REVIEW

Instrumental Measurement of Physical Properties of Cooked Asian Wheat Flour Noodles

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ABSTRACT

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Instrumental texture tests on cooked noodles are valuable research tools and are well suited for monitoring noodle texture after changes in formulations, raw materials, and processing. Uniaxial tests are most common, and a variety of test types, strains, strain rates, and probe dimensions are used. Consequently, standardization is a challenge. Compressive tests (cutting and blunt probe compression) are more frequently reported than tensile tests. Combining results of tensile and compressive tests shows potential to uncover aspects of noodle texture not detectable using one method alone. Tensile and blunt-probe compression tests can be both adapted for stress relaxation experiments and may be used to derive fundamental rheological information. Dynamic oscillating rheometry shows promise as a tool for investigating composition/structure/function relationships in cooked noodles. However, unlike large deformation "texture" tests, dynamic oscillating rheometry struggles to match sensory perceptions of noodle texture. This may result from the scale of the deformations applied, which are commonly much smaller than the deformations required for rupture. Limitations of small deformations become more evident when considering fracture properties of noodles and how these are affected by changes in flour composition and inhomogenieties in noodle structure at the macro-, meso-, and micro-scales. Combining information from small and large deformations has been used to investigate changes in noodle texture occurring after changes in amylose and protein composition. This combined approach may prove to be useful in resolving differences and similarities in noodle texture wrought by changes in the constituent polymers of wheat flour.

Asian noodles are made in a wide variety of types that are categorized based on formulation, particularly the presence or absence of alkali, cross-sectional dimensions, and postcutting processes such as steaming, frying, drying, or boiling (Hou and Kruk 1998; Hatcher 2000; Hou 2001; Crosbie and Ross 2004). For consumers of these products, the quality of the noodles themselves is primarily defined by texture and appearance. Other factors are also important, for example, for instant fried noodles, rehydration rates of during final preparation, or the presence or absence of rancid taste after extended storage. This article is devoted entirely to the instrumental measurement of the mechanical, rheological, and geometric properties of noodles as they relate to noodle texture. "Texture" itself is not measured instrumentally but is perceived through the human senses of kinesthesis and touch during food handling and consumption and is therefore a sensory attribute (Szczesniak 2002). Instrumental methods, on the other hand, measure the underlying mechanical and physical properties of foods that lead to the perception of texture. To do this, instrumental tests usually apply relatively simple deformation geometries to food samples in clean laboratory environments. This contrasts quite markedly with the complex deformation geometries (Lucas et al 2002) and somewhat messy environment found in the mouth. One source of complexity in the mouth that is rarely accounted for in instrumental testing is saliva, which is a lubricant, alters the moisture content and consistency of food during chewing, and contains α-amylase that can reduce amylose and amylopectin molecular size very effectively. There are reports of the effects of saliva applied during instrumental texture analyses but these are relatively infrequent (e.g., Engelen et al 2003; Dunnewind et al 2004,). Additionally, use of saliva provides some interesting procedural challenges for instrumental testing related to how much saliva to use, how to apply it appropriately, and how to deal with changes in saliva composition dependent upon when and how production was stimulated, and from whom it was sampled. Nonetheless, despite profound differences in the "test" environments, repeated studies have shown the ability of instrumental texture tests, of a variety of types, to correlate closely with related sensory texture attributes. Specific incidences of these relationships for noodles are cited in the relevant sections of this article.

Instrumental testing performs a necessary function, either as a stand-alone technique, or as a complement or a preliminary to sensory testing. Therefore, as food texture might be defined as ''the sensory and functional manifestation of the structural, mechanical and surface properties of foods detected through the senses of vision, hearing, touch and kinesthetics'' (Szczesniak 2002), then the essential and unique function of instrumental testing is its ability to quantify those structural, mechanical, and surface properties, which, in turn, interact with oral physiology to be perceived by humans as texture. The power of instrumental testing is that it provides researchers and product developers a convenient, cost-effective way to track changes in mechanical properties as a result of changes in raw materials, formulation, or process before proceeding to the more elaborate, resource-intensive and necessary scrutiny by sensory analysis.

The application of mechanical or rheological methods to noodle-like products has a venerable history. Binnington et al (1939) applied a compressive test to cooked macaroni products where the load was increased at a measured rate (12 g·sec^{-1}) and the loads at 0.115 in. of deformation and the breakpoint were recorded. Glabe et al (1957) used a similar test to that applied by Binnington et al (1939) using, for the time, more modern instrumentation and were able to show changes in cooked texture in spaghetti supplemented with carrageenan. For Asian noodles, the first report of texture testing in the English language literature appears to be Shimizu et al (1958), who reported a custom-built extensimeter that was used to determine spontaneous elasticity, viscous flow, retarded elasticity, elastic modulus, breaking energy, and stress relaxation of cooked salted noodles. Shimizu et al (1958) were able to show differences in the rheological behavior of the salted noodles at various protein contents and temperatures, and could differentiate noodles made from two different sources of wheat. Currently, the most widely used mechanical methods are uniaxial, and these are done most commonly in compression, using either cutting probes

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that are relatively thin or sharp, or blunt probes that compress samples without cutting them. Tensile tests are also reported in the literature. These are not as widely used as compressive tests by Western research groups but are more common in research reports originating from Asian researchers.

With respect to descriptors of noodle texture, there appear to be concensus terms between mechanical and sensory testing when considering hardness and firmness (or softness). These terms are used interchangeably to describe a physical property measured mechanically as peak force or total work (area under force/time curve) observed during a single cutting, compression, or stretching operation. The analogous sensory property can be described as the force required to bite through a noodle sample or, more generally as "force required to compress a substance between molar teeth (in the case of solids)" (Szczesniak 2002). However, for elastic components of cooked noodle texture, differences between sensory texture descriptors and descriptors of physical properties are evident. I subscribe to a hypothesis that "elasticity" of noodles as described by mouthfeel does not describe their fundamental elasticity (Ross and Crosbie 1997) but describes the integration by the senses of a number of mechanical signals such as apparent modulus, or stiffness (Walstra 2001), cohesiveness, fracture properties (brittle or ductile), and relative hardness. To distinguish the two "types" of elasticity, it worthwhile to note that modulus of elasticity or Young's Modulus is characteristically measured at very low strains where the stress/strain function remains linear (≈6% strain for cooked noodles) (Miki and Yamano 1991) and stress is lower than the yield value for the material. Mouthfeel elasticity is generally measured at large strains approaching or exceeding the yield (rupture) point of the material during chewing. Nontheless, Lucas et al (2002) suggested that Young's Modulus of a food was a critical parameter during application of the teeth to a piece of food.

