Invited Review: Sensory and Mechanical Properties of Cheese Texture¹

E. A. Foegeding and M. A. Drake²

Department of Food Science, Southeast Dairy Foods Research Center, North Carolina State University, Raleigh 27695

ABSTRACT

Instrumental mechanical properties (instrumental tests that measure force and deformation over time) of cheese and cheese texture (sensory perception of cheese structure) are critical attributes. Accurate measurement of these properties requires both instrumental and sensory testing. Fundamental rheological and fracture tests provide accurate measurement of mechanical properties that can be described based on chemical and structural models. Sensory testing likewise covers a range of possible tests with selection of the specific test dependent of the specific goal desired. Establishing relationships between instrumental and sensory tests requires careful selection of tests and consideration and analysis of the results. A review of these tests and a critical analysis of establishing relationships between instrumental and sensory tests is presented.

Key words: texture, sensory analysis, mechanical properties, rheology

INTRODUCTION

The most appropriate way to start a review on cheese texture is to ask the question, what is texture? For foods, texture is generally defined as those elements that do not involve the senses of smell and taste. That leaves the properties that we perceive with sight, hearing, and touch as contributors to the collective texture of a food. Regarding cheese, texture is generally limited to the sensations experienced when masticating, suggesting the predominant role of mechanical properties. However, although force and deformation do occur as part of mastication, other processes such as manipulation of the chewed mass by the tongue and mixing with saliva also occur and result in unique sensory texture perceptions that are not currently measured by instrumentation.

Because texture is a sensory property, the texture of a given cheese should be described by a series of texture terms evaluated during mastication. For example, we investigated the effect of aging on the texture of Mozzarella and Monterey Jack cheese using sensory and mechanical analysis (Brown et al., 2003). Five of the 10 sensory texture terms were able to differentiate the ages of the cheeses within varieties, and 96.1% of the total variation in samples could be explained by 3 principal components. This allows one to hypothesize that if you wanted to make a low-fat Monterey Jack cheese similar in texture to the full-fat product, then the low-fat and full-fat cheeses need to have similar values for the 10 texture terms. This could be done by empirically altering the cheese-making process and hoping for the best, or could be based on a fundamental understanding of what properties of the cheese determine each texture term. Therefore, it has been a common quest among researchers to understand the mechanical properties of cheese and relate mechanical properties determined instrumentally to sensory texture terms.

Mechanical tests can be fundamental or empirical. Fundamental mechanical tests apply stresses or strains to a specimen of defined geometry at a given rate such that physical properties can be measured. Fundamental tests are generally restricted to materials that can be considered homogeneous and isotropic on the scale of testing. Mechanical properties determined from fundamental tests are inherent to the material and not dependent on the instrument. In contrast, empirical tests place fewer restrictions on testing geometry and material composition. For example, the much-used “instrumental texture profile analysis” method (Bourne, 1978) defines a 2-cycle compression test without restricting sample composition (homogeneous or nonhomogeneous), geometry, maximum compression, or compression rate. The choice between using a fundamental or empirical test depends on the goal of the experiment. Fundamental mechanical properties such as elastic modulus and fracture stress can be explained by theoretical models relating interactions of molecules forming the cheese network and overall network structure. Because the ultimate goal is to understand how the structure and interactions of the cheese network determine sensory texture, fundamental mechanical proper-

Received October 25, 2006.

Accepted November 27, 2006.

¹Use of names, names of ingredients, and identification of specific models of equipment is for scientific clarity and does not constitute any endorsement of product by authors, or North Carolina State University.

²Corresponding author: mdrake@unity.ncsu.edu

ties should be measured when investigating molecular mechanisms of texture (Tunick, 2000; Lucey et al., 2003).

This review will focus on fundamental mechanical properties of cheese and how they relate to sensory texture. Cheese is considered a soft solid material consisting of a network composed of mainly protein, water, and lipid (Walstra, 2003). The mechanical properties of cheese are related to network composition, structure, and interactions among molecules within the network (Lucey et al., 2003). Therefore, in order to understand how network properties determine sensory texture, the following steps need to be taken.

1. Develop a texture lexicon (list of texture terms) that describes the complete sensory texture for an individual type or groups of cheese.
2. Evaluate each term for logical mechanical mechanisms.
3. Characterize the mechanical properties of the cheese under conditions that cover those used in sensory evaluation (e.g., strain rate and temperature).
4. Determine general relationships between sensory terms and mechanical properties.
5. For those mechanical properties that are associated with sensory terms, evaluate models that relate mechanical properties to aspects of cheese network structure and interactions (i.e., types and extent of bonding among the molecules forming the network).
6. Validate models by altering the cheese network to demonstrate that changes in textural properties are predicted by changes in network structure and properties.

SENSORY ANALYSIS OF CHEESE TEXTURE

Sensory analysis is a *scientific* method to measure human responses to external stimuli. Sensory science is a discipline that has evolved from more than 150 yr of psychological, physical, and physiological science. Tests are conducted using specific procedures that have been established based on scientific observations of human behavior. Results can be objective or subjective depending on the specific goal and sensory procedure selected. Too often, an inappropriate procedure is selected or a selected procedure is not conducted appropriately. The result is inaccurate or inappropriate conclusions. It is important to keep in mind that, just as is the case with any other scientific tool or experiment, attention to detail and appropriate procedures and controls are crucial.

There are 2 basic groups of sensory tools: analytical tests and consumer tests, with the latter often referred to as affective tests. The results from these tests are, respectively, objective and subjective. Analytical sensory tests generally use screened or trained judges depending on the specific test, whereas affective sensory tests use consumers (Lawless and Heymann, 1999). The most powerful analytical sensory test, descriptive analysis, is generally the sensory tool of choice when determining or establishing relationships with instrumental measurements. Descriptive analysis consists of training a group of individuals (generally 6 to 12) to identify and quantify specific sensory attributes or all of the sensory attributes of a food. The panelists are trained (sometimes for several hundred hours) to operate in unison as an instrument, and each individual panelist serves a function analogous to an individual sensor on an instrument. The panel replicates measurements analogous to replication of instrumental measurements and the data collected are analogous to instrumental data. Techniques and approaches to descriptive analysis are reviewed elsewhere (Lawless and Heymann, 1999; Murray et al., 2001; Delahunty and Drake, 2004). Consumer tests are used when information on consumer liking and perception is desired (experts or trained panelists are NOT appropriate for determination of acceptability), and these tests require large numbers of consumers (at least 50) in order to obtain results that have any relevance to the consumer (Lawless and Heymann, 1999; Meilgaard et al., 1999).

Grading and judging comprise a completely separate group of tools from analytical or affective sensory tests. These are tools that were designed by the dairy industry in the early 1900s to address quality and consistency among products and to assist with training students to identify what were common sensory quality issues of that era (Bodyfelt et al., 1988; Delahunty and Drake, 2004; Bodyfelt et al., 2007). By these techniques, a "defect-oriented" selection of categories is used to generate "quality scores." These tools continue to play a useful role in product screening, troubleshooting, and student activities, but they suffer from several shortcomings that make them inappropriate for research and establishing relationships—with instrumentation or the consumer (Jack and Paterson, 1992; Delahunty and Drake, 2004; Bodyfelt et al., 2007).

