A Comparison of Warner-Bratzler Shear Force Assessment Within and Among Institutions[1,2]

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ABSTRACT: Our objective was to compare measurement of Warner-Bratzler shear force of beef longissimus within and among institutions when each institution used its own protocol and when all institutions used a standardized protocol. In Exp. 1, each of five institutions (A, B, C, D, and E) received two adjacent steaks from each of 27 beef strip loins (longissimus lumborum). Warner-Bratzler shear force was measured for both steaks using the procedures normally used at each institution. In Exp. 2, each institution received two adjacent steaks from each of 45 strip loins. Shear force was measured for both steaks using a standardized protocol. In Exp. 1, Warner-Bratzler shear force was highest ($P < .05$) for A (4.7 kg) and lowest ($P < .05$) for B (2.9 kg). Repeatability of shear force was highest for A and C (.73 and .72), intermediate for D (.63), and lowest for B and E (.39 and .44). In Exp. 2, Warner-Bratzler shear force was highest ($P < .05$) for A (5.1 kg) and lowest ($P < .05$) for E (3.7 kg). Repeatability of shear force was highest for A (.87), intermediate for B, D, and E (.81, .75, and .80), and lowest for C (.67). Shear force values differed within and among institutions due to protocol, execution of the protocol, and instrument variation. Thus, comparisons of Warner-Bratzler shear force data among institutions are currently not valid. However, it is possible for institutions to obtain the same mean shear force value and have high repeatability if a standard protocol is properly executed with calibrated equipment.

Key Words: Accuracy, Beef, Methodology, Repeatability, Shear Strength, Tenderness

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Introduction

Numerous attempts have been made to develop an accurate instrument for the measurement of meat tenderness (Pearson, 1963; Szczesniak and Torgeson, 1965; Bouton and Harris, 1972; Culioli, 1995). However, Warner-Bratzler shear force (Warner, 1928, 1952; Bratzler, 1932, 1949, 1954) has remained the most popular (Culioli, 1995) and accurate (Szczesniak and Torgeson, 1965) instrumental measure of meat tenderness, despite its critics (Hurwicz and Tischer, 1954; Voisey, 1976; Culioli, 1995).

Wheeler et al. (1994, 1996) demonstrated that differences in protocol could result in spurious variation in Warner-Bratzler shear force values. Differences in mean shear force values reported in the literature by various institutions raise the question of how much of that variation in shear force is attributable to institutional effects. Nonetheless, it has been possible to detect treatment differences in tenderness in most experiments with these measurements because any errors in procedure or its execution were averaged across replications within treatment. However, when the objective is to measure or predict tenderness of meat from an individual animal, the opportunity to average errors no longer exists. In addition, recent interest from the seedstock segment of the beef industry in obtaining genetic information on tenderness via Warner-Bratzler shear force requires that various institutions collecting these data have comparable shear force values (NCA, 1994). The objective of this study was to compare the repeatability and mean values for Warner-Bratzler shear force

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[2]Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval of the product to the exclusion of others that may also be suitable.

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within and among institutions when each institution used its own protocol and when all institutions used a standardized protocol.

Materials and Methods

Institution Variation (Experiment 1)

Samples. Twenty-seven steers, either 1/2 Piedmontese or 1/2 *Bos indicus* (all 1/2 British) were slaughtered humanely and dressed using typical procedures. Carcasses were chilled at 0°C for 24 h, then boneless strip loins (longissimus lumborum) were removed, vacuum-packaged, and aged 7 to 14 d at 2°C. These samples were obtained from USDA-ARS, Roman L. Hruska U.S. Meat Animal Research Center (**MARC**) and used in order to provide a large range in tenderness. Each strip loin was frozen at –30°C then cut into 12 2.54-cm-thick steaks on a band saw. Each of five institutions received two adjacent, frozen steaks from each strip loin with location within each strip loin alternated from animal to animal for each institution to remove potential location effect.

Protocol. Personnel at each of five institutions (MARC, Texas Tech Univ., Texas A&M Univ., Colorado State Univ., and Univ. of Georgia) were instructed to collect Warner-Bratzler shear force on the longissimus lumborum from each steak according to the procedures normally used at their respective institutions. All steaks were weighed and placed in unsealed plastic bags for thawing. Cooking loss was calculated with cooked weight the numerator and frozen weight the denominator.