This review summarizes instrumental measurements used to measure mechanical properties of cooked Asian wheat-flour noodles made from hexaploid wheats. Durum pastas are, in general, omitted from the discussions although there is considerable overlap in the methods used to determine mechanical properties of both the Asian and European styles of "noodles". Durum pasta test methods were reviewed by Cole (1991).

Sample Preparation in Brief

Consistent sample preparation is critical to texture measurements of Asian noodles and many variables need to be controlled before testing. These variables include the cross-sectional dimensions of the raw or cooked noodles, the time and extent of cooking, how long after rolling and cutting the noodles are left before they are cooked, and how long after cooking the noodles are left before they are tested. Good practice in noodle production and preparation is elaborated at length throughout the literature but readers are encouraged to review the works of Kruger et al (1994) and Oh et al (1983) regarding changes in texture related to resting time after sheeting and cutting, and time after cooking, respectively. Approved Method 66-50 (AACC International 2000) suggests waiting 10 min after cooking before testing the first subsample. Effects of dough resting and standing time after cooking on texture were also investigated by Miki et al (1995). With respect to cross-sectional dimensions, both thickness and width are important. "Thickness" in this regard is defined as the vertical dimension and "width" is defined as the horizontal dimension of the test piece as it is presented to the testing instrument, regardless of whether or not these were the vertical and horizontal cross-sectional dimensions of the noodle test piece during production. Thickness is positively related to cutting force (Oh et al 1983) and width defines the contact area with the probe and hence the absolute force detected by the load cell. Oh et al (1985) used a sample holder with a ruled surface so that cooked noodle width could be measured and the precise contact area with the probe calculated. Final raw noodle thickness should be the thickness appropriate to the noodle type being studied ± 0.05 mm, and this specification, which is reported in the literature (Graybosch et al 2004; Ohm et al 2006), is achievable in practice and can be used as a guide to the minimum precision required for raw noodle thickness when noodles are destined for instrumental testing of mechnical properties. The adjustment of the final roll to achive a specified noodle thickness, rather than using a set final roll gap, is important as final raw noodle sheet thickness through a set roll gap will vary as a result of differential viscoelastic recoil (Engmann et al 2005) resulting from differences in dough strength and protein content. Cooked noodle thickness, even from doughs with the same cross-sectional dimensions, may also vary as a function of the starch swelling properties. If one is specifically interested in fundamental rheological properties then some preliminary work may be necessary to adjust dough thickness so that final cooked noodle thickness meets a predefined tolerance if the experiment is observing flours with variant starch properties. There is certainly insufficient research in this simple but important area of instrumental noodle texture testing. However, Dick and Youngs (1988) did indicate that they considered comparisons of firmness values between spaghetti samples of variable diameter to be invalid. Some researchers contend that the differences in final cooked dimensions are part of the overall mouthfeel and should not be adjusted in instrumental testing. There is validity in this perspective. However, researchers need to be careful to recognize and define their goals, and then appreciate the limitations of the methodology chosen.

International attempts to standardize noodle preparation and testing have so far met with little success, possibly due, in part, to the many factors that affect the measured physical properties of cooked noodles. Apart from the obvious ones, "hidden" variables such as the roller diameter and roll speed can come into play as these affect the residence time of the dough in the region of the roller that is applying work to the dough sheet. Sheeting is an area of technology with highly complex mathematics. In reducing the complexity of the partial differential equations that define sheeting operations, one assumption is that dough thickness is small in relation to roll diameter (Levine and Drew 1990). This assumption is not valid for some of the small benchtop units used in laboratories that have roll diameters as small as 25 mm and where initial dough thickness can be as much as 15–20% of roll diameter. Accordingly, precise scale-up from small to large rollers is very difficult, even using empirical or trial and error methods. Hence, differences in roll diameters, and thus work applied to the doughs in sheeting, may prove a key obstacle to achieving the same absolute results for many different aspects of noodle quality from noodle rolling machines with different roll diameters. However, to achieve repeatability, even within a single laboratory, one must pay close attention to these and other variables, and eliminate them or determine tolerances within which acceptable repeatability can be achieved.

Regarding issues of repeatability, it is highly recommended that researchers use 5–10 repeated measures of the chosen test for each sample in their experimental design. This done to arrive at a valid mean value for the mechanical property being measured and is required as cooked noodles are not as homogeneous as they look to the naked eye, having microcracks and discontinuities resulting from preexisting inhomgeneities in the dough or from the vigorous shaking noodles receive in the boiling process. The need for repeated measures was recognized from the very first application of texture testing to boiled dough strings where Binnington et al (1939) recommended five repeated measures. This concept has been extended at least to the level of seven repeated measures where the high and low values were discarded to arrive at a representative mean value for the sample (Seib et al 2000). One may question discarding the high and low values. However, in my experience of instrumental testing of cooked noodle texture, there are often unexplained outlier values that confound the interpretation of results.

Uniaxial Tests

Hardness, firmness, or softness of cooked noodles is simple to measure instrumentally and provides a high degree of alignment between instrumental and sensory assessments. Hardness, or firmness, is most commonly defined as a the peak force during a deformation operation in compression or tension and is considered to be an aspect of the bulk rheology of noodles. Approved Method 66-50 (AACC International 2000) describes "firmness" as either maximum cutting stress (force/unit area) or the work to cut (area under the force/time curve during cutting). One must be cautious only to measure the area under cutting or compression part of the force-deformation curve if defining the parameter as work to cut or compress, as using the area under the entire compression/decompression curve is not a valid way of measuring work to cut noodles (Cole 1991). With respect to terminology, one useful approach is taken by the Canadian Grain Commission, Grain Research Laboratory (GRL; see various references herein by Hatcher and Kruger, as well as Collado and Corke 1996, and Huang and Morrison 1988). GRL simply defines instrumental parameters such as maximum cutting stress (MCS), and resistance to compression without recourse to the use of an analogous "sensory" term. This approach avoids using terms to describe mechanical properties that can be confused with sensory terms that use the same words but which may not be precisely defined or which may not have the same specific meaning. However, use of terms such as hardness, firmness, elasticity, or springiness to describe mechanical properties is exceedingly convenient, and for sake of narrative clarity these descriptors are retained in this article.