A key aspect of a trained sensory panel is that the results are analogous to instrumental data. As such, the sensory instrument should be as precise and reproducible as possible. One way of minimizing variability is panel training. However, a crucial step to facilitate panel training and performance and to establish any relationship to physical or instrumental measurements is to have clearly defined terms for sensory attributes

(Drake and Civile, 2003). Defined terms facilitate panel training and minimize variability but they also set the parameters for understanding instrumental measurement of the sensory attribute. For example, is cheese firmness measured by compression with fingers, bite force with incisors, bite force with the molars, or compression between the tongue and the hard palate? What is the defined size and shape of the sample? Sample size and geometry can certainly influence results just as with instrumental measurements. Cheese firmness might be measured by the fingers, tongue, incisors, or molars depending on the type of cheese. Many cheese texture attributes in addition to firmness can be evaluated by hand manipulation in a specific manner (Drake et al., 1999a; Sandra et al., 2004). Drake et al. (1999a) showed that hand and mouth evaluation of specific cheese texture attributes were equally sensitive. A clear attribute definition also facilitates comparison with other studies. Table 1 shows a list of defined texture terms that have been applied by trained panelists to document texture attributes of several different types of cheeses. Note that some attributes such as firmness can be measured by hand, by first bite of the incisors, first bite of the molars, or the first few bites (chewdown term). Also, some attributes have multiple definitions, whereas for others the attribute descriptor is different but the definitions are identical. Clearly, definitions are a requirement for understanding. Visual attributes (surface wetness, color homogeneity, etc.) should also be considered when generating a lexicon. These attributes may or may not be significant, depending on the type of cheese(s) evaluated.

Table 2 is a cheese texture lexicon (or sensory language) developed by the authors. The language has been used to profile the texture properties of a variety of hard and processed cheeses (Drake et al., 1999a,b; Gwartney et al., 2002; Brown et al., 2003; Yates and Drake, 2007). The language uses a product-specific scale (i.e., it covers the range of cheese textures), has clearly defined terms, and has cheese examples to aid panelists in use of the scale. The language also covers the temporal aspects of texture with first bite, chewdown, and residual (postswallow or expectoration) attributes evaluated. Cheese sensory texture terms are grouped into 3 categories or temporal aspects: hand terms, first bite terms, and chewdown terms (Figure 1). Each of these attributes plays a crucial role in the overall texture profile or texture of a cheese. Different cheese types can be differentiated, or perhaps more importantly, the effect of various parameters such as age, starter or adjunct culture, composition, and fat content, on a particular cheese type can be determined.

Cheese texture comprises a lot more than just firmness, and the physiological and biological aspects of the

entire mastication process will be covered later in this review. Development of instrumental measurements to mimic or measure sensory texture perception would mean covering all of these terms, not just first bite terms if an entire picture of texture is to be obtained. For instance, fat reduction in cheese results in changes in sensory perception of texture (Drake and Swanson, 1995; Banks, 2004). Previous sensory research using judging and scoring confirmed that cheese texture was altered by fat reduction and that texture defects were more prevalent in reduced-fat or low-fat cheeses (Drake et al., 1995, 1998). As previously described, the exact nature of the texture changes is difficult to determine using this sensory approach, which is one of many reasons why this technique is no longer an acceptable technique for research. Descriptive sensory analysis has more recently, and appropriately, been applied to document how fat reduction alters cheese texture. These changes in texture are characterized (by trained panelists) by increased springiness, decreased cohesiveness, decreased smoothness of mass, and decreased residual mouth smoothness (Drake et al., 1996; Gwartney et al., 2002; Yates and Drake, 2007). It is important to note that firmness is not necessarily a characterizing sensory attribute of fat reduction. Of the terms listed previously, only springiness is a first bite or hand-evaluated term. A study that measured only instrumental compression or sensory firmness would potentially miss some of the critical differentiating texture attributes. The other key attributes are chewdown terms. Currently, there are no instrumental tests that provide a comprehensive measure of these critical sensory attributes. These issues will also be addressed later in this review.

Texture clearly plays a role in consumer acceptance of cheeses. The exact role that texture plays with consumer acceptance is difficult to define because flavor cannot be uncoupled from texture when the consumer evaluates cheese. Visual appearance cues may also affect both flavor and texture perception. For instance, consumers generally scored texture liking for reduced- and low-fat cheeses lower than texture liking for full-fat cheeses (Drake et al., 1995, 1996). However, the same trends were also observed for flavor liking and overall liking of these reduced- and low-fat cheeses. Consumers often either totally like or dislike products. That is, if the product is liked, all attributes are positively scored and if the product is disliked, all attributes are negatively scored. Flavor, texture, and visual cues are coupled together in the mind of the consumer to determine product quality and liking. These reasons underscore why trained panelists are used for objective sensory measurements. When a trained panel is evaluating both flavor and texture attributes, it is advised

Table 1. Terms that have been identified and defined by trained descriptive panels to document texture attributes of various cheeses¹

