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USE OF POISSON'S RATIO FOR OBJECTIVE-SUBJECTIVE TEXTURE CORRELATIONS IN BEEF. AN APPARATUS FOR OBTAINING THE REQUIRED DATA[1]

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ABSTRACT

A device is described for measuring the transverse deformation of cylindrical samples during axial compression. The device is fitted to an Instron Universal Testing Instrument and requires only standard Instron electronics and data recording systems. Calculations showing that the transverse deflection gives a good estimate of Poisson's ratio are valid for both isotropic and anisotropic materials.

Correlation coefficients for magnitude estimates of three sensory texture attributes in beef increase from 0.5 to 0.9 when Poisson's ratio is substituted for the uniaxial "modulus of elasticity." This indicates that Poisson's ratio may be a very promising objective parameter for predicting the sensory texture quality in meat.

INTRODUCTION

Texture is a major attribute of quality when assessing the acceptability of beef. A considerable amount of work has been done in different laboratories on establishing instrumental measures of physical properties that would correlate with subjective judgments of textural attributes. Stanley *et al.* (1972) obtained correlation coefficients of 0.76—0.90 between Instron extension tests and texture panel evaluation of porcine *psoas* muscles. Recently, Segars *et al.* (1975) used a new shearing device to obtain subjective-objective correlations in beef ranging from 0.92 to 0.98. Many other devices such as penetrometers, Warner-Bratzler shear, Allo-Kramer shear, etc. have been used by other

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workers, but as yet no "standard" test has emerged (Kapsalis and Szczesniak 1976).

Our present interest in the texture of beef originated from a military "beef-roll" fabrication program, the purpose of which is to produce meat rolls of standardized quality by combining cuts of meat from different muscles. The initial work on this problem, reported by Segars *et al.* (1974), showed good instrumental correlations between raw and cooked beef, but did not include sensory evaluation. More important, the study brought out certain anomalies in the mechanical behavior of material when subjected to uniaxial compression, which suggested a new approach to the testing of meat tenderness. The data indicated that in general the apparent modulus of elasticity, E_a, which is a direct measure of stiffness or rigidity (resistance to deformation) decreased as meat toughened. Although there is no strong evidence to suggest that the modulus of elasticity should predict the tenderness of meat, in some materials the modulus of elasticity and the ultimate strength tend to vary in the same direction and there is reason to expect that this latter parameter reflects, to some extent, the consumer response to meat texture.

In connection with the above results, i.e. lack of correlation between the modulus of elasticity and toughness, a mechanical-mathematical model (Segars and Kapsalis 1976) showed that for uniaxial compression testing stress-strain curves with nearly identical modulii of elasticity could be calculated using hypothetical samples of widely different rheological parameters. Conceivably, "tender" meat could have the same or, as our data showed, a steeper (higher modulus) stress-strain curve than "tough" meat. However, when the maximum transverse deformation (deformation perpendicular to the applied axial compression) was calculated from the model, the values showed clear differentiation between samples of similar modulii. It is probable that at least some of the low correlations between instrumental and sensory measurements may be due to this lack of discrimination exhibited by uniaxial testing.

The situation is quite different for homogeneous isotropic materials, especially at small strain levels. For elastic behavior of these materials there exist fixed relationships between the bulk modulus (K), shear modulus (G), elastic modulus (E) and Poisson's ratio (μ). These relationships:

$$E = 3K/(1 - 2\mu) = 2G/(1 + \mu) \tag{1}$$

$$G = E/[2(1 + \mu)] \tag{2}$$

$$K = E/[3(1 - 2\mu)] \tag{3}$$

exist because for such materials there are only two independent variables, Lame's constants. For these materials a correlation between Poisson's ratio and a given modulus, for example E, would be expected, but not assured. Although these relationships do not strictly apply to the uniaxial compression of meat, certain inferences can still be drawn. We know that, in general, a product becomes more compressible as the gas volume within it increases. Its bulk modulus decreases, which may reduce E and, in addition, lowers Poisson's ratio. Measurements on various foam rubbers showed that a volume reduction of nearly 50% occurred before a significant increase in transverse deformation was observed, indicating a Poisson's ratio near zero over this range of compression. The other extreme occurs as μ approaches 0.5, where isotropic materials, and probably others, become incompressible (i.e. bulk modulus equals infinity). The meat samples tested in this study were moderately compressible with μ ranging from 0.20 to 0.26.