Many studies use the cutting or compression methods devised by Oh et al (1983) or modifications of those methods (Table I). Approved Method 66-50 (AACC International 2000) is also based in part on the same report. Modifications have been made to the Oh et al (1983) method with regard to number of noodle strands tested (Huang and Morrison 1988), cross-head speed (Yun et al 1997), and total strain applied (Yun et al 1997), among others. Frequently, these minor alterations have been made with no explanation as to what advantage, if any, was gained by the modification. This has generated a variety of "variations on a theme" (Table I), which, although the same in principle within a test type, are not easily compared across studies because of the different machine parameters. However, each variant is perfectly suitable to comparisons within studies. Peak force or work

TABLE I
Survey of Machine Parameters Used in Uniaxial Mechanical Testing of Asian Noodles

Test Type and Study	Probe	Noodle Strands and Orientation[a]	Crosshead Speed (mm/sec)	Deformation
Compressive (cutting)				
Oh et al 1983	1 mm flat blade	3 strands 90°	0.83	Cut to failure
Collado and Corke 1996	"Shear blade"	1 strand 90°	0.17	75% strain
Graybosch et al 2004	1 mm flat blade	3 strands 90°	0.8	Cut to failure
Graybosch et al 2004	1 mm flat blade	3 strands 90°	1.0	1.0 mm
Hatcher and Preston 2004, Hatcher et al 2002, Kruger et al 1994, 1998	1 mm blade	3 strands 90°	4.0	Cut to failure
Huang and Morrison 1988	1 mm flat blade	1 strand 90°	0.83	Cut to failure
Kojima et al 2004	V-shaped blade	1 strand 90°	0.1	90% strain
Lang et al 1998	1 mm flat blade	4 strands 90°	1.5	≈70% strain (probe stopped 0.3 mm above support)
Zhao et al 2005	V-shaped, 55 mm × 1.0 mm	7 strands 90°	1.0	50% strain
Compressive (compression)				
Oh et al 1983	3.5 mm blade	3 strands 90°	0.42	Compress to defined stress of 1.3 $\text{kg} \cdot \text{cm}^{-2}$
Oh et al 1985	3.5 mm blade	1 strand 90°	0.17	< 10% strain
Hatcher and Preston 2004, Hatcher et al 2002, Kruger et al 1994, 1998	10 mm flat probe	3 strands 90°	4.0	Compress to defined stress of 1.3 kg*cm^{-2}
Hatcher et al 2005, Hatcher 2004	10 mm flat probe	3 strands	0.1	Compress to 250 g, hold, measure time to relax to 85% of applied stress
Huang and Morrison 1988	5 mm flat blade	1 strand 90°	0.33	98% strain
Sasaki et al 2004	55 mm dia. disk	20 mm dia. disk	1.0	99% strain
Sasaki et al 2004	3.5 mm wide blade	2 × 4 mm wide strands 90°	1.0	99% strain
Seib et al 2000	"L" hook	1 strand	0.5	50% strain
Zhao et al 2005	Rectangular, 50 mm × 4.0 mm	1 strand 0°	1.0	50% strain
Compressive (TPA)				
Tam et al 2004 (based on Kim and Seib 1993)	Cylinder 38 mm	5 strands	1.0	75% strain
Baik and Czuchajowska 1997, Baik et al 1994ab	5 mm flat blade	5 strands 90°	0.8	70% strain
Baik et al 2003, Baik and Lee 2003	3.175 mm blade	5 strands 90°	0.8	70% strain
Epstein et al 2002	5 mm flat blade	4 strands 90°	1.0	70% strain
Graybosch et al 2004	9 mm flat blade	3 strands 90°	0.45	70% strain
Kim and Seib 1993	Cylinder 38 mm	1 strand	1.0	75%
Kim et al 1998	Cylinder 15 mm	2 strands	1.7	not stated
Martin et al 2004	6 mm flat	5 strands 90°	1.0	70% strain
Ohm et al 2005, this article	5 mm flat blade	3 strands 90°	1.0	70% strain
Park and Baik 2004a,b; Park et al 2003	3.175 mm metal blade	5 strands 90°	1.0	70% strain
Park and Baik 2002	1.5 mm metal blade	5 strands 90°	1.0	70% strain

[a] 90° = perpendicular to axis of probe, 0° = parallel to axis of probe, only for compression mode and where specifically stated in the reference.

measured by the Oh et al (1983) methods and their variants have significant positive correlations with sensory hardness (Oh et al 1983) and negative correlations with sensory softness (Yun et al 1997; Ross et al 1998). Cutting or compression tests can also be used as stand-alone methods to monitor changes in noodle texture related to technological parameters of flour, for example, starch damage and particle size (Hatcher et al 2002). Other compressive tests that can be used for hardness measurements use shear blades (Collado and Corke 1996; Jang et al 1999) or forward extrusion (e.g., Lee et al 1987). Multiple shear blade geometries might be especially suitable for assessment of products such as knife-cut Chinese noodles that vary widely in thickness within each strand as this type of geometry tests the whole noodle mass, rather than isolated individual noodles. Knife-cut Chinese noodles have an overall texture that is almost "meaty" in a structural sense as a result of variations in noodle thickness and hardness in the mass that is eaten (H. Corke, *personal communication*). The Oh et al (1983) method and other methods that use probes with rectangular cross-section contact surfaces generally align the noodles perpendicular to the long axis of the probe. Recent work by Zhao and Seib (2005) has shown better discrimination between samples when test pieces were aligned along the long axis of a cutting probe (55 × 1 mm wide contact surface, Table I), giving the probe a larger "sample" of each individual test piece to sense than would have been sensed in crossways orientation. This method distinguished differences in resistance to compression between 11 of 13 cooked noodle samples rather than 5 of 13 cooked noodle samples when tested crossways. A special holder was needed to accomplish the alignment of the noodle test piece.

TPA of noodles involves a two-cycle compression (Fig. 1) of noodle strands with a flat-based probe. Blunt rectangular probes from 1.5 to 9 mm wide, and the flat ends of cylinders ranging from 25 to 38 mm in diameter have been applied to noodles (Table I). For TPA, strains in the range of 70–75% are applied most commonly in noodle testing and TPA hardness is the peak force on the first compression cycle. These strains levels appear to be appropriate for the product as Baik et (1994) tested strains at 50–90% and found the low value provided insufficient discrimination between samples, and the high value gave a cutting action that was undesirable in TPA compression tests. TPA has the perceived advantage of measuring a number of parameters from a single test. These will be discussed later. TPA hardness, like other methods of measuring mechanical hardness, has also correlated with sensory assessments (e.g., Tang et al 1999).