Standard Warner-Bratzler shear force involves measurement of cooked meat tenderness using a Warner-Bratzler shear machine or a testing machine equipped with a Warner-Bratzler attachment that adheres to the following specifications: 1) shearing blade thickness of 1.016 mm, 2) a vee-shaped cutting blade with a 60° angle, 3) the cutting edge beveled to a half-round, 4) the corner of the vee should be rounded to a quarter-round of a 2.363-mm-diameter circle, 5) the spacers providing the gap for the cutting blade to slide through should be 1.245 mm thick, 6) the cooked meat samples should be round cores 1.27 cm in diameter removed parallel to the longitudinal orientation of the muscle fibers, and 7) the cores should be sheared once at the center, perpendicular to the fibers, to avoid hardening that occurs toward the surface of the cooked sample (Bratzler, 1932, 1949; AMSA, 1995; Wheeler et al., 1995; Tennison Collins, personal communication, G-R Electric, Manhattan, KS). Shear tests conducted with modifications to these specifications (e.g., square holes in the blade, square meat samples, straight cutting blade, or blade edge not beveled) should not be referred to as Warner-Bratzler shear force.

Institution A followed these procedures: 1) thawed steaks at 4°C for 24 h; 2) monitored temperature during cooking with an iron/constantan thermocouple wire (Omega Engineering, Stamford, CT) inserted into the geometric center of the steak; 3) cooked steaks on a Farberware Open-Hearth electric broiler (Kidde, Bronx, NY) until they reached an internal temperature of 40°C, turned steaks and cooked until an internal temperature of 70°C was reached, then removed steaks from broiler; 4) placed steaks in a plastic bag and cooled overnight at 4°C; 5) removed (by hand) six 1.27-cm-diameter cores parallel to the longitudinal orientation of the muscle fibers; and 6) sheared each core once at its center, perpendicular to the muscle fiber orientation with a Warner-Bratzler shear attachment to the Instron Universal Testing Machine model 1132 (Instron, Canton, MA) using a crosshead speed of 50 mm/min.

Institution B followed these procedures: 1) thawed all steaks at 2 to 5°C for 18 to 24 h; 2) monitored temperature with thermocouple wires inserted into the geometric center of the steak and several other locations; 3) cooked steaks on a Farberware Open-Hearth electric broiler until they reached an internal temperature of 35°C, turned steaks and cooked until an internal temperature of 68°C was reached, then removed steaks from the broiler (multiple locations were probed to determine the final end point temperature); 4) placed cooked steaks on a tray, covered with clear PVC wrap, and chilled 18 to 24 h at 5°C; 5) removed (by hand) 8 to 15 (depending on the size of the steak) 1.27-cm-diameter cores parallel to the longitudinal orientation of the muscle fibers; and 6) after all cores had been taken, sheared each core once at the center on a Warner-Bratzler shear machine (G-R Electric Manufacturing Co., Manhattan, KS).

Institution C followed these procedures: 1) thawed steaks at approximately 4°C for 24 h; 2) monitored temperature during cooking with copper/constantan thermocouple wire inserted into the geometric center of the steak and attached to a hand-held Omega temperature recorder; 3) cooked steaks on a Farberware Open-Hearth electric broiler until they reached an internal temperature of 35°C, turned steaks and cooked until an internal temperature of 70°C was reached, then removed steaks from broiler; 4) placed cooked steaks on non-absorbent wax-coated paper to cool to room temperature (minimum of 4 h, not more than 8 h); 5) removed (with a motorized drill) as many 1.27-cm-diameter cores as possible (leaving a thin line of cooked steak between core locations) parallel to the longitudinal orientation of the muscle fibers; and 6) sheared each core once at its center using a Warner-Bratzler shear machine.

Institution D followed these procedures: 1) thawed steaks at 2°C for 48 h; 2) monitored temperature with a digital thermometer (Hantover, Model TM99A-H) inserted into the geometric center of the steak; 3) cooked steaks on a Farberware Open-Hearth electric broiler until they reached an internal temperature of ~45°C, turned steaks and cooked until an internal temperature of 70°C was reached, then removed steaks from broiler (if cooking time was excessive and crust was forming, steak was turned again); 4) cooled steaks at 25°C for at least 4 h; 5) removed as many 1.27-cm-diameter cores as possible (by hand with a brass corer) parallel to the longitudinal orientation of the muscle fibers; and 6) sheared the six most uniform cores (that were free of fat and connective tissue) once at the center, perpendicular to the muscle fiber alignment with a Warner-Bratzler shear machine.

