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Relationship of texture profile analysis and Warner-Bratzler shear force with sensory characteristics of beef rib steaks

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Abstract

Cyclical texture profile analysis (TPA) parameters measured using a star-shaped probe with two cycles of 80% penetration and Warner-Bratzler shear force (WBS) were compared as predictors of objective tenderness and subjective sensory characteristics of rib steaks from 52 beef loins. The TPA parameters of hardness, cohesiveness and chewiness were negatively correlated ($P<0.05$) with trained panel sensory characteristics of initial tenderness ($r=-0.64$, -0.41, -0.62, respectively), amount of connective tissue ($r=-0.57$, -0.27, -0.55, respectively), overall tenderness ($r=-0.68$, -0.39, -0.64, respectively) and overall palatability ($r=-0.56$, -0.37, -0.53, respectively). These sensory characteristics were also negatively correlated ($P<0.05$) with WBS ($r=-0.61$, -0.49, -0.60, -0.56, respectively). Stepwise regression analysis generated prediction equations that included the TPA parameters of hardness and adhesiveness, which accounted for 47, 36, 51 and 38% of the variation in initial tenderness, amount of connective tissue, overall tenderness and overall palatability, respectively. Prediction equations using WBS accounted for 37, 24, 36 and 31% of the variation in initial tenderness, amount of connective tissue, overall tenderness and overall palatability, respectively. Hence, TPA explained more of the variation in subjective sensory tenderness of the rib steaks than WBS.

Keywords: Beef tenderness; Texture profile analysis; Warner-Bratzler shear force

1. Introduction

Human perception of meat palatability is derived from a complex interaction of sensory and physical processes during chewing. Of the various subjective characteristics determining meat palatability, tenderness is the most important (Jeremiah, 1982).

Several objective methods of predicting meat tenderness have been developed, however these usually rely on measuring a single parameter and none fully imitate the complexity of the chewing motion (Bouton & Harris, 1972; Pearson, 1963; Szczesniak & Torgeson, 1965). Recognizing this limitation, the mechanical process of mastication has been simulated using texture profile analysis (TPA). This objective method measures the compression force of a probe and the related textural parameters of a test food during two cycles of deformation. The TPA of various foodstuffs including fruits, vegetables, bakery and meat products have been reported (Penfield & Campbell, 1990). The range in variation of subjective sensory characteristics of beef tenderness determined by sensory panels, explained by the objective textural parameters of TPA varies from 3 to 85% (Szczesniak, 1968). Rhodes, Jones, Chrystall, and Harries (1972) used stepwise regression to rank the relationship between various textural parameters of roast beef determined from the force-deformation curves of an instrumental compression device as compared to that of trained panelist ratings for tenderness and juiciness. All together the instrument textural parameters accounted for about 50 and 30% of the sensory-variability for tenderness and juiciness characteristics of warm roast beef, respectively.

Warner-Bratzler shear force (WBS) is an imprecise predictor of beef tenderness characteristics determined by trained panelists (Shackelford, Wheeler, & Koohmaraie, 1995, 1997). Correlations of WBS with sensory assessment of beef tenderness have been variable, ranging from -0.60 to -0.85 (Pearson, 1963) and -0.32 to -0.94 (Szczesniak, 1968). In spite of the 10–89% range

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of variation reported in the aforementioned studies, mean values of −0.75 (Pearson, 1963) and −0.77 (Shackelford, Wheeler, & Koohmaraie, 1999) suggest that WBS explains a substantial proportion of variation in sensory assessment of beef tenderness. Consequently, WBS has become the most common objective method for evaluating beef tenderness (Boleman et al., 1997; Miller et al., 1995).

Previous reports indicate TPA and WBS have similar capabilities to predict sensory assessment of tenderness and subjective characteristics of beef, however there is limited information comparing these two instrumental methods under similar test conditions. Therefore, the present study was undertaken to correlate TPA parameters obtained using a star-shaped compression probe and WBS with trained-panel ratings of the sensory characteristics of cooked rib steaks.