Method of analysis/attribute	Definition
Hand evaluation terms	
Cohesiveness	Manipulate sample using thumb and 2 fingers 5 times and then score the degree to which the sample holds together during manipulation.
Crumbly/crumbliness	Manipulate sample using thumb and 2 fingers 5 times and then score the ease with which the sample breaks apart and crumbles with manipulation.
Firm/firmness	Definition 1: The force required to squeeze a cube (1.5 × 1.5 × 1.5 cm) of cheese flat between the first finger and thumb. Definition 2: Press sample gently using thumb and 2 fingers for 1 to 2 s without breaking. The force required to compress the sample.
Rate of recovery	Depress sample between thumb and first finger 30%, evaluate the speed or rate at which the sample returns to its original shape.
Softness	Yielding easily to pressure, easily molded, pliable, easily spreadable.
Springiness	Definition 1: Press sample gently using thumb and 2 fingers for 1 to 2 s without breaking. Evaluate rate at which sample springs back after compression. Definition 2: Depress sample between thumb and first finger 30%, evaluate the total amount of recovery of the sample.
Sticky/stickiness	Manipulate sample using thumb and 2 fingers 5 times. Evaluate how the sample sticks to the fingers.
First bite terms	
Crustiness	The force required to break through the crust of the cheese when taking the first bite, assessed using the front teeth.
Firm/firmness	Definition 1: The amount of force required to take the first bite of cheese assessed using the front teeth. Definition 2: The amount of force required to completely bite through the cheese assessed using the molars.
First-bite sticky	Sticky sensation experienced during the first bite.
Fracturability at first bite	Completely bite through the sample with the molars and evaluate the degree to which the sample fractures.
Rubbery/rubberiness	The degree of springiness experienced while biting the sample.
Hardness	The force required to bite the sample (first bite).
Chewdown terms	
Adhesiveness	The degree to which the chewed mass sticks to mouth surfaces, evaluated after 5 chews.
Chewy	Degree of chewing needed to break up the cheese; requiring a good deal of mastication, toffee-like texture.
Cohesiveness	The degree to which the chewed mass holds together, evaluated after 5 chews.
Creamy/creaminess	Definition 1: The extent to which the texture has broken down to a creamy semiliquid texture, assessed between tongue and palate during mastication. Definition 2: The feeling associated with heavy whipping cream (e.g., >30% fat content).
Crumbly/crumbliness	Definition 1: The extent to which the cheese structure breaks up in the mouth, assessed during the first 2 to 3 chews. Definition 2: The feeling in the mouth when the sample falls apart quickly in mouth during mastication.
Curdiness	The extent to which a curdy or mealy texture is perceived in the mouth during mastication.
Degree of breakdown	The amount of breakdown that occurs in the sample because of mastication, evaluated after 5 chews.
Dry	The degree of dryness or moistness sensed in the mouth during mastication.
Firm/firmness	The extent of resistance offered by the cheese, assessed during the first 5 chews using the front teeth; ranging from soft to firm.
Grainy	Definition 1: The extent to which granular structures are formed as the sample breaks down, perceived in the second half of chewing. Definition 2: The feeling of coarse particles in the mouth during mastication.
Mealy	The feeling in mouth when the sample breaks down in small pieces and it is difficult to gather them for swallowing.
Moist	Definition 1: The perceived moisture content of the cheese; ranging from dry to moist. Definition 2: The extent to which the cheese has a moist or wet texture around the palate during mastication.
Mouth-coating	Definition 1: The extent to which the cheese coats the palate and teeth during mastication. Definition 2: The degree of coating on the tongue and palate during mastication.
Oily	Oily, fatty, greasy mouthfeel of any kind.
Residual mouthfeel	The degree of "bittiness" or graininess in the mouth just before swallowing.
Residual smoothness of mouth coating	The degree of smoothness felt in the mouth after expectorating the sample.
Residuals	Manipulate sample using thumb and 2 fingers 5 times. Evaluate tactile feeling (residual) left after discarding sample.
Rubbery/rubberiness	The extent to which the cheese returns to its initial form after biting, assessed during the first 2 to 3 chews.
Slimy	Of the nature of slime, soft, glutinous, or viscous substance, soft, moist and sticky.
Smooth/smoothness	Definition 1: The smoothness of the cheese against the palate as it breaks up during mastication. Definition 2: The degree to which the chewed mass surface is smooth, evaluated after 5 chews.
Sticky/stickiness	Definition 1: The stickiness of the cheese against the palate and around the teeth during mastication. Definition 2: Overall sensation of stickiness during mastication.
Viscous	The mouthfeel associated with consuming very viscous fluids like heavy whipping cream or honey.

¹Terms and definitions are organized by method of evaluation and temporal order of evaluation (hand, first bite, chewdown). Adapted from Delahunty and Drake (2004), with permission from Elsevier.

Table 2. Descriptive sensory language for cheese texture¹

Sensory term	Definition	Reference cheese
Hand evaluation terms		
Hand firmness	Press fingers completely through the sample. Evaluate the force required to completely compress the sample.	Velveeta = 3 Muenster = 7 Sharp Cheddar (Kraft) = 10 Parmesan = 15
Hand springiness	Depress sample 30% between thumb and first 2 fingers. Evaluate total amount of recovery of sample. (If sample fractures as it is depressed, it is not springy.)	Parmesan = 1 Velveeta = 4 Sharp Cheddar (Kraft) = 7 Muenster = 13
Hand rate of recovery	Depress sample 30% between thumb and first 2 fingers. Evaluate rate of recovery (how long it takes to recover to the original shape)	Feta = 1 Velveeta = 3 Sharp Cheddar (Kraft) = 6 Muenster = 9
Mouth evaluation terms—first bite		
Firmness	Using molars, take one complete bite through the sample. The amount of force required to completely bite through the sample	Velveeta = 2 Muenster = 6 Sharp Cheddar (Kraft) = 9 Parmesan = 14
Fracturability	The amount of fracturability in sample after biting	Velveeta = 1 Sharp Cheddar (Kraft) = 5 Feta = 14
Mouth evaluation terms—chewdown		
Degree of breakdown	Chew the sample 5 times and evaluate the chewed mass. Evaluate how much the sample has broken down during mastication	Parmesan = 1 Muenster = 9 Sharp Cheddar (Kraft) = 11 Velveeta = 14
Cohesiveness	The degree to which the chewed mass sticks together in the mouth	Parmesan = 1 Feta = 3 Muenster = 7 Sharp Cheddar (Kraft) = 11 Velveeta = 14
Adhesiveness	The degree to which the chewed sample sticks to the surfaces of the mouth and teeth	Parmesan = 1 Muenster = 7 Sharp Cheddar (Kraft) = 10 Feta = 12 Velveeta = 14
Smoothness of mass	Evaluate the smoothness of the chewed mass	Parmesan = 1 Feta = 3 Muenster = 8 Sharp Cheddar (Kraft) = 10 Velveeta = 14
Mouth evaluation—residual		
Smoothness of mouthcoating	Expectorate the sample: evaluate the residue in the mouth. Evaluate the degree of smoothness felt in the mouth	Parmesan = 1 Feta = 5 Muenster = 10 Sharp Cheddar (Kraft) = 11 Velveeta = 14

¹Adapted from Brown et al. (2003).

to evaluate flavor and texture in separate sessions with different product codes to further eliminate the possibility of flavor and texture cross-influence.

Results certainly suggest that specific textures are expected or accepted by consumers for particular cheeses. Carunchia Whetstone et al. (2006) evaluated consumer acceptance of Cheddar cheese and part of the same block of Cheddar cheese that had been ground and re-formed. Flavor profiles of the 2 cheeses were identical by descriptive analysis and consumers agreed that the flavor intensity of the 2 cheeses were identical. However, texture-liking scores were decreased compared to texture liking of the original cheese and concur-

rently, overall liking scores of the re-formed cheeses were decreased compared with the original cheese. Yates and Drake (2007) also documented that a specific texture was expected by the consumer for Gouda cheeses, and cheeses that deviated from the expected texture were less liked overall even if flavor-liking scores were similar. Descriptive analysis was used to explore the desired texture profile of the Gouda cheeses. Consumers preferred Goudas that were moderately firm, not springy, cohesive, exhibited high breakdown, and had high smoothness of mass and mouthcoating. Cheeses that were firm, springy, and fracturable were not as desirable. However, cheeses that were too soft

Figure 1. Principal component analysis biplot of sensory parameters used to differentiate Mozzarella (●), Monterey Jack (■), and Process (▼) cheeses by age (indicated by numbers beside symbol). Sensory parameters: hand firmness (hfm), hand springiness (hsp), hand rate of recovery (hrc), first bite firmness (ffm), first bite fracturability (ffr), chewdown degree of breakdown (cbr), chewdown cohesiveness (cco), chewdown adhesiveness (cad), chewdown smoothness (csm), residual smoothness (rsm). From Brown et al. (2003).

and too high in breakdown and smoothness of mass were also not as desirable as the cheeses that fell in the optimum range.