The need for experimental measurements of transverse deformation required the design and construction of test equipment which was not commercially available. The scope of the present paper is to report on the development of a Poisson's ratio device for the measurement of the transverse deformation by standard uniaxial compression, and to present data on the use of this device for obtaining rheological measurements on food samples.

DESCRIPTION OF THE POISSON'S RATIO DEVICE

Figure 1 shows the Poisson's ratio device mounted on the Instron Universal Testing Instrument. A pivot arm support clamps to the vertical frame of the floor model Instron via a slotted bar (partly shown in the figure). The pivot arm support is rotated and translated relative to this bar to facilitate positioning of the pivot arms and sensing plates. Two T-shaped pivot arms, 14 cm in length, are attached to the support. The arms are held in place by pointed screws threaded through the pivot arm support and into the center of ball bearing assemblies mounted at the top and bottom surfaces of the vertical section of the pivot arm. This vertical part is a cylindrical rod 1.2 cm in diameter and 3 cm long. The screws are adjusted until the pivot arms have the correct height (sensing plates at the center of the sample) and the bearings have the correct pressure (arms rotate freely without loose motion). The screws are then secured with locking nuts. A cylindrical tube welded to the free end of the pivot arm holds the sensing plate. The latter is a flat stainless steel disk 1.2 cm in diameter welded to the end of a 0.6 × 4 cm stainless steel rod sliding through the cylindrical tube and

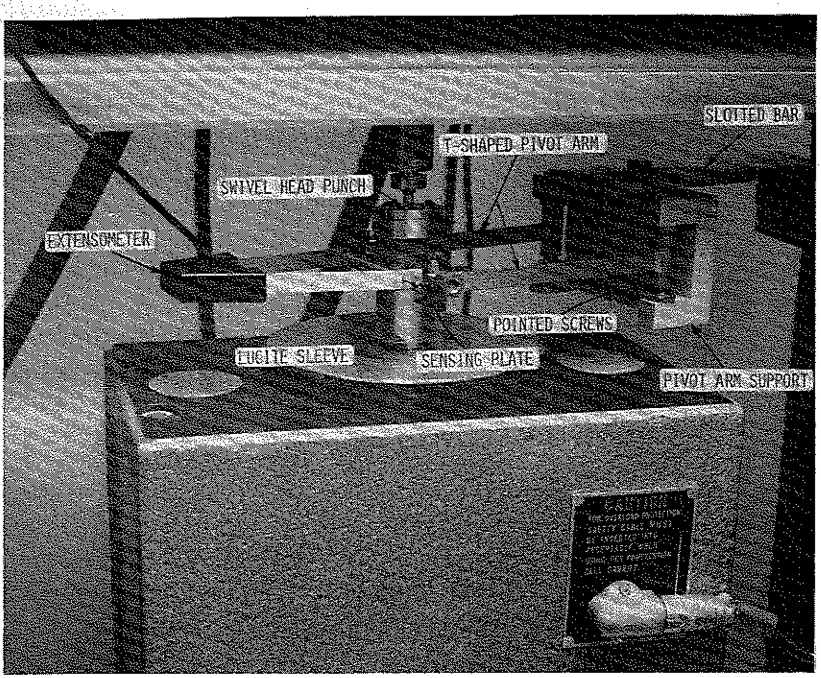

FIG. 1. PHOTOGRAPH OF THE POISSON'S RATIO DEVICE SHOWING THE PIVOTING ARMS EXTENDING OUT OVER THE LOAD CELL, THE INSTRON EXTENSOMETER, THE SWIVEL MOUNTED UPPER COMPRESSION PLATE AND THE CYLINDRICAL MEAT SPECIMEN

held in place by a set screw. The Instron strain gage extensometer mounts on these rods (one rod extending from each pivot arm) and monitors the change in separation of the sensing plates.

The device uses electronics that is part of the Instron system except that a second recorder or, preferably, a single two-pen recorder is needed. It is calibrated using standard Instron procedures applicable to the extensometer. Care is required in adjusting the sensing plates so that they only touch the cylindrical sides of the sample without applying pressure. However, it will be shown later that small differences in contact pressure are compensated for in the analysis.

Also shown in Fig. 1 is a stainless steel swivel-head compression punch which is threaded into the rod extending down from the hydraulic ram mounted on the moving crosshead of the Instron. The compression surface of this punch tilts to allow uniform contact over the top surface of wedge-shaped samples. Knife-edge rings on the compression surface eliminate slipping when the punch is tilted and prevent swelling (lateral expansion) of the ends of the sample.