2. Materials and methods

2.1. Preparation of rib steaks

Three adjacent 25 mm steaks were cut from the left *longissimus thoracis* (LT) of 52 Canada 1 yield grade beef carcasses (Agriculture and Agri-Food Canada, 1992). The steaks were collected 24 h post-mortem from the carcasses of steers that had been slaughtered and dressed in the normal commercial manner at the Lacombe Research Centre abattoir in accordance with the principals and guidelines established by the Canadian Council on Animal Care (1993). Steaks were vacuum-packaged, placed in a cooler (2 °C, wind velocity of 0.5 m/s) to age for 14 days and, thereafter, frozen separately on stainless steel trays at −25 °C. The three steaks cut from each LT muscle were assigned on a random basis to one of the measurement techniques (TPA, WBS or sensory panel).

2.2. Texture profile analysis

Steaks were removed from the freezer and placed in a cooler (2 °C) to thaw for approximately 24 h. Once thawed, a thermocouple (10 cm spear point, T-type) was inserted horizontally at the midpoint of the steak's width to the center of the steak. The thermocouple was then attached to a Data Logger (Model HP34970A, Hewlett Packard Co., Boise, ID) and the steak was placed on a grill (Model # ED30B, Condon Barr Food Equipment Ltd. 1959, Edmonton, AB; with a surface temperature of 210 °C) and cooked on one side to an internal temperature of 40 °C then turned and cooked to a final internal temperature of 72 °C. After cooking, steaks were placed in a polyethylene bag and immediately immersed in an ice bath to arrest further cooking and then stored overnight in a cooler (2 °C) as previously described by Janz, Aalhus, Price, and Schaefer (2000). The following day, samples for TPA were obtained by laying the steaks flat and scoring them perpendicular to their longitudinal axis with a knife at 25 mm intervals beginning at the end proximal to the backbone. Four strips were then cut using the scoring marks as a guideline. The first strip was discarded and the next three were used for TPA.

Each strip was immobilized between specially constructed stainless steel plates with the cut surface oriented so a star-shaped, cherry-pitter probe (Instron Model 2830-005, Instron Canada, Burlington, ON) would penetrate the strip perpendicular to the muscle fibre orientation. Each sample underwent two cycles of 80% compression (relative to sample width, 200 mm/min crosshead speed) using the above probe fitted to an Instron Materials Testing Machine (Model 4301, 100 kg load cell, Series 12 Cyclic Testing software, Instron Canada, Burlington, ON). Two separate TPA were done per strip for a total of six measurements per steak. Force-by-time data from each test were used to calculate mean values for the TPA parameters of each steak. A typical force-by-time curve plot for calculation of TPA values is presented in Fig. 1. Values for hardness (peak force of the first compression cycle in kg), cohesiveness (ratio of the positive force area during the second compression to that during the first compression or Area 2/Area 1), springiness (ratio of the time duration of force input during the second compression to that during the first compression or Length 2/Length 1), resilience (ratio of the negative force input to positive force input during the first compression or Area 5/Area 4), adhesiveness (negative area under the baseline between the compression cycles or Area 3) and chewiness (hardness multiplied by cohesiveness multiplied by springiness in kg) were determined as described by Bourne (1978).

2.3. Warner-Bratzler shear force

For determination of WBS values, steaks ($n=52$) were thawed, cooked and stored overnight as previously described for TPA. The following day, six 19 mm diameter round cores were obtained from each steak as described by Janz et al. (2000) in similar locations to the TPA compression sites. The steak cores were collected parallel to the muscle fibres, using a hand-held steel cork borer. The steak cores were sheared perpendicular to the fibres using the same Instron 4301 (100 kg load cell, 200 mm/min crosshead speed) used for TPA except equipped with a Warner-Bratzler head (Janz et al., 2000).