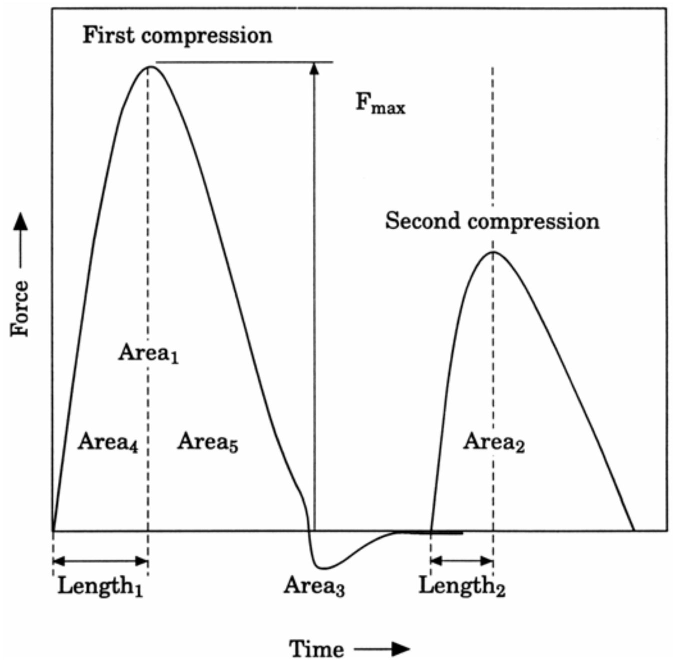

Fig. 1. Texture profile analysis of white salted noodles showing primary texture measurements and showing areas and distances used to derive secondary texture parameters. Reprinted from Epstein et al (2002) with permission from Elsevier.

TABLE I (continued)
Survey of Machine Parameters Used in Uniaxial Mechanical Testing of Asian Noodles

Test Type and Study	Probe	Noodle Strands and Orientation[a]	Crosshead Speed (mm/sec)	Deformation
Compressive/extrusion				
Lee et al 1987	Close tolerance piston in steel cup with 69 holes (dia. unspecified)	Amount of cooked noodles based on 2.0 g dry wt	26.4	Extrude, measure initial force, maximum force, slope; initial to maximal, work
Shelke et al 1990	Close tolerance piston in cell with extrusion grid	75 g of cooked noodles	0.83	Extrude, measure peak force
Compressive/stickiness				
Guan and Seib 1994	Custom stickiness probe	1 strand	0.1 on compression, 3.0 on withdrawl	100 g force, measure adhesion
Lang et al 1998	Rectangular, dimensions not stated	6 strands 0°	1.5	70% (probe stopped 0.3 mm above support)
Lee et al 2002	45 mm dia. cylindrical	Noodle sections 0.25–0.4 g	0.1	Hold 0.1 sec at deformation for 300, 400, or 500 g maximum force withdraw probe to measure stickiness (adhesion)
Compressive/creep				
Sasaki et al 2004	55 mm dia. disk	20 mm dia. disk	10	Variable force to maintain 10% strain
Tensile				
Seib et al 2000, Guan and Seib 1998	Custom clamp and "L" hook	1 strand	5.0	Stretch to failure
Shimizu et al 1958	Custom clamp	1 strand 5 or 20 cm long, 0.13 cm^2 cross-section	2.0	Constant force (20 g), measure deformation and recovery
Shimizu et al 1958	Custom clamp	1 strand 5 or 20 cm long, 0.13 cm^2 cross-section	2.0	Constant elongation (10 mm), measure stress dissipation
Yu et al 2004	Two grips	1 strand	0.83	Stretch to failure
Zhao et al 2005	Custom clamp and "L" hook	1 strand	1.0	Stretch to failure

[a] 90° = perpendicular to axis of probe, 0° = parallel to axis of probe, only for compression mode and where specifically stated in the reference

Tensile tests can also measure hardness (Table I). Additionally, if cooked noodles are stretched to breaking point, they can also be used to provide an indication of extensibility (stretchability). Ross et al (1998), using a cooked noodle ring as the test piece, showed that peak force at 20-mm extension, final force after holding the 20-mm extension for 30 sec, and the slope of the initial increase in tensile force (apparent modulus) were all significantly and negatively correlated with sensory noodle softness. Seib et al (2000) used a different type of sample presentation based on clamping individual strands with a special noodle clamp and stretching them using an L-shaped hook. In that study, tensile force, among samples of equal flour protein content, was related to starch swelling power in alkaline noodles but not in salt noodles. Yu and Ngadi (2004) used tensile tests to show increases in maximum tensile (break) strength of boiled instant noodles related to increased guar gum concentrations from 0.15 up to 0.37% (w/w, flour basis), increased dough water from 27 to 41%, and additions of acetylated potato starch up to 9%. The changes in tensile strength were accompanied in general by increases in strain at breakage. Given the proportionality of strain and stress below rupture, it is not surprising that maximum tensile strength increased as the stretchability (strain at breakage) increased. Further valuable information about ingredient or process changes may be gained by applying the same tensile tests but in addition to measuring force and distance at breakage, also measuring force at a given deformation (strain or absolute displacement), as the applied strain at the break point can vary from sample to sample.

One cautionary note about tensile testing of cooked noodles is needed. Careful attention must be applied to ensure that the clamping method does not cause the noodles to break at the point of attachment. In this way, the tensile characteristics of the whole noodle, not just the clamped piece are assessed. No matter how it is approached, the method of fixing cooked noodles to the apparatus for tensile testing needs to be done carefully to achieve meaningful results. Tensile methods are available in the English language literature that can be used as starting points. (Shimizu et al 1958; Seib et al 2000; Yu and Ngadi 2004). Other valuable guidance on tensile test parameters can be found in Asian language literature (Imai and Shibata 1979; Miki and Yamano 1991; Kojima et al 1995).