The cylindrical sample is placed on a stainless steel cylinder (2.54 cm in diameter by 3.1 cm long) that threads, via an adapter, into the compression load cell. A Lucite sleeve fits tightly around this cylinder, protruding 0.1 cm above the top. This rim holds the bottom surface of the sample in place (prevents lateral expansion) during compression. Visual observation indicates that the sample holder functions as described; the sample is constrained to a vertical axis and it remains symmetric about this axis throughout compression.

THEORETICAL CONSIDERATIONS

When a cylindrical sample is compressed using the holder described above, its ends, in addition to being constrained to a vertical axis, are prevented from swelling. Unless the sample is highly compressible, it must swell or buckle at its mid-section in order to maintain the proper volume. With short samples (length to diameter ratio near unity) buckling is rare and symmetric barreling occurs. Our device measures the magnitude of this barreling which, in essence, represents the maximum swelling of the sample.

For theoretical considerations, we shall first investigate the feasibility of relating the above maximum transverse deformation to the Poisson's ratio. If this could be done, then shear stresses might be predicted from uniaxial compression data.

Poisson's ratio is defined as the ratio of transverse strain to axial strain. Theoretically, it is restricted to ideal deformations that lie within the elastic limit of the material. In practice, it is applied to deformations which approximate ideal conditions, i.e. small, not always totally elastic, and nearly constant deformations throughout the sample.

Deformations obtained with the sample holder described above do not approximate ideal conditions; barreling is evident as soon as compression begins. At this point, an assumption is required to relate the actual compression to the ideal case. The approach used here assumes that the transverse deformation is elastic for small deformations and hence its average value is the arithmetic mean of all deformations (which are zero at the ends of the sample and maximum at the center). This is basically the assumption used by Hammerle and McClure (1971) for viscoelastic materials at low strains. The average deformation, $\overline{\delta}$, is equal to $\overline{r}$-r_0, where $\overline{r}$ is the radius of the ideal (constant radius) cylinder that has the same length and volume as the barreled sample, and r_0 is the radius of the sample before compression. Let this volume be v and the length $2z_1$, then:

$$r = [V/(2\pi z_1)]^{1/2} \tag{4}$$

and Poisson's ratio becomes:

$$\mu = -\epsilon_r/\epsilon_z = -\ln(\bar{r}/r_0)/\ln(z_1/z_0) \tag{5}$$

where ϵ_r is the true (Hencke) strain in the radial direction, ϵ_z is the true strain in the axial direction (applied strain) and $2z_0$ is the length of the sample before compression. True strains are used here to permit a more accurate representation of large strain conditions. The volume of the sample before compression is:

$$V_0 = 2\pi r_0^2 z_0 \tag{6}$$

Combining Equations (4) and (6) yields:

$$\bar{r}/r_0 = (z_0/z_1)^{1/2} (V/V_0)^{1/2} \tag{7}$$

which upon substitution into Equation (5) gives:

$$\begin{aligned} \mu &= -\tfrac{1}{2} \ln[(z_0/z_1)(V/V_0)]/\ln(z_1/z_0) \\ &= -\tfrac{1}{2}[\ln(V/V_0) - \ln(z_1/z_0)]/\ln(z_1/z_0) \end{aligned} \tag{8}$$

Thus, Poisson's ratio can be obtained at any axial strain ($\ln(z_1/z_0)$) if the volume of the compressed sample is known.

For samples fitting the general description given above, barreling is symmetric about the axis of compression and since the position of both ends is known at all compression levels, the volume of the compressed sample can be calculated accurately. For example, assume that the sides of the bulged sample are elliptical as shown in Fig. 2 and obtain the equation of the ellipse passing through the points $y = r_0$ at $z = \pm z_1$ and $y = r_0 + \delta$ at $z = 0$. This equation is:

$$y^2 = (r_0 + \delta)^2 - (z/z_1)^2 [(r_0 + \delta)^2 - r_0^2] \tag{9}$$

The volume of the compressed sample is that obtained by rotating this ellipse 360 degrees about the z-axis and truncating at $z = \pm z_1$. This volume is obtained by considering a disk shaped volume element, dV, lying between the planes z and z + dz. Then:

$$dV = \pi y^2 \, dz \tag{10}$$

where y is the radius of the deformed sample at plane z and is given by

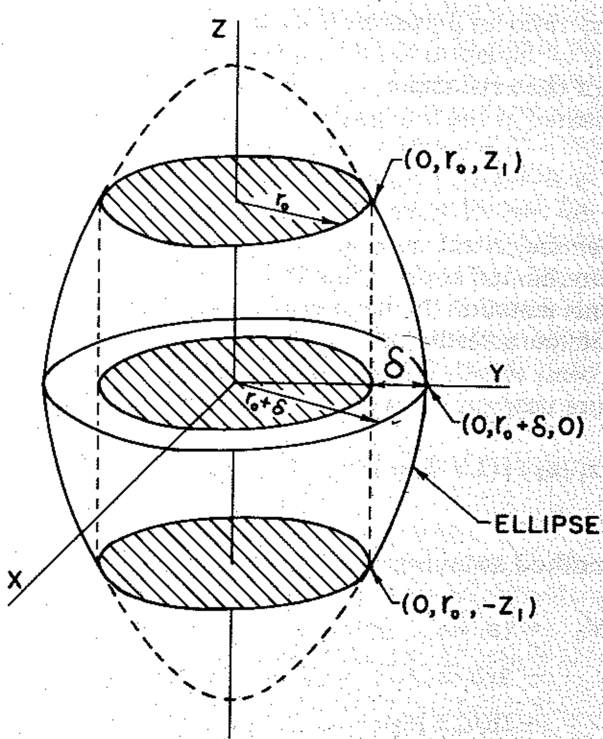

FIG. 2. SCHEMATIC DIAGRAM IDENTIFYING QUANTITIES USED IN THE DEVELOPMENT OF EQUATIONS RELATING TO POISSON'S RATIO

Equation (9). Substitution of Equation (9) into Equation (10), integrating from $z = 0$ to $z = z_1$ and multiplying by 2 gives the total volume of the compressed sample:

$$V = 2 \int_0^{z_1} \pi y^2 \, dz$$

$$= 2\pi \int_0^{z_1} \{(r_0 + \delta)^2 - (z/z_1)^2 \, [(r_0 + \delta)^2 - r_0^{\,2}]\} dz \qquad (11)$$

$$= 2/3 \, \pi \, r_0^{\,2} \, z_1 \, [2\,(1 + \delta/r_0)^2 + 1]$$

Using Equations (6) and (11) to obtain the volume ratio V/V_0 yields:

$$V/V_0 = 1/3\,(z_1/z_0)\,[2\,(1 + \delta/r_0)^2 + 1] \qquad (12)$$

which is the ratio of compressed to initial volume at any axial strain. Substitution of Equation (12) into Equation (8) gives Poisson's ratio as a function of the axial strain ($\epsilon_z = \ln (z_1/z_0)$) and the transverse deformation measured at the midlength of the sample (δ):

$$\mu = -\tfrac{1}{2} \ln [2/3\,(1 + \delta/r_0)^2 + 1/3] / \ln (z_1/z_0) \tag{13}$$

The above treatment assumes that the sides of the barreled sample can be approximated by an ellipsoid. The closeness of this approximation or some measure of the sensitivity of the compressed volume to the shape of the bulged sides must be determined. Two other assumptions have been tested. Assume the sides are parabolic; then following the procedure used for elliptical sides the volume ratio becomes:

$$V/V_0 = (z_1/z_0)\,[(1 + \delta/r_0)^2 - 2/3\,(\delta/r_0)(1 + \delta/r_0) + 1/5\,(\delta/r_0)^2] \tag{14}$$

The same method assuming circular sides gives:

$$\begin{aligned} V/V_0 \; = \; & (z_1/z_0)\,\{[(h + r_0 + \delta)/r_0]^2 - h(r_0 + \delta)/r_0{}^2 \\ & - 1/3\,(z_1/r_0)^2 \;\; (1 + h/[2\,(h + r_0 + \delta)]) \\ & - (h/r_0)\,[([h + r_0 + \delta]/r_0)^2 - (z/r_0)^2]^{1/2}\} \end{aligned} \tag{15}$$

where

$$h = (z_1{}^2 - \delta^2 - 2\,r_0\,\delta)/(2\,\delta) \tag{16}$$

is the displacement along the y-axis of the center of curvature, i.e. $y = -h$ ($x = z = 0$ at center of curvature) and where $\sin^{-1} [z_1/|h + r_0 + \delta|]$ is replaced by the first two terms of its Taylor expansion.