2.4. Sensory panel evaluations

Rib steaks used for sensory panel evaluations were cooked as previously described for TPA, removed from

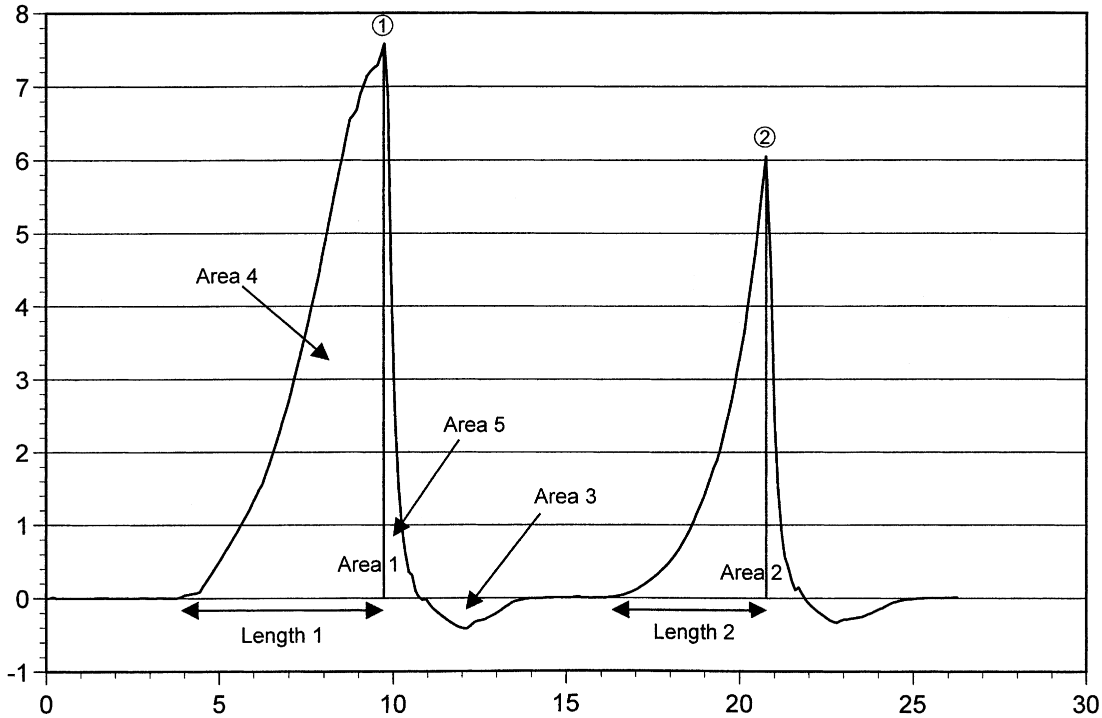

Fig. 1. Typical force-by-time plot through two cycles of penetration of a *longissimus thoracis* rib steak to determine texture profile analysis parameters. Peak force ① is hardness; cohesiveness = Area 2/Area 1; springiness = Length 2/Length 1; resilience = (Area 1−Area 2)/2; chewiness = hardness×cohesiveness×springiness; adhesion = Area 3.

the grill and immediately sub-sampled by cutting 1.9×1.9×1.9 cm cubes, taking care to avoid large pieces of fat or connective tissue. Cubes were then placed in covered glass containers in a circulating water bath (70 °C) for temperature equilibration prior to being served to a six-member sensory panel. Members of the sensory panel were selected and trained according to the guidelines of the American Meat Science Association and National Livestock and Meat Board (1995). Distilled water and unsalted soda crackers were provided to purge the palate of residual flavor notes between samples. All panel evaluations were conducted in well-ventilated, partitioned booths with 882 *lx* of incandescent and fluorescent light. Cubes were evaluated for initial and overall tenderness, amount of perceptible connective tissue, juiciness and flavour intensity using nine-point descriptive scales, as follows: 9 = extremely tender, no perceptible connective tissue, extremely juicy and intense beef flavour; 1 = extremely tough, abundant connective tissue, extremely dry and bland beef flavour. In addition, a nine-point hedonic scale (9 = extremely desirable, 1 = extremely undesirable) was used to evaluate flavour desirability and overall palatability.