As simple as hardness measurements are, measurement and definition of hardness for cooked noodles may not be as straightforward as first appearance suggests. Current approaches are well suited to prediction of sensory attributes or simple comparisons of samples. However, if researchers wish to delve more deeply into the fundamental building blocks of cooked noodle texture, then they might consider observing the behavior of samples over the entire course of the applied deformation. To begin with, relative resistance to cutting or compression of different samples appears to be dependent on the extent of the applied strain. Recently, Sasaki et al (2004), using a series of compressions at 20–95% strain, showed that at ≤50% strain, noodles made from flours with "normal" amylose contents had higher resistance to compression than noodles made from flours with reduced starch amylose contents. This could be anticipated from the literature, where lower amylose wheat cultivars routinely derive noodles that are described or measured as softer. However, at 95% strain, noodles derived from the "softer", lower amylose lines showed higher resistance to compression than the noodles derived from the higher amylose, normal lines. Sasaki and colleagues concluded that at >80% strain, the low amylose noodles had not broken, or had not begun to break, leading to their higher resistance to compression compared with the noodles made from the higher amylose, normal starch cultivars. This aligns with the personal sensory experience of the author, where noodles made from partially waxy wheats or with added tuber starches were experienced as having a "longer" texture (i.e., they are more chewy, not because they are harder, but because they don't just break apart after strains in the region of ≥80% have been applied by the teeth. The results of Sasaki et al (2004) also are in accordance with observations of Ross and Crosbie (1997). In that study, force/time curves (Fig. 2A), showed that the poor quality cultivar Lawson, assessed in sensory testing as being intermediate in hardness between the other two samples used, had marginally higher resistance to cutting (was marginally harder) than both other samples ≤60% strain but fell below the cutting force of the Australian Prime Hard/Australian Hard (APH/AH) sample after that. First derivative curves calculated from the raw force/time data (Fig. 2B) showed that the Lawson-derived noodles suffered a precipitous collapse in the rate of increase in cutting stress at ≈50% strain. These authors took this observation to indicate that the Lawson-derived noodles had begun to fracture under compression well before other, higher quality samples. The fracturing was probably a result of internal structural collapse of the polymeric architecture of noodles before macroscopic collapse or fracture was observed. The behavior of the Lawson sample under deformation has implications for elasticity as well, and the phenomenon observed could be also be described as "short texture", usually an undesirable mouthfeel trait for wheat flour noodles (Akashi et al 1999). Associated with this discussion of fracture is the suggestion that the geometry of failure for rodlike food pieces in the mouth may be better visualized as a three-point bend loading as a result of the topological prominence of the cusps of the molar teeth (Lucas et al 2002) rather than a homogeneous loading across the surface of the food. Accordingly, much of the force applied may be directed to crack initiation and propagation rather than to overall compression of the food piece. This may make the geometry of initial compression in the mouth more analogous to cutting tests than to blunt probe compression tests and indicate, in part, why cutting tests have proven effective at predicting mouthfeel parameters related to hardness.

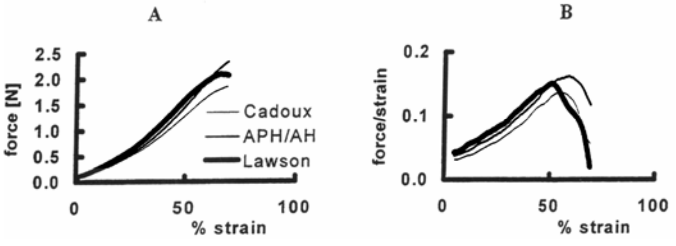

Fig. 2. Force/strain (**A**) and 1st derivative (**B**) curves for salted noodles made from the 60% extraction flours of the wheat cultivars Cadoux and Lawson, and from a blend of APH and AH wheats. Reprinted from Ross and Crosbie (1997) with permission.

Surface Hardness/Firmness

Another aspect of hardness that can be approached using compressive tests is surface hardness or firmness. This is a useful parameter as cooked noodles are cooked differentially in their core or surface zones as a result of the differential availability of water during boiling. These zones and attendant moisture gradient are visible using electron or conventional microscopy (Moss et al 1987; Sekine and Harada 1990) but have also been strikingly visualized with magnetic resonance imaging (Kojima et al 2001, 2004). Surface firmness can only be determined through cutting or compression tests and this constitutes one limitation of the otherwise useful tensile tests. Oh et al (1985) presented a method for testing surface firmness where the initial slope of the time force curve (between first point of contact of a blunt blade and deformation at an applied force of 60 g·cm^{-2}) was measured. Others have used single-point measurements of the absolute displacement of the cutting probe at a predetermined force (Sørensen et al 2000). In this method, if a higher distance or strain to achieve the predetermined force was needed, then the surface was softer. Alternatively, single-point measurements of force at a predetermined probe displacement can be made (Graybosch et al 2004). An unstated assumption in these methods is that all the information being generated is a result of the characteristics of the outer portion of the noodle alone. This is a practical working assumption, although there may be instances where the assumption could be broken, particularly where the core portion of the noodle is very compressible and deforms with the compression of the outer portion, making the surface appear softer than it is.

Elasticity, Springiness, and Related Parameters

Instrumental measurement of elasticity or springiness in noodles normally involves the compression of the noodle strands with a blunt probe rather than cutting them (Table I), although Ross and Crosbie (1997) were able to derive indicators of elasticity from cutting tests. Elastic behavior can also be tested in tension and this will be discussed below. Oh et al (1983) used a 3.5-mm wide flat blade and compressed three noodle strands to a constant force of 1.3 kg·cm^{-2}. From this they measured the resistance to compression (force) and the recovery from compression (% of original dimensions recovered). Both of these parameters had highly significant correlations to the sensory term "chewiness", which was defined in this instance as the length of time required to masticate 10 g of cooked noodle to a swallowable end-point. Using a very similar method and also a 3.5-mm wide compression probe, Yun et al (1997) reported a highly significant correlation between the sensory attribute "elasticity" and compressive force peak area divided by time. Elasticity in this case was defined as the amount of rebound force felt when the noodles were squeezed gently between the molars (from BRI Australia's sensory testing definitions, K. Quail, *personal communication*).

Others have used similar compression tests without recourse to comparisons with sensory testing and this approach is more than adequate for some needs. In one study, a compression test was used to assess the impact of rye flour additions to the formulations of nonalkaline noodles (Kruger et al 1998). The method was able to clearly show the loss of both resistance to compression and recovery from compression as the proportion of rye flour increased. Kovacs et al used a viscoelastograph to measure proportional and absolute recovery of cooked pasta (1995) and noodles (2004) after a defined force was applied.