Institution E followed these procedures: 1) thawed steaks at 2°C for 24 h; 2) monitored steak temperature with a thermometer (Atkins K thermocouple thermometer) inserted into the approximate center of the steak before cooking, 10 min after initiation of cooking, and as cooking end point approached; 3) cooked steaks on a Farberware Open-Hearth electric broiler until they reached an internal temperature of 35°C, turned steaks and cooked until an internal temperature of 68 ± 3°C was reached, then removed steaks from broiler; 4) cooled steaks to room temperature for 2 h; 5) removed (by hand) six 1.27-cm-diameter cores parallel to the orientation of the muscle fibers; and 6) sheared each core twice with a Warner-Bratzler shear machine. All institutions removed cores so as to represent the entire longissimus.

Institution Variation (Experiment 2)

Samples. One hundred thirty-four steers from MARC were slaughtered humanely and dressed using typical procedures. Carcasses were chilled at 0°C for 24 h, then boneless strip loins (longissimus lumborum) were removed, vacuum-packaged, and aged 7 to 14 d at 2°C. Forty-five of these strip loins were selected for this experiment based on longissimus thoracis shear force at 7 and 14 d postmortem obtained at MARC from the right carcass side. These 45 samples came from right carcass sides of 7 British crossbred, 31 *Bos indicus* × British crossbred, 6 Belgian Blue × British crossbred, and 3 Tuli × British crossbred steers. The 45 strip loins included 15 each with low, intermediate, and high shear force to ensure variation in tenderness. Each strip loin was frozen at –30°C then cut into 12 2.54-cm-thick steaks on a band saw. Each institution received two adjacent, frozen steaks from each strip loin with location alternated to remove potential location effect.

Instructions. This experiment was conducted to determine whether institutional differences in mean and repeatability of longissimus lumborum shear force could be decreased by providing a standardized protocol to follow when collecting shear force data. The following protocol was provided: 1) thaw all steaks at 2 to 5°C and cook after an internal temperature of 2 to 5°C is attained; 2) monitor temperature with thermocouple wire inserted into the geometric center of the steak; 3) cook steaks on a Farberware Open-Hearth electric broiler until they reach an internal temperature of 40°C, turn steaks and cook until an internal temperature of 70°C is reached, then remove from the broiler; 4) cool steaks overnight at 2 to 5°C; 5) remove six 1.27-cm-diameter cores (representing the entire longissimus cross-section) parallel to the longitudinal orientation of the muscle fibers; and 6) shear each core once at its center, perpendicular to the muscle fiber orientation to obtain Warner-Bratzler shear force.

Historical Data

Institution A has, in addition to the above experiments, duplicate measurements of Warner-Bratzler shear force and trained sensory tenderness rating measurements collected over a period of 10 yr that were used to calculate the repeatability of longissimus shear force and tenderness rating. Warner-Bratzler shear force measurements were collected according to the protocol described above for Institution A in Exp. 1. These data came from numerous experiments involving various breeds and aging times. The shear force data were presented in three formats: 1) complete data set, 2) data edited by deleting extremes and randomly deleting observations to provide a range and SD for shear force similar to that for Institution A in Exp. 1, and 3) data edited as described above to provide a range and SD for shear force similar to that for Institution A in Exp. 2. Sensory tenderness ratings were obtained from an eight-member panel (with an average of 11 yr of experience and a range in experience from 6 to 14 yr) selected and trained according to Cross et al. (1978). Tenderness rating data were divided into two groups: 1) data collected before refresher training and 2) data collected after extensive refresher training. Refresher training consisted of evaluation and discussion (on 6 d over a 2-wk period) of samples representing the entire tenderness rating scale. Two steaks were used for each sensory evaluation sample to provide enough meat for each panelist to evaluate three cubes (1 cm × 1 cm × steak thickness) per sample. The duplicate tenderness rating measurements were obtained from paired samples that were served, one in each of the two daily sessions. Thus, one set of duplicate measurements was obtained on every panel day for monitoring panel performance.