2.5. Statistical analysis

Mean, minimum and maximum values and standard deviations of the descriptive variables were calculated using the MEANS procedure of the Statistical Analysis System Institute, Version 6.12 (SAS, 1996). Pearson correlation coefficients were generated to describe the relationship between TPA parameters, WBS values and sensory characteristics using the CORR procedure (SAS, 1996). Prediction equations were developed using the REG procedure (SAS, 1996). Dependent variables included sensory panel characteristics of initial tenderness, juiciness, flavour desirability, flavour intensity, amount of perceivable connective tissue, overall tenderness and overall palatability and TPA parameters of hardness, cohesiveness, springiness, chewiness, resilience and adhesiveness. Warner-Bratzler shear force was the independent variable. Regression diagnostics included coefficients of determination (R^2), significance levels for models used to develop the prediction equations (*P* value), root mean square errors (RMSE) and standard errors of the estimates for regression β coefficients. Similarly, prediction equations were developed with the aforementioned sensory panel characteristics as the dependent variable and TPA parameters as independent variables using the STEPWISE procedure (SAS, 1996). All possible combinations of the independent variables, which had a significant *F* statistic at the 0.15 entry level were sequentially added or deleted from the models until maximum R^2 values were obtained for the prediction equations. Diagnostics included significance level for the models (*P* value), Mallows *Cp* statistic for selection of the models, standard errors of the estimates for regression β coefficients and partial and overall coefficients of determination.

3. Results

3.1. Textural and sensory characteristics of rib steaks

Of all the variables measured, WBS had the highest coefficient of variation (27.5%). For TPA parameters, adhesiveness (26.3%) and chewiness (20.7%) had the highest coefficient of variation while springiness (4.3%) and cohesiveness (7.3%) had the lowest coefficient of variation (Table 1). For subjective sensory characteristics the coefficient of variation ranged from 7.0% for flavour intensity to 19.0% for initial tenderness.

In addition to the TPA parameters reported in Table 1, further information may be obtained by analysis of the force-by-time deformation curves (Fig. 1). The asymmetric shape and similar initial slope of both of the compression curves indicate steaks had a firm elastic quality (quickly returning to its original shape after probe withdrawal). This finding is in agreement with the low resilience and intermediate cohesiveness and springiness values.

Table 1
Descriptive statistics ($n = 52$) for Warner-Bratzler shear force, texture profile analysis parameters and trained-panelist sensory characteristics of rib steaks

Item	Mean	Minimum	Maximum	SD
Warner-Bratzler shear force (kg)	7.74	3.13	11.94	2.13
Texture profile analysis parameters				
Hardness (kg)	6.04	4.09	8.42	0.99
Cohesiveness	0.41	0.35	0.45	0.03
Springiness	0.70	0.61	0.77	0.03
Chewiness (kg)	1.74	1.01	2.51	0.36
Resilience	0.09	0.07	0.13	0.01
Adhesiveness (kg × s)	−1.48	−3.28	−0.80	0.39
Sensory characteristics[a]				
Initial tenderness	5.01	3.30	6.70	0.95
Juiciness	5.99	4.00	7.20	0.63
Flavour desirability[b]	5.81	4.70	7.00	0.54
Flavour intensity	5.82	5.00	6.50	0.41
Connective tissue	5.59	4.00	7.00	0.67
Overall tenderness	5.18	3.20	7.00	0.98
Overall palatability[b]	5.28	3.80	6.80	0.75

[a] Values for initial and overall tenderness, amount of perceptible connective tissue, juiciness and flavour intensity were based on a descriptive scale, as follows: 9 = extremely tender, no perceptible connective tissue, extremely juicy and intense beef flavour; 1 = extremely tough, abundant connective tissue, extremely dry and bland beef flavour.