TPA can also be used to determine springiness, cohesiveness, and resilience. These parameters were tabulated by Epstein et al 2002 (following Bourne 1968 and Peleg 1976) using the lengths, forces, and areas shown in Fig. 1) as Cohesiveness: area2/area1 (ratio); Springiness: length2/length1 (ratio); Resilience: area5/area4 (ratio).

Of these, springiness in particular is the attribute most like the "recovery from compression" parameter described above for non-TPA compressive tests. Data from our own laboratory on salted noodles made from 30 hard white wheat (HWW) flours of diverse protein compositions and contents, showed springiness values of 91–98%. These correspond to literature values for salted noodles made from flours with normal amylose contents (Baik and Lee 2003; Park et al 2003) but were slightly higher than springiness values reported for cooked instant fried noodles (Park and Baik 2004a,b) and cooked long-life salted noodles (Kim et al 1998). These relatively high values for springiness (≥ ≈ 90%) indicate that cooked noodles are largely solid and elastic in nature when deformed without rupture. The range of springiness values may seem constrained, but to highlight the utility of this measure as an indicator of real differences in noodle texture, a simple example is presented. Noodles made from the 30 HWW flour samples were either tested immediately after cooking or after a 15-min holding period in room temperature water. When springiness was compared between two holding times, the values were significantly lower ($P \le 0.001$) for noodles that were held in water for 15 min before testing. Cohesiveness and resilience were also both significantly ($P \le 0.001$) lower for noodles tested after the 15-min holding time.

Tang et al (1999) were able to demonstrate highly significant correlations between TPA-derived springiness values and values for sensory elasticity (defined as stretching the noodles by hand). However, in the Tang et al (1999) study, TPA-derived springiness was also significantly correlated with mouthfeel firmness, indicating the possibility that in TPA applied to noodles, firmness and springiness vary similarly and do not provide further useful information. Our own results have shown consistent significant correlations between certain pairs of TPA attributes in noodle testing, particularly between hardness and chewiness, and cohesiveness and resilience (Table II). Similar correlations between TPA parameters were reported for cooked salted noodles by Epstein et al (2002). This might suggest some degree of redundancy in the

TABLE II
Linear Correlation Coefficients for TPA Parameters on Cooked Asian Salted Noodles[a,b]

	Study 1[c]		Study 2[d]		Study 3[e]			
	t0[f]	t15[g]	t0	t15	t0 Fixed[h]	t15 Fixed	t0 Opt[i]	t15 Opt
Hardness/adhesiveness	ns	–0.52		–0.35		ns		
Hardness/springiness	ns	ns	ns	ns	ns	ns	ns	ns
Hardness/cohesiveness	–0.49	ns	ns	0.39	ns	0.44	0.47	0.36
Hardness/chewiness	0.95	0.93	0.98	0.97	0.96	0.95	0.93	0.95
Hardness/resilience	–0.45	–0.47	ns	ns	ns	ns	0.35	ns
Adhesiveness/springiness	0.71		ns		0.75		0.60	
Adhesiveness/cohesiveness	0.47		ns		ns		ns	
Adhesiveness/chewiness	ns		–0.43		ns		ns	
Adhesiveness/resilience	0.62		ns		ns		0.40	
Springiness/cohesiveness	ns	ns	ns	ns	ns	ns	ns	ns
Springiness/chewiness	ns	ns	ns	ns	ns	ns	ns	ns
Springiness/resilience	ns	ns	ns	ns	ns	ns	ns	0.48
Cohesiveness/chewiness	ns	ns	0.47	0.56	0.49	0.66	0.70	0.62
Cohesiveness/resilience	0.80	0.69	0.87	0.80	0.76	0.80	0.88	0.85
Chewiness/resilience	ns	ns	ns	0.43	ns	0.33	0.58	0.50

[a] All indicated r values are significant at $P < 0.01$.
[b] All noodles had finished raw noodle cross-sections 1.2 mm thick × 2.5 mm wide.
[c] Study 1 hard winter wheats $n = 30$, fixed cooking time.
[d] Study 2 soft winter wheats $n = 46$, fixed cooking time.
[e] Study 3 soft winter wheats $n = 60$, fixed and optimum cooking times.
[f] Tested immediately (within 5 min) after cooking and cooling in RT water.
[g] Held in water and tested 15–20 min after cooking and cooling in RT water, adhesiveness not measured.
[h] Fixed cooking time of 6.0 min.
[i] Optimum cooking time.

measurements. However, except for the correlations between TPA hardness and TPA chewiness, where other correlations between TPA parameters were significant, they were not of a magnitude to be considered predictive of each other. Also, it appears that hardness can either be negatively (Epstein et al 2002) Table II, study 1) or positively (Table II, studies 2 and 3) related to resilience and cohesiveness. Apart from correlations with sensory attributes, as with other tests, TPA can be used to track changes in noodle texture as a result of changes in process or storage (e.g., Kim et al 1998).

Tensile tests used to measure elasticity and related attributes are amenable to interpretations of the raw time/force data that can derive fundamental rheological parameters. Tensile methods can also be used to do stress relaxation studies if the noodles are not stretched to breaking point (Shimizu et al 1958; Miki and Yamano 1991), a feature they share with blunt probe compression tests (Hatcher et al 2005). Shimizu et al (1958) used a static noodle stretching test, which included a stress relaxation step, to indicate physical parameters of cooked noodles such as spontaneous and retarded elasticity. Significant correlations were established between a number of test parameters and mouthfeel elasticity when ring-shaped noodles were stretched and held under tension (Ross et al 1998). However, there were significant cross-correlations between parameters measuring "elasticity" and parameters measuring firmness. Seib et al (2000) showed with noodles made from flours from different sources that breaking length and tensile strength were significantly correlated with each other (r = 0.63 and r = 0.57, $P \leq 0.05$ for salt and alkaline noodle, respectively, calculated from published data of Seib et al 2000). However, observations of individual samples indicated that there was no nexus and that the relationship between breaking length and tensile strength could be broken for specific samples. For example, a Japanese commercial flour sample had higher tensile strength than predicted given its low protein content and moderate breaking length. The capacity for tensile tests to investigate fundamental aspects of noodle texture are further highlighted by the Seib et al 2000 data. From that data, a raw quotient has been calculated for the ratio of breaking length over tensile strength. This showed that alkaline noodles had length-to-strength ratios of 0.31–0.53. mm·g-force^{-1}. However, salt noodles made from 10 of the same 11 samples were, in general, more stretchable than the alkaline noodles with length-to-strength ratios of 0.46–0.67 mm·g-force^{-1}. This manipulation of the raw tensile test data showed what seems to be a fundamental difference in the relationship between tensile strength and stretchability of the noodles that was related to presence or absence of alkali alone. The capacity of tensile tests to investigate elastic components of noodle texture has the potential to be more extensively exploited, in some cases simply by applying appropriate transformations to the raw data.