The volume ratios calculated from Equations (12), (14) and (15) show clearly that results are not appreciably affected by the specific shape chosen for the barreled sides. Values of δ corresponding to materials that range from highly compressible ($\mu < 0.1$) to incompressible ($\mu = 0.5$) give values of V/V_0 that are within 0.5% of each other for axial strains up to 30%. Differences between the three equations are reduced as compressibility increases and as the axial strain decreases. Thus, for small deformations the volume ratio, and subsequently the Poisson's ratio, can be accurately determined from the data obtained with our device.

Equations (12), (14) and (15) show that the volume ratio V/V_0 is a function of the axial strain and the transverse deformation δ. Poisson's ratio, μ, obtained from them as in Equation (13) would also be a function of these variables. The data in Fig. 3 show δ to closely approximate a linear function of deformation, hence it must also change linearly with z_1. A study of Equation (13) shows that if δ is proportional to z_1, then μ must also vary with z_1, i.e. μ is a function of axial strain. Flügge (1967) has shown that this is to be expected for viscoelastic materials, even at relatively small loads. The creep compliance of these materials is usually anisotropic; thus Poisson's ratio not only changes with axial deformation, but also with time if held at any given deformation. Therefore, it becomes necessary to choose a "standard" strain level and describe a method to obtain the best value of Poisson's ratio

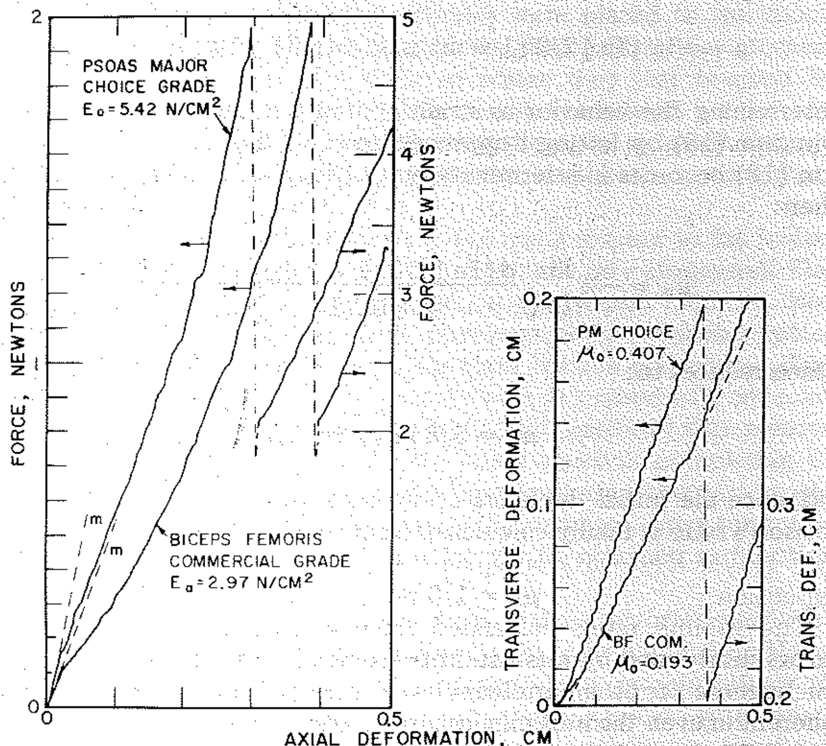

FIG. 3. TRACINGS OF TYPICAL FORCE VERSUS AXIAL DEFORMATION AND TRANSVERSE DEFORMATION VERSUS AXIAL DEFORMATION CURVES OBTAINED WITH THE POISSON'S RATIO DEVICE ON COOKED MEAT

Data for tough meat (*biceps femoris*, commercial grade) and for tender meat (*psoas major*, choice grade) are shown based on that choice. Previous discussions suggest that ideal behavior is more closely approximated at small deformations where the assumptions made are more nearly satisfied. It is logical then to choose the region of initial deformation for the calculation of Poisson's ratio. In our work the value obtained by extrapolating to zero strain is taken as Poisson's ratio, μ_0, for the sample.