[b] Values for flavour desirability and overall palatability were based on a hedonic scale, as follows: 9 = extremely desirable; 1 = extremely undesirable.

3.2. Relationship among textural and sensory properties

For initial tenderness, amount of perceptible connective tissue, overall tenderness and overall palatability, there was an inverse relationship ($P < 0.05$) with TPA parameters of hardness, cohesiveness and chewiness (Table 2). Hardness and chewiness had the highest negative correlations values, which were also similar in magnitude for the aforementioned sensory characteristics. However, chewiness was calculated using hardness as a factor, which suggests resistance to compression force was probably the main textural property determining tenderness characteristics. Similarly, WBS had a negative correlation with initial tenderness (−0.61), amount of perceptible connective tissue (−0.49), overall tenderness (−0.60) and overall palatability (−0.56). These results were in agreement with a positive relationship between WBS and the TPA characteristics of hardness (0.35) and chewiness (0.36), indicating both instrumental methods were probably measuring similar textural properties. In contrast, none of the TPA parameters or WBS had significant ($P > 0.05$) correlations with juiciness, flavour desirability or flavour intensity. There were tendencies for springiness ($P = 0.06$) and resilience ($P = 0.09$) to be

Table 2
Correlation coefficients (P values) for Warner-Bratzler shear force (WBS) and texture profile analysis parameters applied to trained-panelist sensory characteristics of rib steaks

	WBS	Texture profile analysis parameters					
		Hardness	Cohesiveness	Springiness	Chewiness	Resilience	Adhesiveness
WBS	–	0.35 (0.01)	0.36 (0.01)	−0.07 (0.62)	0.36 (0.009)	0.14 (0.33)	0.18 (0.20)
Initial tenderness	−0.61 (0.0001)	−0.64 (0.0001)	−0.41 (0.003)	0.11 (0.46)	−0.62 (0.0001)	−0.01 (0.93)	−0.04 (0.77)
Juiciness	−0.13 (0.34)	−0.13 (0.36)	0.08 (0.57)	0.05 (0.73)	−0.08 (0.57)	0.24 (0.09)	0.05 (0.74)
Flavour desirability	−0.22 (0.11)	−0.17 (0.22)	−0.05 (0.73)	0.17 (0.22)	−0.11 (0.44)	0.23 (0.10)	−0.20 (0.16)
Flavour intensity	−0.22 (0.12)	−0.02 (0.89)	−0.16 (0.25)	0.26 (0.06)	−0.01 (0.97)	−0.09 (0.50)	−0.21 (0.13)
Connective tissue	−0.49 (0.0002)	−0.57 (0.0001)	−0.27 (0.06)	0.01 (0.96)	−0.55 (0.0001)	−0.03 (0.83)	−0.00 (0.99)
Overall tenderness	−0.60 (0.0001)	−0.68 (0.0001)	−0.39 (0.005)	0.12 (0.38)	−0.64 (0.0001)	−0.00 (0.99)	−0.01 (0.94)
Overall palatability	−0.56 (0.0001)	−0.56 (0.0001)	−0.37 (0.007)	0.14 (0.31)	−0.53 (0.0001)	0.06 (0.68)	−0.07 (0.60)

positively correlated to flavour intensity and juiciness, respectively.

3.3. Step-wise regression analysis of sensory characteristics

Step-wise regression analysis, which included the TPA parameters of hardness and adhesiveness, explained 46.6, 36.1, 50.8 and 37.6% of the variation in initial tenderness, amount of perceptible connective tissue, overall tenderness and overall palatability, respectively (Table 3). Prediction equations using WBS explained a corresponding 36.8, 23.8, 36.2 and 31.3% of the variation in initial tenderness, amount of perceptible connective tissue, overall tenderness and overall palatability, respectively.