Instrument Variation (Experiment 3)

This experiment was conducted to determine whether any of the among-institution variation in Warner-Bratzler shear force could be attributed to differences among instruments. Ten British crossbred steers (14 to 16 mo of age) were slaughtered humanely and dressed conventionally. Carcasses were chilled at 0°C for 24 h then boneless strip loins (longissimus lumborum) were obtained, vacuum-packaged, and aged at 2°C for 14 d. Five longissimus lumborum steaks from each strip loin were all cooked by Institution A as described in Exp. 1. The steaks were chilled at 4°C overnight, then one steak from each animal was shipped on ice to each of the three other institutions, one institution from Exp. 1 and 2 (E) and two new institutions (F, University of Nebraska and G, USDA-ARS, Meat Science Research Laboratory, Beltsville, MD). In addition, Institution A sheared cores from the fourth steak with a Warner-Bratzler attachment to an Instron Universal Testing Machine (Institution A) and cores from the fifth steak with a Warner-Bratzler shear machine (Institution A1). All institutions removed six 1.27-cm-diameter cores from each cooked longissimus lumborum steak parallel to the muscle fiber orientation. All steaks were cored and sheared on d 2 after cooking. Institution E sheared with a Warner-Bratzler shear machine as in Exp. 1 and 2. Institutions F and G sheared with a Warner-Bratzler attachment to an Instron Universal Testing Machine at 50 mm/min crosshead speed.

Crosshead Speed (Experiments 4 and 5)

These experiments were conducted by Institution A to determine the effects of crosshead speed and full scale load setting on the measurement of Warner-Bratzler shear force using an Instron Universal Testing Machine. Experiment 4 used 90 strip loin (longissimus lumborum) steaks (nine from each of 10 carcass sides) and Exp. 5 used 200 ribeye (longissimus thoracis) steaks (four steaks from the 8th to 9th ribs) from 50 carcasses. All carcasses were from 14- to 16-mo-old crossbred steers (dams were either Angus, Hereford, or MARC III; sires were either Angus, Hereford, Brahman, Boran, Tuli, or Belgian Blue). The steers were slaughtered humanely and dressed conventionally and the carcasses chilled 24 h at 0°C. The subprimals (strip loins and ribeye rolls) were aged 7 to 14 d at 2°C. Experiment 4 was conducted as a factorial arrangement of the main effects of crosshead speed (50, 100, 200, and 500 mm/min) and full scale load (10 and 20 kg) in a completely randomized design. In addition, one steak from each of the 10 sides was prepared and sheared with a Warner-Bratzler shear machine. Experiment 5 was conducted as a completely randomized design for the main effect of crosshead speed (50 or 200 mm/min). For Exp. 4 and 5, steaks were prepared for Warner-Bratzler shear force analysis as described for Institution A in Exp. 1.

Statistical Analysis

Data from Exp. 1, 2, and 3 were analyzed by ANOVA for repeated measures for a model including animal and institution effects in a completely randomized design (SAS, 1988). Mean separation was accomplished by Tukey's test (Steel and Torrie, 1980). Data from Exp. 4 were analyzed by ANOVA for the main effects of crosshead speed and full scale load and their interaction in a factorial arrangement of a completely randomized design. Data from Exp. 5 were analyzed by ANOVA for a model including animal and crosshead speed effects in a completely randomized design. Least squares means were calculated and mean separation was accomplished with the PDIFF option of the least squares procedure (a pairwise *t*-test). Repeatability of duplicate shear force measurements within institutions was determined from PROC VARCOMP option MIVQUEO (SAS, 1988) estimates of variance components (σ^2_{animal} and σ^2_{error}) such that repeatability = $\sigma^2_{animal}/(\sigma^2_{animal} + \sigma^2_{error})$.

Results and Discussion

Normal Protocol

Personnel at each institution were asked to evaluate duplicate steaks for shear force according to their usual procedures. Although personnel at all institutions intended to thaw steaks to between 2 and 5°C, mean initial internal temperatures ranged from 5.0 to 14.6°C, and the initial internal temperature of individual observations ranged from a low of –1.5°C to a high of 18.3°C (Table 1). Institution E had the lowest ($P < .05$) mean initial internal temperature, followed by Institution A, then Institutions C and D, and Institution B had the highest ($P < .05$) initial internal temperature. These data clearly indicate the need for greater control of thawing conditions and(or) greater control of the time steaks are at room temperature while thermocouples are inserted before cooking commences. Three institutions had no samples with an initial internal temperature that fell within the recommended (AMSA, 1995) and targeted range of 2 to 5°C. These initial internal temperature differences also indicate potential bias in shear force within and among institutions (Berry and Leddy, 1990; Wheeler et al., 1996).