To determine μ_0, consider the behavior of Equation (13) as strain approaches zero. Let m be the slope of the transverse deformation versus time curve whence $\delta = mt$. Then writing:

$$z_1 = z_0 - v_p t \tag{17}$$

where v_p is the constant cross-head velocity, Equation (13) becomes:

$$\mu = -\tfrac{1}{2}\,\{\ln[2/3\,(1 + mt/r_0)^2 + 1/3]\}/\ln(1 - v_p t/z_0) \tag{18}$$

Determining the behavior as strain approaches zero is accomplished in Equation (18) by letting t approach zero. In the limits as $t \to o$, Equation (18) becomes indeterminate and L'Hospital's rule must be applied. Then:

$$\mu_0 = -\tfrac{1}{2} \lim_{t \to o} \frac{d\{\ln[2/3\,(1 + mt/r_0)^2 + 1/3]\}}{d\,\{\ln(1 - v_p t/z_0)\}} \tag{19}$$

which reduces to:

$$\mu_0 = 2/3\; m\, z_0/(v_p r_0) \tag{20}$$

and since the initial thickness of the sample is $T_0 = 2\,z_0$, one value of Poisson's ratio is finally calculated from the equation:

$$\mu_0 = 1/3\; m\, T_0/(v_p r_0) \tag{21}$$

Errors introduced by the assumptions made in developing this equation are believed to be insignificant in comparison to experimental errors inherent in even the best experimental techniques.

EXPERIMENTAL PROCEDURE

The experimental data reported here were obtained on samples of *psoas major*, *biceps femoris* and *semitendinosus* muscles from one U.S. Choice and one U.S. Commercial animal. The measurements were made concurrently with those of a previous study using a punch and die test (Segars *et al.* 1975) and are, thus, directly comparable. The cooking procedure has been described in detail in the previous report. Briefly, the muscles were placed in polyethylene bags and suspended in a steam kettle maintained at approximately 64° C. They were cooked in this bath until their internal temperature reached 63° C. Holding the bath temperature just slightly higher (1 or 2° C) than the final temperature of the meat produced muscles that appeared uniformly cooked from surface to center and from end to end.

Samples for instrumental measurements were prepared by cutting the cooked muscles with a knife into slices approximately 2.54 cm thick. Cylindrical samples were then excised from the slices using a 2.54 cm diameter knife edged cutter mounted on a drill press.

The 2.54 × 2.54 cm cylindrical samples were placed in the special holder shown in Fig. 1. The sensing plates that follow the transverse deformation were rotated into position where they just touched the sides of the sample. The Instron extensometer mounted on the rods holding the sensing plates was adjusted by sliding its arms on the rods until the force applied to the sides of the sample by the sensing plates was nearly zero.

The extensometer was connected in the usual manner to the Instron strain gage amplifier whose output was displayed on a Honeywell Electronic 19 recorder; force was displayed on the Instron recorder. Both the force-measuring system and the transverse-strain measuring system were calibrated and operated using standard Instron procedures. Each sample was compressed along the axis of fibers at a speed of 2 cm min^{-1} to a maximum axial strain of at least 20%. The crosshead then reversed its direction and returned to the zero strain position completing the load-unload cycle. The axial force and the transverse deformation were recorded as functions of time for this cycle; however, since the rate of compression is constant, both quantities can be obtained as functions of axial strain.

The sensory data given here are identical to those reported previously (Segars *et al.* 1975). They were obtained using the method of Magnitude Estimation where the numbers assigned to a sample reflect the relative magnitude of the particular attribute being judged with respect to other samples and, to some extent, to other attributes. Seventeen panelists were asked to rate three texture attributes as follows:

(1) **Difficulty of Cutting** — effort required to cut the sample into two or more parts using the teeth.

(2) **Chewiness** — overall effort required to chew the sample during the first three or four chews.

(3) Residue — amount of material left in the mouth just before swallowing.

Each panelist received six samples, one from each muscle; the order in which they were presented provided a position-balanced design.

RESULTS AND DISCUSSION

From the instrumental data, which included both the uniaxial force-deformation curves and the transverse deformation versus time charts, the following parameters were calculated:

(1) Apparent modulus of elasticity, E_a; equal to the slope of the initial linear segment of the stress-strain curve. This slope, shown by the dashed lines labeled m in Fig. 3, indicates linear behavior which in this work existed for axial strain up to approximately 1%.

(2) Stress at a given strain, σ_ϵ; in this study the selected strain was 20%.

(3) Poisson's ratio; calculated from Equation (21).