MECHANICAL PROPERTIES OF CHEESE

The classification of cheeses into groups of very hard, hard, semi-soft, and soft speaks to the range of textures encountered in cheese (Fox et al., 2000). From a materials perspective, cheese is a viscoelastic material, implying a mixture of fluid- and solid-like properties. These properties can be determined by applying small stresses (force per unit area) or strains (deformation per unit length) at levels that do not cause significant irreversible changes in the cheese. For the sake of simplicity, tests will be classified by the level of strain realizing that instruments apply either a stress or strain. Small-strain rheological tests are applicable for a range of cheese textures from soft Brie to hard Cheddar. In these tests, a stress or strain is applied to the cheese and the resulting strain or stress is measured. The type of mechanical properties measured depends on the relationship between stress and strain and can

be separated into regions of linear, nonlinear, and fracture. Small-strain test should be conducted in the linear viscoelastic region, defined as where stress is linearly proportional to strain at a given strain rate (Barnes et al., 1989; Steffe, 1996). Most modern rheometers operate by providing an oscillatory shear to the sample by applying a constant stress or strain at a given frequency. This produces a wave form for stress and strain. If the wave forms for stress and strain are completely in phase, then the phase angle is 0° and the material is behaving as an elastic material. If the stress and strain have a phase angle of 90° , then the material is behaving as a viscous fluid (Barnes et al., 1989; Steffe, 1996). Viscoelastic materials have phase angles between 0° and 90° . The phase angle and overall amplitude of stress and strain are used to calculate the following properties (Barnes et al., 1989; Steffe, 1996): 1) Complex modulus (G^*): stress amplitude divided by the strain amplitude; 2) Elastic or storage modulus (G'): the energy stored and released per oscillation (represents the elastic portion of the complex modulus); and 3) Viscous or loss modulus (G''): the energy lost per

Figure 2. Storage (G' , a) and loss (G'' , b) moduli over changing frequencies for Monterey Jack cheese at 4 (○), 10 (▽), 17 (□), and 38 (◇) d of age. Values are the average for 2 replications. From Brown et al. (2003).

oscillation (represents the viscous portion of the complex modulus).

Figure 2 shows the frequency dependence of G' and G'' for Monterey Jack cheese as a function of age (4 to 38 d). The overall trend of an increase in G' as frequency increases can be attributed to more of the network structure “not relaxing” during the shorter period as frequency increases. In this case, “relaxing” can be considered a flow of molecules past each other. There is

Figure 3. Phase angle (δ) over changing frequencies for Monterey Jack cheese at 4 (○), 10 (▽), 17 (□), and 38 (◇) d of age. Values are the average for 2 replications. From Brown et al. (2003).

less change seen in G'' with frequency but note that the scale for G'' is one order of magnitude less than G' . A general decrease in G' is observed when comparing the 4- and 38-d samples, which can be attributed to changes in the amount of elastic network or the bonding within the elastic network (Lucey et al., 2003).

The phase angle reflects the overall viscoelasticity of the cheese (Figure 3). It can also be expressed as the loss tangent ($\tan \delta = G''/G'$; Barnes et al., 1989; Steffe, 1996). As frequency increases, the relative elastic response increases, as indicated by a decrease in phase angle. Also, note that aging causes an increase in phase angle, indicating a relative increase in the viscous component.

Frequency dependence of rheological properties is called a “mechanical spectrum” because it characterizes the mechanical properties across time (frequency $\propto 1/\text{time}$) in a way similar to determining the absorbance of a pigment across a range of wavelengths of light. It provides a fingerprint of the mechanical properties determined within the linear viscoelastic region. Moreover, it emphasizes that the mechanical properties of a viscoelastic material depend on the rate (in this case frequency) at which the deformation is applied. Ideally, when relating mechanical properties to sensory texture the deformation rate of the mechanical test should coincide with the deformation rate experienced during mastication. This will be elaborated on in the oral processing section.

A second approach to determining viscoelastic properties is to apply a constant stress or strain, and follow the changes in the paired parameter. In creep tests, a constant stress is applied and the strain in the material

Figure 4. Creep recovery curves for Mozzarella cheese at 4 (○), 10 (▽), 17 (□), and 38 (◇) d of age. Initial compliance (J_0) and maximum compliance (J_{max}) are indicated in the figure. Values are the average for 2 replications. From Brown et al. (2003).

is measured as a function of time. The compliance ($J = \text{strain}/\text{stress}$) of Mozzarella cheese during creep and creep recovery is shown in Figure 4. After a time in creep (constant stress), the stress is removed and the “recovery” of strain is measured. The instantaneous compliance (J_0) is the compliance at time zero and is determined by extrapolation of the compliance to zero time. The maximum compliance (J_{mx}) is the compliance at the end of the creep test; in this experiment set at 600 s. Note that J_{mx} increases as the cheese ages. Because $J_{mx} = \text{strain}/\text{stress}$, and stress is constant, it shows that as the cheese ages, the level of deformation for a given stress increases. This observation, like the decrease in G' seen with aging (Figure 2), is consistent with changing the amount of elastically active strands in the network, or the degree or type of bonding, or both, among the strands. One of the differences between creep tests and oscillatory tests is the period of testing. A frequency of 0.001 Hz requires 1,000 s per cycle. When conducting a frequency sweep from 0.001 to 10 Hz, with an adequate number of sampling frequencies in between, an extended period will be required to run the test. Therefore, a creep test is more amenable to longer time relaxations. However, because strain is measured and not controlled, one has to determine if the maximum level of strain is still within the linear viscoelastic region. The recovery test provides information on elas-

ticity and viscoelasticity. An ideally elastic material would spring back to its original shape once the stress was removed (zero strain) and have a percentage recovery value of 100%. In contrast, a viscous fluid would show no recovery. The retardation time provides a characteristic time for the material to “recover” and is defined as the time required for the strain to reach 62.3% of its final value. An elastic material would recover instantaneously.

As stated previously, small-strain tests are conducted at strain levels that, hopefully, only cause reversible deformation and do not change the cheese structure. For example, a strain of 0.01 is often within the linear viscoelastic range when testing hard and semi-soft cheeses. If you were biting down on a cheese cube with a height of 2 cm, a strain of 0.01 would be reached when the height was decreased by 0.02 cm! This is, clearly, not something easily done in a sensory test. Fracture can occur at large deformations. This is observed in cheeses that are firm enough to show a clean fracture and separation of pieces. Soft cheeses such as Brie will not show fracture but may show a yielding behavior. The predominance of flow and yielding in mechanical properties, and thickness and creaminess in sensory texture, makes soft cheeses very different from hard and semi-soft cheeses when it comes to mechanical characterization. For simplicity, we will focus on

Figure 5. Effect of torsional strain rate on fracture strain of Monterey Jack cheese aged for 4 or 38 d. Data from Brown (2002).