Hardness was the singular most important TPA parameter accounting for 40.6, 32.7, 45.7 and 31.1% of the variation in initial tenderness, amount of perceptible connective tissue, overall tenderness and overall palatability, respectively (Table 4). Corresponding variation explained by adhesiveness was only 6.1, 3.4, 5.1 and 6.5%. Surprisingly, none of the other TPA parameters, notably cohesiveness and chewiness, reached the 0.15 significance level required to be included in the step-wise regression models applied to the sensory characteristics associated with textural properties. On the other hand, resilience accounted for 5.8 and 5.3% of the variation in juiciness ($P=0.09$) and flavour desirability ($P=0.10$) of the steaks, respectively. Similarly, springiness accounted for 6.9% of the variation in flavour intensity ($P=0.06$).

4. Discussion

Consistent measurement of tenderness and other qualities of beef, traditionally determined by sensory panel evaluation, is complicated by the interaction of physical and sensory processes during mastication (Jeremiah, 1982). Sensory evaluations are labour intensive, time consuming and expensive. Given the current emphasis in the retail industry on providing beef products of consistent quality to consumers, a strong impetus exists to develop objective non-invasive instrumental methods, which reliably estimate tenderness and sensory characteristics of meat. Results from the present experiment indicate TPA explained slightly more of the variation in sensory panel characteristics of beef

Table 3
Regression equations using Warner-Bratzler shear force (WBS) and stepwise regression equations using texture profile analysis (TPA) parameters to predict trained-panelist sensory characteristics of rib steaks

Prediction equations[a]	RMSE/*Cp*[b]	R^2	*P* value
Regression using Warner-Bratzler shear force			
IT = 7.10 (0.40)–0.27 (0.05)×WBS	0.76	0.368	0.0001
JU = 6.29 (0.33)–0.04 (0.04)×WBS	0.63	0.018	0.34
FD = 6.25 (0.28)–0.06 (0.03)×WBS	0.53	0.050	0.11
FI = 6.15 (0.21)–0.04 (0.03)×WBS	0.41	0.048	0.12
CT = 6.77 (0.31)–0.15 (0.04)×WBS	0.59	0.238	0.0002
OT = 7.31 (0.42)–0.28 (0.05)×WBS	0.79	0.362	0.0001
OP = 6.79 (0.33)–0.20 (0.04)×WBS	0.63	0.313	0.0001
HA = 4.80 (0.49) + 0.16 (0.06)×WBS	0.94	0.120	0.01
CO = 0.37 (0.01) + 0.004 (0.002)×WBS	0.02	0.126	0.01
SP = 0.71 (0.02)–0.001 (0.002)×WBS	0.03	0.005	0.62
CH = 1.28 (0.18) + 0.06 (0.02)×WBS	0.33	0.129	0.009
RE = 0.09 (0.01) + 0.001 (0.001)×WBS	0.01	0.019	0.33
AD = -1.74 (0.20) + 0.03 (0.03)×WBS	0.38	0.033	0.20
Stepwise regression using TPA parameters			
IT = 8.21 (0.65)–0.68 (0.10)×HA–0.63 (0.27)×AD	0.71	0.466	0.0001
JU = 4.84 (0.66) + 12.09 (6.92)×RE	−1.63	0.058	0.09
FD = 4.87 (0.57) + 9.92 (5.96)×RE	3.42	0.053	0.10
FI = 3.56 (1.18) + 3.24 (1.69)×SP	−1.56	0.069	0.06
CT = 7.66 (0.50)–0.42 (0.08)×HA–0.33 (0.21)×AD	−0.34	0.361	0.0001
OT = 8.74 (0.64)–0.74 (0.10)×HA–0.60 (0.27)×AD	0.91	0.507	0.0001
OP = 7.42 (0.55)–0.48 (0.09)×HA–0.52 (0.23)×AD	1.54	0.376	0.0001

[a] Abbreviations used in the prediction equations were, as follows: IT = initial tenderness, JU = juiciness, FD = flavour desirability, FI = flavour intensity, CT = perceptible connective tissue, OT = overall tenderness, OP = overall palatability, HA = hardness, CO = cohesiveness, SP = springiness, CH = chewiness, RE = resilience and AD = adhesiveness. Values in parenthesis are standard error of the estimate for the corresponding regression coefficients.