Means for each sensory attribute, the apparent modulus of elasticity, (E_a), and the Poisson's ratio (μ_0) are given in Table 1. The narrow range of values for μ_0 relative to the changes observed in E_a indicate the precision and reproducibility required in the measurement of this parameter. Table 2 shows the correlation coefficients between each attribute and both instrumental measures. A comparison of r-values shows the advantage gained by using μ_0 instead of E_a in subjective-objective correlation studies. The r-values for E_a average about 0.5, i.e. only 25% of the variation between muscles is explained by this parameter. The r-values for μ_0 are about 0.9, indicating that Poisson's ratio accounts for about 80% of the variation.

The high correlation between a non-failure parameter (Poisson's ratio) and what are normally considered to be failure parameters (sensory attributes) may at first be surprising. Mohsenin and Mittal (1977) projected the hypothesis that no correlation should exist between the two. However, we believe that our results are best explained as follows. It is probable that Poisson's ratio reflects primarily the amount of connective tissue as well as its small strain elastic properties. (The extent of swelling depends both on the absolute amount of connective tissue and its elastic properties.) The attribute "residue," although evaluated only through destruction of the sample, was not a failure parameter here. It was mainly a measure of the amount of connective tissue present (see definition of residue under Experimental Procedure). A good correlation with Poisson's ratio would not then be surprising. With regard to the other two sensory parameters, the

Table 1. Geometric means of sensory attributes and arithmetic means with standard deviation for instrumental parameters

Muscle Identification	Sensory: Difficulty of Cutting[1]	Sensory: Chewiness[1]	Sensory: Residue[1]	Instrumental: E_a	Instrumental: μ_0
Psoas Major — Choice	5.4	4.5	2.6	0.774 ± .375[3]	0.262 ± .080[3]
Psoas Major — Commercial	11.9	10.5	6.8	1.189 ± .465[3]	.232 ± .068[3]
Biceps Femoris — Choice	14.8	12.3	10.7	1.579 ± .766[5]	.228 ± .062[5]
Semitendinosus — Choice	21.1	15.7	12.2	.785 ± .523[4]	.236 ± .094[4]
Semitendinosus — Commercial	37.1	26.2	18.5	.962 ± .433[5]	.227 ± .047[5]
Biceps Femoris — Commercial	58.2	45.6	31.4	.575 ± .284[2]	.197 ± .043[2]

[1] mean of 17 evaluations
[2] mean of 9 evaluations
[3] mean of 10 evaluations
[4] mean of 12 evaluations
[5] mean of 13 evaluations

Table 2. Correlation coefficients between data means

	Chewiness	Residue	E_a	μ_0
Difficulty of cutting	0.996[a]	0.992[a]	−0.502	−0.876[c]
Chewiness		.994[a]	− .490	− .899[b]
Residue			− .432	− .916[b]
E_a				.126

[a]significant at $P<0.001$
[b]significant at $P<0.02$
[c]significant at $P<0.05$

following arguments apply: "Chewiness" probably reflects not only the disintegrative properties of the sample, but also the amount and elasticity of the connective tissue prior to the disintegration. Therefore, it will correlate, in a secondary way, with Poisson's ratio. The same arguments apply to the "difficulty of cutting." In fact, the high correlation between the three sensory attributes (residue, chewiness, difficulty of cutting) suggests that a single characteristic, which according to the above arguments is the amount of connective tissue, predominates in the sensory evaluation of each.

The considerable scatter of the experimental values, which is inherent in meat measurements, was accentuated by our difficulties in applying the new Poisson's ratio device for the first time. These difficulties included the proper adjustment of the sensing arms, the accurate measurement of sample diameter, and the synchronization of the two recorders. The high correlation coefficient obtained between instrumental and sensory measurements is only indicative of the usefulness of the device. More experimental work is needed before such a correlation can be reliably used as a basis for a standard test.

Mechanical measurements obtained subsequently to this study on alginate gels showed clearly that the experimental scatter can be greatly reduced. These measurements (to be reported separately) strongly indicate that our Poisson's ratio device measures a textural quantity not readily evaluated by other means. Its further investigation and use are warranted.

CONCLUSIONS

Experimental data showed that standard uniaxial compression parameters derived from tests made at a compression rate of 2 cm/min with a maximum compression of 20% fail to characterize adequately the mechanical texture properties of beef.

The additional measurement of transverse deformation which, according to our calculations, can be related to Poisson's ratio of transverse to axial strain, provides much more information on textural characteristics.

Our method allows for non-ideal test conditions (sample barreling) and meets the experimental requirements of actual use.

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