Mean cooking times did not differ greatly, although Institutions A and B had longer ($P < .05$) cooking times than the other institutions (Table 1). However, the range in cooking time within all institutions was large, particularly for Institution C. Cooking times were not consistent with initial internal temperature differences, even though all institutions cooked on Farberware electric broilers. These data indicate potential differences in heating temperatures and(or) uniformity of temperatures of different Farberware broilers. Berry and Dikeman (1994) reported that several institutions had high variability in temperatures among Farberware grills. Mean cooking losses were similar, but Institution C had lower ($P < .05$) mean cooking loss than all other institutions. The range in cooking losses was large and may be attributable to the cooking instruments.

Table 1. Effect of institution on least squares means, simple statistics, and repeatability of cooking traits and Warner-Bratzler shear force when institutions followed their normal procedures (Exp. 1)

Institution	n	Mean	SD	Minimum	Maximum	Repeatability
		Initial internal temperature,°C				
A	53	8.2[c]	2.2	.0	12.0	—
B	52	14.6[a]	3.0	7.0	18.0	—
C	52	10.9[b]	3.1	5.0	18.3	—
D	52	10.7[b]	2.5	6.7	16.5	—
E	52	5.0[d]	2.6	−1.5	9.1	—
SEM		.4				
		Cooking time, min				
A	53	25.0[a]	3.7	19.0	36.0	—
B	52	23.8[a]	4.8	15.0	33.0	—
C	47	21.4[b]	6.5	12.0	42.0	—
D	52	21.8[b]	3.5	16.0	28.0	—
E	52	20.7[b]	3.8	15.0	30.0	—
SEM		.6				
		Cooking loss, %				
A	53	24.3[a]	3.7	15.2	31.7	—
B	51	23.8[a]	5.1	11.9	33.9	—
C	44	21.4[b]	5.4	10.4	35.1	—
D	51	25.0[a]	3.4	18.2	36.4	—
E	51	25.4[a]	3.4	16.7	31.6	—
SEM		.8				
		Warner-Bratzler shear force, kg				
A	53	4.7[a]	1.1	2.6	7.6	.73
B	52	2.9[d]	.5	1.7	4.0	.39
C	52	3.2[c]	.8	2.0	5.4	.72
D	52	3.4[b]	.9	2.1	6.6	.63
E	52	3.4[bc]	.7	2.5	5.4	.44
SEM		.1				

[a,b,c,d]Within a given trait, means that do not share a common superscript letter differ ($P < .05$).

The amount of variation in mean shear force was less than for other traits and not unexpected based on previously published shear force data from these institutions. Institution A had the highest ($P < .05$) shear force and Institution B the lowest ($P < .05$) shear force (Table 1). However, four of the five institutions had mean shear force within .5 kg of one another; mean shear force for Institution A was 1.3 to 1.8 kg higher than means for other institutions. Repeatability of the duplicate shear force measurements was highest for Institutions A and C, intermediate for Institution D, and lowest for Institutions B and E. These data indicate a wide range in precision of collecting shear force data.

Although thawing protocol was not much different, the initial internal temperature was quite variable within and among institutions. Berry and Leddy (1990) and Wheeler et al. (1996) reported that higher initial internal temperature could result in lower shear force. Differences among institutions in protocol likely had some effect on shear force. The slightly lower end point temperature (68°C) used by Institutions B and E may have contributed to a slightly lower shear force than would have resulted if 70°C had been the end point. Institutions used one of two general approaches to cooling steaks before coring. Institutions A and B chilled steaks overnight at 4°C, whereas Institutions C, D, and E cooled steaks at room temperature for 2 to 8 h. However, it has been demonstrated that this difference in cooling would not affect shear force (Hedrick et al., 1968; Crouse and Koohmaraie, 1990; Wheeler et al., 1994). Institution A sheared cores with a Warner-Bratzler attachment to an Instron Universal Testing Machine at a crosshead speed of 50 mm/min, whereas all other institutions sheared cores with a Warner-Bratzler machine. This difference in shearing instruments should not affect shear force (Wheeler et al., 1994). However, data in Tables 4 and 5 contradict those results and will be discussed later. Institution E sheared each core twice rather than once, which has been shown to result in higher shear force values (Wheeler et al., 1996).