[b] Root mean square error and Mallows *Cp* statistic reported for regression equations using WBS and stepwise regression equations using TPA parameters, respectively.

Table 4
Partial R^2 coefficients of determination (P value) from step-wise regression analysis using texture profile analysis parameters to predict trained-panelist sensory characteristics of rib steaks

	Texture profile analysis parameters					
	Hardness	Cohesiveness	Springiness	Chewiness	Resilience	Adhesiveness
Initial tenderness	0.406 (0.0001)	NS[a]	NS	NS	NS	0.061 (0.022)
Juiciness	NS	NS	NS	NS	0.058 (0.087)	NS
Flavour desirability	NS	NS	NS	NS	0.053 (0.102)	NS
Flavour intensity	NS	NS	0.069 (0.060)	NS	NS	NS
Connective tissue	0.327(0.0001)	NS	NS	NS	NS	0.034 (0.115)
Overall tenderness	0.457(0.0001)	NS	NS	NS	NS	0.051 (0.029)
Overall palatability	0.311(0.0001)	NS	NS	NS	NS	0.065 (0.028)

[a] Texture profile analysis parameters, which did not meet the 0.15 significance level for entry into the stepwise regression equations.

tenderness than WBS. However, objective methods used in this study do not fully explain subjective measures. Variation among sensory panel members is inherent to subjective assessment of meat characteristics (Pearson, 1963). Therefore, it may not be possible, on a consistent basis, to explain more of the variation in beef tenderness than has been previously reported. Variation between sensory evaluations of beef tenderness and corresponding objective measurements from TPA (Rhodes et al., 1972) and WBS (Shackelford et al., 1999) may be reduced if instrumental measurements are determined on warm beef, immediately after cooking. However, objective measurements are usually determined on meat samples at room temperature (20 °C), in order to evaluate all samples at similar temperature and to improve the ease of core preparation.

In the present study, step-wise regression analysis of TPA parameters indicate hardness and adhesiveness can be useful in explaining a significant proportion of variation in tenderness of rib steaks . As expected, juiciness, flavour desirability and flavour intensity are not well correlated with TPA parameters. Step-wise regression analysis included the TPA parameters of springiness and resilience in models to predict juiciness, flavour desirability and flavour intensity, but only explained minor variations. It could be speculated that springiness and resilience might be highly related to intramuscular fat content, which, in turn, is a determining factor in juiciness and flavour desirability. Jeremiah, Aalhus, Robertson, and Gibson (1996) reported higher panel scores for juiciness and flavour intensity of *longissimus thoracis* steaks with higher contents of intramuscular fat. Hardness, springiness and cohesiveness of beef patties has also been reported to decrease ($P < 0.05$) as fat content increases from 5 to 30% (Trout et al., 1992). Subsequent studies to investigate the relationship between objective TPA parameters such as springiness, resilience, juiciness and flavour desirability for beef cuts known to differ in these qualities are warranted.

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References

Agriculture and Agri-Food Canada. (1992). *Livestock and poultry carcass grading regulations*. Ottawa, ON: Agriculture and Agri-Food Canada, Canadian Food Inspection Agency.

American Meat Science Association and National Livestock and Meat Board. (1995). *Research guidelines for cookery, sensory evaluation and instrumental tenderness measurements of fresh meat*. National Livestock and Meat Board, Chicago, IL: American Meat Science Association.