Figure 6. Effect of torsional strain rate on fracture stress of Monterey Jack cheese aged for 4 or 38 d. Data from Brown (2002).

cheeses that show clear fracturing behavior when masticated.

Fracture properties of cheeses represent the stresses and strains required to break 1 piece of cheese into 2 or more pieces. Note that for Monterey Jack the fracture strains are in the range of 1.1 to 1.9, whereas the maximum strain within the linear region for Monterey Jack is 0.15 (Brown, 2002; Figure 5). Fracture strain increases with aging, indicating a more deformable network. There is a tendency for the fracture strain to decrease with increasing strain rate (Figure 5), whereas fracture stress shows a clear increase with strain rate (Figure 6). Again, this demonstrates the importance of strain rate when determining fracture properties of viscoelastic materials such as cheese. Coinciding with changes in G' , fracture stress decreases with aging. A more extensive analysis and discussion of fracture properties of cheese is found in Luyten et al. (1991).

ORAL PROCESSING

In the previous section, we discussed how rheometers assess the mechanical properties of materials. This section will address the mastication process as a way to measure mechanical properties of foods. The oral processing of foods is accomplished in 3 stages (Guinard and Mazzucchelli, 1996). The first stage is positioning before mastication, followed by chewing, and finally swallowing. The chewing phase is referred to as the *objective masticatory function* (defined as masticatory

performance), and is the individual's ability to grind or pulverize food (van der Bilt, 2002). This process varies with occlusal factors, maximum bite force, sensory feedback, manipulation of food, age, saliva, swallowing threshold, and food texture and taste (van der Bilt, 2002). Agrawal et al. (1997) modeled the chewing process as fracture being initiated by a 3-point bend and cracks starting remotely from a cusp, or at the cusp due to stresses from the cusp exerted on the food. They evaluated 28 different foods and determined that:

$$\sqrt{\text{surface area of food particles}} \propto \sqrt{R/\sqrt{E}}$$

where R is the food toughness, defined as the energy required to generate one unit of surface area as a crack progresses, and E is Young's modulus (normal stress/normal strain). Their results suggested that fracture occurred remotely from a cusp, and thus resistance to jaw movement provides sensory information on the deformation, fracture, and fragmentation of foods. Note that the parameter of interest, the surface area of food particles, reflects the view of mastication as a process to reduce particle size and does not consider aspects associated with likes or dislikes of food texture. Another approach to understanding masticatory performance is the measurement of muscle activity when subjects are chewing foods of known mechanical properties. Mioche et al. (1999) used electromyography to measure the activity of the masseter and temporalis muscles during mastication of toffee, coconut, Swiss cheese, French

cheese, and frankfurters. The muscle activity was related to the mechanical properties of the foods. The mechanical properties determined were 1) the stress at maximum strain (proportional to elastic properties) and 2) the stress at maximum strain rate (proportional to viscous properties) during a sinusoidal deformation (maximum strain of 0.3). The best relationship was found with a power law relationship that predicts:

$$\text{Mean muscle work by chew} = 0.03(\text{stress at maximal strain})^{0.31}.$$

The power law relationship suggested that muscle work per chew might act as a sensory input for texture perception (Mioche et al., 1999). The results of Agrawal et al. (1997) and Mioche et al. (1999) establish that a combination of properties from fracture mechanics (R) and rheological properties (E, and stress at maximum strain) are associated with oral processing of foods. However, these measurements were restricted to mechanical properties associated with hardness and particle size reduction because the primary focus was on understanding the ability to reduce particle size during each chew cycle. Textural properties that are important to the perceived quality of foods, such as adhesiveness to teeth during chewing, were not addressed in these studies.

As mentioned in the section on mechanical properties, cheese is a viscoelastic material and therefore the mechanical properties sensed during chewing will depend on the rate of jaw closure. In a study by Meullenet et al. (2002), average first bite velocities were assessed using electrognathography. The average bite velocities for 7 subjects ranged from 19.8 to 35.1 mm/s when chewing 15.9 mm³ cheese samples. This information can be used to approximate a chewing strain rate of 1.2 to 2.2 s⁻¹. The lapsed time for a first bite of cheese took approximately 0.5 to 1 s. Mechanical properties of cheese ideally should be tested within strain rates and fracture times that encompass those observed during chewing. More investigations are needed to determine the range of chewing strain rates observed among a wide range of consumers and cheese types.

Although not a subject of this review, it should be remembered that texture and flavor are evaluated simultaneously during mastication, and that food texture can influence flavor release. An increase in gel hardness is associated with a decrease in sensory flavor intensity, whereas the nosespace flavor concentration does not change (Weel et al., 2002). This suggests that gel texture, rather than in-nose flavor concentration, determines flavor intensity. Subsequent investigations suggest that gel hardness determines the chewing pattern

and physiological response, and that these 2 processes determine temporal patterns of flavor release (Mestres et al., 2005, 2006). Interestingly, Carunchia Whetstone et al. (2006) did not note decreases in specific flavors or perceived flavor intensity by consumers or trained panelists when they compared flavor properties of ground and re-formed Cheddar cheese with the original cheese. These discrepancies may be due to the differences between model systems and actual foods or they may be product or texture specific. For example, whey protein gels are not cheeses and the texture properties of whey protein gels are not identical to cheese.

ESTABLISHING RELATIONSHIPS BETWEEN SENSORY AND MECHANICAL PROPERTIES

A brief discussion of the differences between sensory and mechanical testing is required before evaluating correlations between methods. During mastication of cheese the temperature increases from initial temperature towards body temperature, particles are mixed with saliva, and the crushing process is between jagged surfaces of teeth. Mechanical testing at fracture is done isothermally; however, changes in viscoelastic properties can be determined isothermally and during a temperature change. The surfaces are flat, and testing in compression is done such that adhesion between the cheese and instrument surfaces is prevented. Although these differences are known, their precise influence on texture measurements remains to be established.

The property of cheese texture that is most easily measured by instrumental and sensory analysis is hardness or firmness (Wium et al., 1997; Drake et al., 1999a,b). This is because the human mouth and mechanical property-testing instruments are very good at measuring force. Indeed, if hardness were the defining textural term for cheese, then altering cheese-making processes to achieve a desired level of hardness would be a simple task. Therefore, finding a correlation between sensory hardness and mechanical properties depends more on the range of hardness values examined than the appropriateness of the test. As will become evident in the following discussion, properties that are assessed by chewing, such as cohesiveness, adhesiveness, and smoothness, become more problematic.