Other Surface Characteristics

Two additional surface characteristics of interest are smoothness and stickiness. Interestingly, surface smoothness is both a physical (frictional) and geometric property, the two being aspects of surface roughness at different scales. Other aspects of geometry are important. For example, the relative sharpness of edges may provide a sensory cue to other textural attributes but this is largely in the domains of sensory testing or image analysis. A critical issue in dealing with smoothness and stickiness measurements is systematically dealing with the water on the noodle surface. An important requirement is that the noodles be maintained at a high relative humidity to ensure they do not dry out before testing. On the other hand, it is necessary to avoid testing immediately after the noodles have been removed from water or soup as the lubricating surface water will confound smoothness and stickiness measurements. Although based on pasta, Smewing (1997) provides clear guidelines regarding sample handling for stickiness measurements.

The principle of most stickiness methods is to apply a predetermined force to the noodle surface with a wide flat probe and measure the force required to pull the probe away from the surface. This is known more generally as a compression-decompression test (Dunnewind et al 2004). Of course, the noodle test piece must be fixed to the surface so that it is not simply lifted away by the retracting probe. Noodles tested using compression-decompression protocols show a typical adhesive failure pattern where there is a clean break between the test surfaces and the sample piece on decompression with little or no necking (tensile deformation) of the test piece, in contrast to cohesive failure where the test piece fails somewhere in its bulk, leaving considerable residues on the test sufaces (Kilcast and Roberts 1998; Dunnewind et al 2004). TPA has an analogous parameter, adhesiveness, that is determined in a similar fashion between the first and second cycles of compression ("area 3", Fig. 1). However, the TPA method compresses to a preset strain rather than a preset force (normal load or stress) and so force at the preset strain may be variable as a result of variability in the absolute force applied. As apparent adhesivness increases as a function of increasing compressive deformation or normal load (Miki et al 1996; Lee et al 2002), it is important to control the compressive pretest component of stickiness determinations. A variety of methods are published and there are many more written with respect to European-style pastas. The method of Guan and Seib (1994) used the same principle but used a modified probe. Fiszman and Damasio (2000) published a review of adhesiveness measurements more generally that may be of interest to readers contemplating innovative test methods.

Smoothness is difficult to determine instrumentally but attempts have been made using friction measurements with glass, teflon (Rice and Caldwell 1996), or stainless steel slides (Miki et al 1996). Chen et al (2004) presented an apparatus that could be adapted to noodles that used a stainless steel disk as the friction substrate for measuring surface friction of whey gels. However, they did indicate that sliding speeds and, again, the normal load applied to mate the test and substrate surfaces were both parameters that needed careful attention. Rougher whey gels showed higher normal load dependence. Smoothness/roughness testers such as the Surftest series of instruments (Mitutoyo Co., Japan) are available and have been applied successfully to the measurement of roughness of hydrocolloid/wax coatings on low-density polyethylene supports (Chen and Nussinovitch 2001). X-ray-mode scanning electron microscopy (Miki et al 1996), confocal laser scanning microscopy (Chen et al 2004) or image analyses of the surface topography could also be employed. However, sensory evaluations may remain the most effective method for the determination of surface smoothness of noodles.

Uniaxial Tests in Summary

All of the uniaxial tests discussed above can reliably indicate one or more physical properties of cooked Asian noodles. In some instances, such as with elasticity or springiness, care should be taken to relate the data to the sensory parameter of true interest, and this appears to be partly dependent on the specific definition used for sensory elasticity. Slow progress in establishing relationships between comparable physical and sensory terms may be a result of variably defined or "weak" sensory definitions (van Vliet 2002). This aspect however, does not detract from the simple elegance of uniaxial tests as reliable indicators of changes of physical properties of cooked noodles that are wrought by changes in raw material, formulation, or processing. Combining results of tensile and compressive testing within individual studies has the potential to illuminate aspects of noodle mechanical properties not uncovered using either approach alone.

Fundamental Dynamic Rheometry

An alternative to the uniaxial tests is the use of dynamic oscillating rheometry to establish fundamental physical attributes of cooked noodles. However, as observed in this article, "conventional" texture testing of cooked noodles has been far more prevalent than fundamental testing and this reflects the prevalence of "texture" tests in food texture investigations more generally (Mulvaney 2005). Mulvaney (2005) also indicated, that to be of value, fundamental rheology has to provide information that is additional to information that can be obtained from the more conventional texture analyses. Of the few fundamental investigations of cooked noodle rheometry that have been reported, these are dominated by dynamic rotational oscillatory tests at small deformations, and extensional tests. Notably, these tests have been more commonly applied to wheat flour doughs, rather than cooked noodles. Nonetheless, there are a small number of useful recent studies where these techniques have been applied to cooked noodles (Bejosano and Corke 1998; Kaneko et al 2000; Tanifuji et al 2003; Sasaki 2004). Dynamic rheometers applied to solid or semi-solid foods generally apply small strains in sinusoidal oscillation. Plate/plate test geometry is most appropriate for noodle testing but with any test geometry used the forces measured are transformed to determine a number of fundamental rheological properties such as; storage modulus (*G'*), the amount of energy stored in the system as mechanical energy after a deforming force is applied; loss modulus (*G"*), the amount of energy not recoverable after a deforming force is applied; and phase angle (δ), often expressed as tan-δ (*G"/G'*). The phase angle, between 0 and 90°, is an indicator of the solid-like, liquid-like balance of a viscoelastic material, 0° representing an ideal elastic solid (application of deformation and detection of resultant stress completely in-phase), and 90° representing an ideal viscous liquid (application of deformation and detection of resultant stress completely out-of-phase). Accordingly, tan-δ, values < 1 (*G" < G'*) indicate more solid like behavior, values > 1 (*G" > G'*) indicate more liquid-like behavior. Cooked noodles have been reported as having tan-δ values <<1, indicating primarily solid like behavior (range 0.15–0.25) (Tanifuji et al 2003; Sasaki et al 2004). Phase angle (δ) values were reported at 9–11° (tan-δ = 0.15–0.19) for white salted noodles (Bejosano and Corke 1998). The values are also in accordance with tan-δ reported for starch gels in the concentration range 60–150 $g \cdot kg^{-1}$ and flour gels in the concentration range 80–300 $g \cdot kg^{-1}$ (Champenois et al 1998).