Boleman, S. J., Boleman, S. L., Miller, R. K., Taylor, J. F., Cross, H. R., Wheeler, T. L., Koohmaraie, M., Shackelford, S. D., Miller, M. F., West, R. L., Johnson, D. D., & Savell, J. W. (1997). Consumer evaluation of beef of known categories of tenderness. *Journal of Animal Science*, *75*, 1521–1524.

Bourne, M. C. (1978). Texture profile analysis. *Food Technology*, *33*, 62–66.

Bouton, P. E., & Harris, P. V. (1972). A comparison of some objective methods used to assess meat tenderness. *Journal of Food Science*, *37*, 218–221.

Canadian Council on Animal Care. (1993). *Guide to the care and use of experimental animals, vol. 1* (2nd ed.). Ottawa, ON: CCAC.

Janz, J. A. M., Aalhus, J. L., Price, M. A., & Schaefer, A. L. (2000). The influence of elevated temperature conditioning on bison (*Bison bison bison*) meat quality. *Meat Science*, *56*, 279–284.

Jeremiah, L. E. (1982). A review of factors influencing consumption, selection and acceptability of meat purchases. *Journal of Consumer Studies and Home Economics*, *6*, 137–154.

Jeremiah, L. E., Aalhus, J. L., Robertson, W. M., & Gibson, L. L. (1996). The effects of grade, gender and postmortem treatment on beef. II. Cooking properties and palatability attributes. *Canadian Journal of Animal Science*, *77*, 41–54.

Miller, M. F., Hoover, L. C., Cook, K. D., Guerra, A. L., Huffman, K. L., Tinney, K. S., Ramsey, C. B., Brittin, H. C., & Huffman, L. M. (1995). Consumer acceptability of beef steak tenderness in the home and restaurant. *Journal of Food Science*, *60*, 963–965.

Pearson, A. M. (1963). Objective and subjective measurements for meat tenderness. In *Proceedings Meat Tenderness Symposium* (pp. 135–158). New Jersey: Campbell Soup Co.

Penfield, M. A., & Campbell, A. M. (1990). Evaluating food by objective methods. In *Experimental Food Science* (3rd ed., pp. 23–50). San Diego, CA: Academic Press.

Rhodes, D. N., Jones, R. C. D., Chrystall, B. B., & Harries, J. M. (1972). Meat texture. 2. The relationship between subjective assessments and a compressive test on roast beef. *Journal of Texture Studies*, *3*, 298–309.

Shackelford, S. D., Wheeler, T. L., & Koohmaraie, M. (1995). Relationship between shear force and trained sensory panel tenderness ratings of 10 major muscles from *Bos indicus* and *Bos taurus* cattle. *Journal of Animal Science*, *73*, 3333–3340.

Shackelford, S. D., Wheeler, T. L., & Koohmaraie, M. (1997). Tenderness classification of beef: I. Evaluation of beef longissimus shear forces at 1 or 2 days postmortem as a predictor of aged beef tenderness. *Journal of Animal Science*, *75*, 2417–2422.

Shackelford, S. D., Wheeler, T. L., & Koohmaraie, M. (1999). Evaluation of slice shear force as an objective method of assessing beef longissimus tenderness. *Journal of Animal Science*, *77*, 2693–2699.

Statistical Analysis System Institute. (1996). *SAS user's guide: basics statistical analysis*. Cary, NC: SAS Institute.

Szczesniak, A. S. (1968). Correlations between objective and sensory texture measurements. *Food Technology*, *22*, 981–986.

Szczesniak, A. S., & Torgeson, K. W. (1965). Methods of meat texture measurement viewed from the background of factors affecting tenderness. In C. O. Chichester, E. M. Mrak, & G. F. Stewart (Eds.), *Advances in food research* (pp. 33–165). New York: Academic Press.

Trout, E. S., Hunt, M. C., Johnson, D. E., Claus, J. R., Kastner, C. I., Kropf, D. H., & Stroda, S. (1992). Chemical, physical and sensory characterization of ground beef containing 5 to 30 percent fat. *Journal of Food Science*, *57*(1), 25–29.