Sensory and Instrumental Texture Profile Analysis

Instrumental texture profile analysis, as described by Bourne (1978), is an imitative texture test that has been used extensively. It is generally conducted by uniaxial compression of a sample between 2 plates at a chosen cross-head velocity for a chosen level of deformation. Force, deformation, and work (area under the

force–deformation curve) measurements are used to calculate texture parameters of fracturability, hardness, cohesiveness, adhesiveness, springiness, gumminess, and chewiness. In a typical experiment, samples are evaluated by sensory analysis and instrumental texture profile analysis and then correlations are determined. The correlation between sensory texture and instrumental textural profile analysis properties of cheeses varies among investigations (Bryant et al., 1995; Drake et al., 1996, 1999b). Although there are various factors that may explain the variations, the main limitation of this approach is in the mechanics of the test. It is possible that the temperature during mechanical testing is different from the initial temperature during sensory testing. Because sample size and shape are not controlled, nor is the rate or level of compression, the values cannot be compared between investigations. For example, in the above-cited investigations the samples were cylinders (2 cm diameter and 2 cm height), 4-cm cubes, and 1.5-cm cubes compressed at 10 mm/s, unspecified, and 0.4 mm/s, respectively. Moreover, because compression is stopped after a set level, it can be difficult to determine if the sample fractured or just deformed during the test. This type of test may be useful when strong correlations have been established with a particular cheese under standardized testing conditions but, due to its empirical nature, it does not provide fundamental mechanical information that can be used to understand cheese structure (Walstra and Peleg, 1991).

It should be noted that uniaxial compression could be used to obtain fundamental fracture properties of cheese providing that the test is conducted under appropriate conditions. The effects of friction between testing surfaces and the cheese (Charalambides et al., 2001), compression rate (Ak and Gunasekaran, 1992), and sample composition (Weinrichter et al., 2000) all need to be considered.

Relationships Among Sensory Texture and Fundamental Rheological and Fracture Properties

As stated previously, the easiest property to measure by sensory and mechanical testing is hardness. However, the mechanical test should be conducted such that it takes into account the viscoelastic (deformation rate) and fracture (deformation level) properties of the cheese. Xiong et al. (2002) evaluated 28 different cheeses that ranged in sensory hardness from 4.1 to 9.2 on a 15-point scale (Sensory Spectrum methodology). The extent of deformation and the deformation rate were varied to determine the optimal levels for correlating with sensory hardness. The optimum level

of deformation was 70 to 80%, which is consistent with the concept that fracture properties are being evaluated during chewing. At higher levels of deformation, the majority (if not all) of the cheeses fracture during testing; however, lower levels of deformation may or may not cause fracture depending on the cheese type. Correlation coefficients between sensory hardness and mechanical force measurements are <0.2 for deformations between 10 and 40% compared with generally >0.6 for 70 to 90% deformation. The fact that there is no difference in correlation between sensory and mechanical properties once deformation exceeds 70% suggests that fracture has occurred and that additional deformation does not increase force values. The optimal deformation rate in mechanical testing for correlation with sensory texture is 1.0 mm/s (Xiong et al., 2002). For 70 to 90% compression, correlations between sensory and mechanical properties fall sharply below a deformation rate of 1.0 mm/s. A related investigation on 10 cheeses measured first-bite velocities of 7 subjects and then compared sensory hardness with mechanical properties determined at a fixed deformation rate (10 mm/s) or a deformation rate to match an individual's chewing velocity for each cheese (16 to 39 mm/s; Meullenet et al., 2002). The mechanical test compressed cheese between acrylic models of each panelist's teeth. For 5 of the 7 panelists, the mechanical properties were able to predict sensory hardness. The use of individual deformation rates only improved the prediction of sensory hardness for 2 of the panelists. These investigations clearly show that when attempting to correlate mechanical with sensory properties, the deformation rate and extent of deformation should be considered. They also show that individual panelists are not evaluating at the same deformation rate. Despite these differences in the panelists, the sensory panel means for firmness were consistent and reproducible. However, when attempting to establish relationships between sensory perception and instrumental measurements, it would seem most prudent to test over a range of deformation rates and always deform to the point of fracture.

We have investigated the relationships between sensory texture and fundamental mechanical properties of Mozzarella and Monterey Jack cheeses as they aged over a 38-d period (Brown et al., 2003). Sensory terms were those outlined in Table 2. Fracture stress, strain, and fracture modulus (G_f ; fracture stress/fracture strain) were determined at 3 strain rates (0.0047, 0.047, and 0.47 s⁻¹) and rheological properties were determined by small-strain oscillatory and creep testing. The maximum strain rate was less than the range of strain rate (1.2 to 2.2 s⁻¹) calculated from Meullenet et al. (2002). The sensory term that correlated with the most

Table 3. Correlations among sensory texture and mechanical properties¹

Sensory term	Mechanical property ²	Correlation
Hand evaluation terms		
Hand firmness	G'	0.623*
	δ	-0.832***
	J_{mx}	-0.921***
	λ_{ret}	-0.638**
	crp	0.802***
Hand springiness	G_f	0.660**
	λ_{ret}	0.534*
	crp	-0.567*
	G_f	-0.832**
Hand rate of recovery	G_f	-0.575*
Mouth evaluation terms—first bite		
Firmness	G'	0.504*
	δ	-0.671**
	J_{mx}	-0.823***
	crp	0.581*
	J_o	-0.609*
Fracturability		
Mouth evaluation terms—chewdown		
Degree of breakdown	G_f	0.478*
Cohesiveness	None	
Adhesiveness	crp	0.503*
	G_f	0.646**
Smoothness of mass	None	
Mouth evaluation—residual		
Smoothness of mouthcoating	J_o	0.479*

¹Data from Brown et al. (2003).

²Mechanical properties were determined by controlled strain oscillatory testing (G' = storage modulus, δ = phase angle); controlled stress creep and recovery analysis (J_o = instantaneous compliance, J_{mx} = maximum compliance, crp = percentage creep recovery, and λ_{ret} = retardation time); and torsional fracture (G_f = fracture modulus).

* $P \leq 0.05$; ** $P \leq 0.005$; *** $P \leq 0.0001$.

mechanical properties was hand firmness (Table 3). This is not surprising because hand evaluation is the most similar to mechanical testing because it involves compression between relative flat surfaces with no complicating factors such as teeth shape or saliva. In comparison, first bite firmness correlated with similar mechanical properties but the correlation coefficients are lower for each term (with the exception of G_f , where the correlation is below the $P \leq 0.05$ level). Hand and first bite firmness were the only terms associated with mechanical properties determined by oscillatory testing (G' and δ). This may be more of a coincidental increase in values than a correlation linked to a textural mechanism. Note that the presence of a statistically significant correlation does not necessarily equal a cause and effect relationship. The creep analysis involved a 10-min initial deformation time (creep) followed by a 20-min recovery. Maximum compliance (J_{mx} , strain/stress), determined during creep, showed the most significant correlation with sensory firmness. The initial compliance (J_o) correlated negatively with fracturability and positively with smoothness of mouthcoating. It is unclear why the instantaneous rigidity of a cheese

would correlate with these texture terms so these correlations should be viewed with skepticism until some logical structural explanation is developed.