Sasaki et al (2004) and Kaneko et al (2000) showed both lower *G'* and lower *G"* for cooked noodles made from nonwaxy wheat flours with reduced amylose contents. Tanifuji et al (2003) also showed reduced *G'* related to lower amylose content, in this case for noodles made from reconstituted flours. Reassessment of the published data of Sasaki et al (2004) showed indications of nonlinearity in the responses of both *G'* and *G"* to changing amylose content both in the presence and absence of the two waxy wheat samples used in the study. For the full data set, there appeared to be minima in both *G'* and *G"* at ≈10 and 15% amylose, respectively (r^2 values for the quadratic fits were both 0.89). When the fully waxy lines were removed from the data the r^2 values for the quadratic fits increased to 0.98 for *G'* and 0.94 for *G"* and indicated potential minima for both *G'* and *G"* in the 20% amylose region. Unfortunately, there were no samples in the 2–18% amylose region. The gap in the data provides an interesting research opportunity. Sasaki et al (2004) also showed a higher frequency dependency for *G'* in the cooked noodles as flour amylose content decreased (i.e., *G'* changed more as the frequency of oscillations increased from 0.1 to 100 $radians \cdot sec^{-1}$). This was in accordance with observations of higher frequency dependency for *G'* in wheat starch gels as amylose content decreased (Sasaki et al 2002). This parallel increase in frequency dependence related to decreased amylose content in both noodles and starch gels is consistent with our understanding of the primary role of starch in the texture of wheat flour noodles. However, the frequency dependency was more evident in the noodles, possibly indicating the role of the heat-set gluten proteins and potential interactions of proteins with starch.

Tan-δ has been negatively correlated with starch amylose content in noodles made from nonwaxy flours (Kaneko et al 2000; Tanifuji et al 2003; Sasaki et al 2004). That is, as amylose content increased, tan-δ decreased, indicating a shift to more solid-like properties. This seems counterintuitive with respect to the generally held notions about increased elasticity of cooked noodles with reductions in amylose content, but I believe this can be resolved. First, we are dealing with very small strains that are unlike the strains applied in uniaxial testing (Table I) or in the mouth. Second, the observation of increased *G'* with increased amylose content in nonwaxy starches with amylose contents > 15% discussed above indicates more internal connectivity, most likely a result of noncovalent or entanglement associations. However, these small sinusoidal strains tell us little about mechanical properties at large strains, particularly those approaching the rupture of the material. The increased internal connectivity inferred by higher *G'* is associated with higher rigidity (stiffness) at small deformations and a tendency to fracture at less extensive deformations than those attained by materials that are less stiff. These phenomena could be translated to encompass the experiential observations of sensory assessors and results from large deformation instrumental tests that show that cooked noodles made from lower amylose flours do store more energy at relatively high strains (are more elastic) because they have not begun to rupture (Ross and Crosbie 1998; Sasaki et al 2004). Rupture behavior of cooked noodles increases in importance if the three-point bend geometry for failure of rod-like food particles in the mouth proposed by Lucas et al (2002) is considered to be a valid model. In this case, crack initiation and propagation may be the critical parameters.

One useful approach seems to apply both small and large deformation tests to the samples and contrast the results. Tanifuji et al (2003) used this approach. They showed that increases in both amylose content and the strength of gluten in reconstituted flours gave cooked noodles with more solid-like and more fundamentally elastic behavior at small strains. That is, *G'* increased and tan-δ decreased. However, when the noodles were ruptured using large deformations, the rupture of the material required more energy, as amylose content **decreased**, or as gluten strength increased. So as amylose content changed, there was a negative correlation between *G'* and rupture stress; and as gluten strength changed, there was a positive correlation between *G'* and rupture stress. The combination of the two approaches seems to allow a reconciliation of the apparent paradox that both stronger gluten and lower amylose can create more "elastic" noodles. The reconciliation provided by the Tanifuji et al (2003) data is that they observed harder and more elastic noodles made from flours with stronger gluten, and softer and more elastic noodles from lower amylose flours. This suggests that mouthfeel elasticity might be more associated with rupture behavior at large strains, than fundamental elastic behavior at small strains, as was hypothesized in the introduction.

Theoretical considerations of polymeric networks, fundamental elasticity, and fracture behavior, and their potential parallels with cooked noodle structure are only approximations as cooked noodles are inhomogeneous at a number of scales, and lack of homogeneity in foodstuffs is a major cause of misalignment between theoretical considerations and real-world behavior under deformation (van Vliet 2002). At the macro-scale, cooked noodles are inhomogeneous from exterior to interior as a result of the well-documented moisture gradient. They are inhomogeneous at the meso-scale, especially deep in the core where granules have swelled but not dispersed, with a clearly apparent discontinuous phase of swollen starch granules, and a continuous phase of protein and amylose exuded from the starch granules (models: Wang and Seib 1996; Ross et al 1997; Zhao and Seib 2005) (microscopy: Moss et al 1987; Kojima et al 1992). They are also likely to be inhomogeneous at the micro-scale (molecular scale), as one would anticipate a clustering of amylose/amylose and amylose/protein entanglements near granule surfaces, given the poor ability of linear polymers to engage in translational motion, other than reptation, in highly concentrated environments. The incomplete understanding of the stress concentration effects of these scalar inhomogenieties in cooked noodles opens up an exciting area of research for workers with a focus on these products.

Research opportunities lie in decoding the implications of fundamental rheology for understanding composition/structure/function relationships in boiled and nonaerated wheat-based foods. For example, with respect to the changing macromolecular architecture of cooked noodles in response to changing amylose contents. But there are limitations. Bejosano and Corke (1998) pointed out that, although it was possible to indicate changes in *G'* and phase angle of cooked noodles as a result of the additions of protein concentrates from different sources, interpretation of the results was difficult as the dynamic method used in their study did not distinguish between the surface and core of the noodles. This statement could be true of all dynamic rheometry methods applied to noodles. Dynamic rheometry appears to be more suited to measuring the bulk rheology of the material without distinguishing between the laminar differences in moisture content and mechanical properties that are present in cooked noodles. Methods of this type may eventually find their way into routine quality determinations and further advances in their use with respect to noodles bears watching.

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