture favored for many low-moisture biscuit and snack products also requires good control of moisture uniformity during baking to prevent undesirable crack formation known as checking. Moisture loss from the surface during baking typically results in a moisture gradient (Fig. 11). Redistribution of moisture after baking causes differential expansion (10). In a brittle product, excessive moisture gradients can result in stresses that can lead to checking; good control of oven conditions is important to minimize such gradients (8).

The results shown in Figure 10 were for biscuits with 16% fat content. This study (9) also compared the mechanical properties of biscuits with varying fat contents. Biscuits with a higher fat content had lower failure stress, which is consistent with the “short” eating texture often associated with higher fat formulations. However, unlike the effect of increased moisture content, there was no effect on failure strain, and the biscuits retained a brittle, although softer, texture.

One of the objectives of product developers seeking to improve the nutritional profile of biscuit products is to increase the fiber content. The effects of fiber addition on biscuit texture have been studied using a standardized model product developed as part of the DREAM project. The model is based on a digestive biscuit, which is a short dough product containing wholemeal flour. Texture measurements were made using penetrometry with a 2 mm diameter cylindrical probe mounted over a flat plate with a 10 mm hole and a test speed of 0.5 mm/sec to a distance of 10 mm, resulting in complete penetration of the biscuits, which had typical thicknesses of 6–7 mm. Figure 12 shows force traces for replicate biscuits made with the control formulation and mean force traces for control biscuits and biscuits with added fiber. Small peaks can be seen in the traces for the replicates that correspond to microfracture events characteristic of a crunchy texture. The number of peaks to a penetration distance of 3 mm was termed “crunch.” Firmness was defined as the area under the force-distance trace to 3 mm and corresponded to the energy of penetration. The figure shows that this increased with fiber addition. The individual traces showed a high degree of variability, which is typical of penetrometry results for brittle products, and measurements were based, therefore, on tests of 10 replicate samples for each formulation. The mean force traces shown in Figure 12 reveal the presence of an initial failure event within a distance of 1 mm. The peak force of this event was termed “fracturability” in reference to the terminology used in the TPA protocol (Fig. 2).

Measurements were performed for biscuits prepared with the addition of one of two types of fiber-rich ingredients (wheat bran or inulin soluble fiber), in addition to the wholemeal flour content of the control formulation. These were substituted for a portion of the flour in the formulation at levels from 0 to 40%, maintaining a constant mass of flour and fiber ingredients. Three bran particle sizes and five levels of water were also included in the experimental design. Both types of fiber resulted in an increase in firmness as a function of addition level by mass, which was accompanied by a reduction in biscuit thickness. However, they resulted in different textures. Inulin resulted in a hard initial bite and high fracturability value. Added bran, on the other hand, resulted in reduced crunch (Fig. 13).

Conclusions
Baked goods are an important staple food in many parts of the world. As a result, small improvements to their nutritional profiles can have a major impact on public health. For this reason considerable
Effort has been put into reformulating many baked products, with bread in particular being targeted by governments in salt-reduction campaigns. Texture plays an important role in the consumer acceptability of these reformulated products, however. Instrumental testing methods based on measurement of force, in which samples are compressed under controlled conditions, can provide information on many aspects of texture. The examples discussed show the use of various protocols for testing breads, cakes, and biscuits in the context of salt reduction, gluten-free formulations, and fiber supplementation. The illustrations highlight the types of testing geometry and measured parameters appropriate for testing the physical properties of different types of baked products and applications.

Acknowledgments
The research for the collaborative European project, DREAM, received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement FP7-222-654-DREAM.

References

Martin B. Whitworth is a principal scientist for cereal science and technology in the Campden BRI Cereals and Milling Department. He has worked at Campden BRI and its predecessors since 1992. He has a Ph.D. degree in physics from Cambridge University, where he studied fracture mechanics, which he now applies to grain processing and food texture. His other research interests include use of imaging methods to measure food structure, color, and composition. Applications include use of medical CT scanning to image products during baking and hyperspectral NIR imaging to map components such as moisture and fat in food products. Martin is the developer of the C-Cell bread imaging system, and his work on on-line measurement of bran in flour was the basis for the Fluoroscan instrument.

Fred K. Gates is a senior bakery scientist in the Baking and Cereal Processing Department at Campden BRI. Fred has experience in wheat quality assurance, having previously worked for Allied Technical Centre, part of Associated British Foods. He graduated with a degree in food science and was awarded a Ph.D. degree from the University of Helsinki. The emphasis of his research has been on the rheological properties of cereal products in relation to food processing, and he has extensive research experience with rye and oats. Fred has also carried out post-doctoral research at the Division of Material Physics of the University of Helsinki, developing ultrasonic methods to monitor food during processing.