The mechanical property that correlated with the most sensory terms was G_f . This clearly illustrates the importance of deforming to the point of fracture when trying to relate mechanical properties to sensory texture. The chewdown terms were the most problematic to predict based on mechanical properties. The highest correlations were found for adhesiveness and this is logical because rheological properties are known to be involved in pressure-sensitive adhesion (Saunders et al., 1992). In contrast, there were no significant correlations for cohesiveness or smoothness of mass. Both these terms would involve mixing with saliva and may therefore be more related to saliva–cheese interactions and therefore not evaluated in mechanical testing without saliva present. The low or absent correlation between chewdown terms is even more problematic when you consider that the 5 sensory terms that differentiated the ages of the cheeses within variety were the 4 chewdown terms and first bite firmness and that chewdown terms also differentiated fat reduction in cheeses.

There have been other investigations relating fundamental mechanical properties with sensory texture of cheese but with differences in the range of tests and textural properties evaluated. An evaluation of 17 different Cheddar cheeses showed correlations between hand and first bite firmness and a range of mechanical properties (stress and strain at yield, stress and strain at fracture, Young's modulus, and work to fracture; Hort et al., 1997). The one chewdown term evaluated, creaminess, was not correlated with mechanical properties. When several different types of cheeses are evaluated (e.g., mild Cheddar, extra sharp Cheddar, Brie, Feta, Munster, and Parmesan), J_o is correlated with a range of textural properties including first bite and chewdown terms (Drake et al., 1999b). The only terms not correlated with J_o were mouth slipperiness of the mass and adhesiveness to teeth. This correlation may be more related to the dynamic range of textures than to mechanistic links between J_o and texture terms. Indeed, when normal and low-fat versions of Monterey Jack, mild Cheddar, sharp Cheddar, and American cheeses are compared, fracture stress is correlated with first bite (firmness and springiness) and chewdown terms (smoothness, chewiness, and meltability; Gwartney et al., 2002). Generally, low-fat cheeses have increased springiness, firmness (hardness), waxiness, and chewiness (Gwartney et al., 2002; Yates and Drake, 2007). In addition, the textural properties of cohesiveness, stickiness, smoothness, and meltability are decreased. This is most logically associated with an increase in the protein network concentration caused by

a reduction in fat (Bryant et al., 1995). Increasing the concentration of agar in agar gels causes a similar increase in firmness (hardness) and chewiness (Barrangou et al., 2006). Likewise, increased firmness would decrease adhesion based on the Dalquist criterion for pressure sensitive adhesion (Saunders et al., 1992).

GENERAL THOUGHTS

One of the overriding difficulties in establishing links between sensory texture properties and mechanical properties is coincidental correlations without a mechanistic link. One way to minimize this problem is to compare within one type of cheese and have variables of composition or aging. However, in any case, there must always be some logical link between the mechanical and textural properties. With that in mind, the involvement of saliva with the chewdown terms may indicate that simply determining viscoelastic, adhesion, or fracture properties in the absence of saliva is omitting one key element of the textural sensation. Because the chewdown terms are significantly affected by lowering the fat content (Gwartney et al., 2002; Yates and Drake, 2007) and aging (Brown et al., 2003), the ability to instrumentally measure and understand these properties is of great importance to understanding cheese texture.

Chewdown terms that may be key to cheese texture are those that involve adhesion to the teeth, smoothness, and cohesion among cheese particles. This is illustrated by comparison with the texture of agar gels. Agar gels are ideal model systems to study instrumental and sensory texture relationships because they are viscoelastic solids that are not complex, are well understood, and easy to manipulate. When chewed, the gel fractures into individual pieces that are not cohesive and do not adhere to mouth surfaces. Five terms are sufficient to describe the texture of agar gels and they include only 2 chewdown terms (particle breakdown and chewiness; Barrangou et al., 2006). Each texture term is correlated with a mechanical property with an *r*-value of 0.93 or higher. Therefore, when the food shows little to no adhesion to teeth or cohesion of chewed mass, as is the case with agar gels, a combination of mechanical properties is sufficient to explain sensory texture. As might be expected, cheese is a lot more complex and chewdown terms play a potentially critical role. Another challenge is duplicating the temperature environment and strain rates occurring during mastication. Cheese is usually eaten at a temperature between refrigerated and room temperature and then undergoes further warming during mastication. In contrast, rheological and fracture tests are most often done under isothermal conditions.

CONCLUSIONS AND FUTURE WORK

Cheese texture is a critical quality attribute. Sensory texture is determined by descriptive analysis and mechanical texture is determined by rheological and fracture testing. An understanding of mastication (oral processing) is critical to setting parameters in mechanical tests when the desire is to correlate sensory and mechanical tests. Moreover, any correlations between sensory and mechanical tests should be linked with a logical mechanism. There are clear correlations between sensory and mechanical measures of firmness or hardness. In contrast, chewdown sensory terms that measure adhesiveness, cohesiveness, and smoothness are poorly predicted by standard mechanical tests. Future research is needed to develop mechanical measures of these sensory properties. This may involve testing under conditions that account for the deformation rates and temperature changes that occur during mastication.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of Dairy Management, Inc. and the California Dairy Research Foundation. Paper FSR 07-01 of the Department of Food Science, North Carolina State University. The use of trade names does not imply endorsement nor lack of endorsement of those not mentioned.

REFERENCES

- Agrawal, K. R., P. W. Lucas, J. F. Prinz, and I. C. Bruce. 1997. Mechanical properties of foods responsible for resisting food breakdown in the human mouth. *Arch. Oral Biol.* 42:1–9.
- Ak, M. M., and S. Gunasekaran. 1992. Stress-strain curve analysis of Cheddar cheese under uniaxial compression. *J. Food Sci.* 57:1078–1081.
- Banks, J. M. 2004. The technology of lowfat cheese manufacture. *Int. J. Dairy Technol.* 57:199–207.
- Barnes, H. A., J. F. Hutton, and K. Walters. 1989. *An Introduction to Rheology*. Elsevier, New York, NY.
- Barrangou L. M., M. A. Drake, C. R. Daubert, and E. A. Foegeding. 2006. Textural properties of agarose gels. II. Relationships between fracture properties, small-strain rheology, and sensory texture. *Food Hydrocoll.* 20:196–203.
- Bodyfelt, F. W., M. A. Drake, and S. A. Rankin. 2007. Developments in dairy foods sensory science and education—From student contests to impact on product quality. *Int. Dairy J.* (accepted)
- Bodyfelt, F. W., J. Tobias, and G. M. Trout. 1988. *The Sensory Evaluation of Dairy Products*. Van Nostrand Reinhold, New York, NY.
- Bourne, M. C. 1978. Texture profile analysis. *Food Technol.* 32(7):62–66, 72.
- Brown, J. A. 2002. Cheese Texture. MS Thesis. North Carolina State Univ., Raleigh.
- Brown, J. A., E. A. Foegeding, C. R. Daubert, and M. A. Drake. 2003. Changes in rheological and sensorial properties of young cheeses as related to maturation. *J. Dairy Sci.* 86:3054–3067.
- Bryant, A., Z. Ustunol, and J. Steffe. 1995. Texture of Cheddar cheese as influenced by fat reduction. *J. Food Sci.* 60:1216–1219, 1236.
- Carunchia Whetstone, M. E., M. A. Drake, B. K. Nelson, and D. Barbano. 2006. Flavor profiles of full fat and reduced fat cheese

- and cheese fat made from aged Cheddar with the fat removed using a novel process. *J. Dairy Sci.* 89:505–517.
- Charalambides, M. N., S. M. Goh, S. L. Lim, and J. G. Williams. 2001. The analysis of the frictional effect on stress-strain data from uniaxial compression of cheese. *J. Mater. Sci.* 36:2313–2321.
- Delahunty, C. M., and M. A. Drake. 2004. Sensory character of cheese and its evaluation. Pages 455–487 in *Cheese: Chemistry, Physics and Microbiology*. Vol. 1: General Aspects. 3rd ed. P. F. Fox, P. L. H. McSweeney, T. M. Cogan, and T. P. Guinee, ed. Elsevier, London, UK.
- Drake, M. A., T. D. Boylston, and B. G. Swanson. 1996. Fat mimetics in low fat cheeses. *J. Food Sci.* 61:1267–1270.
- Drake, M. A., X. Q. Chen, P. D. Gerard, and S. U. Gurkin. 1998. Composition and quality attributes of reduced-fat cheese as affected by lecithin type. *J. Food Sci.* 63:1018–1023.
- Drake, M. A., and G. V. Civille. 2003. Flavor lexicons. *Compr. Rev. Food Sci.* 2(1):33–40.
- Drake, M. A., P. D. Gerard, and G. V. Civille. 1999a. Ability of hand versus mouth evaluation to differentiate texture of cheese. *J. Sensory Stud.* 14:425–441.
- Drake, M. A., P. D. Gerard, V. D. Truong, and C. R. Daubert. 1999b. Relationship between instrumental and sensory measurements of cheese texture. *J. Texture Stud.* 30:451–476.
- Drake, M. A., W. Herrett, T. D. Boylston, and B. G. Swanson. 1995. Sensory evaluation of reduced fat cheeses. *J. Food Sci.* 60:898–901.
- Drake, M. A., and B. G. Swanson. 1995. Reduced and low fat cheese technology: A review. *Trends Food Sci. Technol.* 6:366–369.
- Fox, P. F., T. P. Guinee, T. M. Cogan, and P. L. H. McSweeney. 2000. Cheese Rheology and texture. Pages 305–333 in *Fundamentals of Cheese Science*. Aspen Publishers, Inc., Gaithersburg, MD.
- Guinard, J. X., and R. Mazzucchelli. 1996. The sensory perception of texture and mouthfeel. *Trends Food Sci. Technol.* 7:213–219.
- Gwartney, E. A., E. A. Foegeding, and D. K. Larick. 2002. The texture of commercial full fat and reduced fat cheeses. *J. Food Sci.* 87:812–816.
- Hort, J., G. Grys, and J. Woodman. 1997. The relationships between the chemical, rheological and textural properties of cheddar cheese. *Lait* 77:587–600.
- Jack, F. R., and A. Paterson. 1992. Texture of hard cheeses. *Trends Food Sci. Technol.* 3:160–164.
- Lawless, H. T., and H. Heymann. 1999. *Sensory Evaluation of Food*. Aspen Publishers, Gaithersburg, MD.
- Lucey, J. A., M. E. Johnson, and D. S. Horne. 2003. Perspectives on the basis of the rheology and texture properties of cheese. *J. Dairy Sci.* 86:2725–2743.
- Luyten, H., T. van Vliet, and P. Walstra. 1991. Characterization of the consistency of Gouda cheese: Fracture properties. *Neth. Milk Dairy J.* 45:55–80.
- Meilgaard, M. M., G. V. Civille, and B. T. Carr. 1999. Selection and training of panel members. Pages 174–176 in *Sensory Evaluation Techniques*. 3rd ed. CRC Press, Boca Raton, FL.
- Mestres, M., R. Kieffer, and A. Buettner. 2006. Release and perception of ethyl butanoate during and after consumption of whey protein gels: Relation between textural and physiological parameters. *J. Agric. Food Chem.* 53:403–409.
- Mestres, M., N. Moran, A. Jordan, and A. Buettner. 2005. Aroma release and retronasal perception during and after consumption of flavored whey protein gels with different textures. 1. In vivo release analysis. *J. Agric. Food Chem.* 53:403–409.
- Meullenet, J.-F., M. L. Finney, and M. Gaud. 2002. Measurement of biting velocities, and predetermined and individual crosshead speed instrumental imitative tests for predicting cheese hardness. *J. Texture Stud.* 33:45–58.
- Mioche, L., P. Bourdiol, J.-F. Martin, and Y. Noël. 1999. Variations in human masseter and temporalis muscle activity related to food texture during free and side-imposed mastication. *Arch. Oral Biol.* 44:1005–1012.
- Murray, J. M., C. M. Delahunty, and I. Baxter. 2001. Descriptive sensory analysis: A review. *Food Res. Int.* 34:461–471.
- Sandra, S., M. A. Stanford, M. R. McDaniel, and L. Meunier Goddik. 2004. Method development for assessing the complete process of crumbling cheese using hand evaluation. *J. Food Sci.* 69:SNQ127–130.
- Saunders, S. R., D. D. Hamann, and D. R. Lineback. 1992. A systems approach to food material adhesion. *Lebensm. Wiss. Technol.* 25:309–315.
- Steffe, J. F. 1996. *Rheological Methods in Food Process Engineering*. 2nd ed. Freeman Press, East Lansing, MI.
- Tunick, M. 2000. Rheology of dairy foods that gel, stretch, and fracture. *J. Dairy Sci.* 83:1892–1898.
- van der Bilt, A. 2002. Human oral function: A review. *Braz. J. Oral Sci.* 1:7–18.
- Walstra, P. 2003. *Physical Chemistry of Foods*. Marcel Dekker, Inc., New York, NY.
- Walstra, P., and M. Peleg. 1991. General Considerations. Pages 3–4 in *Rheological and Fracture Properties of Cheese*. Bull. no. 268. International Dairy Federation, Brussels, Belgium.
- Weel, K. G. C., A. E. M. Boelrijk, A. C. Alting, P. J. J. M. van Mil, J. J. Burger, H. Gruppen, G. J. Voragen, and G. Smit. 2002. Flavor release and perception of flavored whey protein gels: Perception is determined by texture rather than release. *J. Agric. Food Chem.* 50:5149–5155.
- Weinrichter, B., H. Rohm, and D. Jaros. 2000. Mechanical properties of unpressed semi-hard cheeses by uniaxial compression. *J. Texture Stud.* 31:141–152.
- Wium, H., M. Gross, and K. B. Qvist. 1997. Uniaxial compression of UF-Feta cheese related to sensory texture analysis. *J. Texture Stud.* 28:455–476.
- Xiong, R., J.-F. Meullenet, J. A. Hankins, and W. K. Chung. 2002. Relationship between sensory and instrumental hardness of commercial cheeses. *J. Food Sci.* 67:877–883.
- Yates, M. D., and M. A. Drake. 2007. Texture properties of Gouda cheese. *J. Sensory Stud.* (accepted)