Standardized Protocol

All institutions were asked to evaluate duplicate steaks for Warner-Bratzler shear force according to a standardized protocol. Mean initial internal temperature was lowest ($P < .05$) for Institutions E and A, intermediate ($P < .05$) for Institutions D and C, and

Table 2. Effect of institution on least squares means, simple statistics, and repeatability of cooking traits and Warner-Bratzler shear force when all institutions were instructed to follow a standardized protocol (Exp. 2)

Institution	n	Mean	SD	Minimum	Maximum	Repeatability
		Initial internal temperature, °C				
A	89	4.0[c]	1.0	1.0	7.0	—
B	90	11.1[a]	.9	8.8	14.1	—
C	90	9.3[b]	3.9	2.4	17.1	—
D	90	8.7[b]	1.1	6.7	11.4	—
E	89	3.5[c]	1.1	2.0	5.4	—
SEM		.2				
		Cooking time, min				
A	89	29.5[a]	5.2	19.0	41.0	—
B	90	27.1[b]	3.0	21.0	35.0	—
C	90	24.3[c]	4.8	14.0	35.0	—
D	90	20.2[d]	3.8	14.0	33.0	—
E	89	29.4[a]	3.5	22.0	41.0	—
SEM		.4				
		Cooking loss, %				
A	89	26.9[b]	4.4	13.2	36.1	—
B	90	27.5[b]	3.4	19.2	38.8	—
C	90	24.3[c]	4.6	11.8	36.4	—
D	90	27.5[b]	3.4	18.3	34.0	—
E	89	30.3[a]	4.4	21.4	39.5	—
SEM		.4				
		Warner-Bratzler shear force, kg				
A	89	5.1[a]	1.7	2.6	10.7	.87
B	90	4.3[c]	1.2	2.1	7.1	.81
C	90	4.6[b]	1.5	2.2	10.7	.67
D	90	4.2[c]	1.3	2.0	7.7	.75
E	89	3.7[d]	1.5	1.7	8.3	.80
SEM		.1				

[a,b,c,d]Within a given trait, means that do not share a common superscript letter differ ($P < .05$).

highest ($P < .05$) for Institution B (Table 2). Consistency of initial internal temperature was greatly improved for Institutions A and E. They had almost all samples within the targeted range of initial internal temperature. However, Institution D had a mean initial internal temperature even further from the target than in Exp. 1. Institutions B and C had mean initial internal temperatures similar to those in Exp. 1 but even further from the target than Institution D in Exp. 2. Variation in initial internal temperature was much lower for Institution B but slightly higher for Institution C.

Mean cooking time was longest ($P < .05$) for Institutions A and E, followed by Institution B, then Institution C, and Institution D had the shortest ($P < .05$) cooking time (Table 2). As in Exp. 1, mean cooking times among institutions were not consistent with initial internal temperatures, but differences in cooking time between Exp. 1 and 2 were generally consistent with differences in initial internal temperature. All institutions, except Institution A, had the same or less variation in cooking time than in Exp. 1. Mean cooking loss was greatest ($P < .05$) for Institution E, intermediate for Institutions A, B, and D, and lowest ($P < .05$) for Institution C (Table 2). Cooking losses were higher for all institutions in Exp. 2 than in Exp. 1. Institution C had the lowest ($P < .05$) cooking loss in both experiments.

Means, SD, and maximum for shear force were slightly higher for all institutions in Exp. 2, indicating greater variability in tenderness in the experimental sample (Table 2). However, differences in mean shear force among institutions were smaller than in Exp. 1. Institution A still had the highest ($P < .05$) mean shear force, followed by Institution C, then Institutions B and D, and Institution E had the lowest ($P < .05$) mean shear force. The only remaining differences among institutions in protocols for Exp. 2 were the use of an Instron rather than a Warner-Bratzler shear machine by Institution A, although the accuracy with which the procedures were conducted could still vary. The institution with the highest SD for initial internal temperature also had the lowest shear force repeatability (Table 2).

Repeatability of duplicate shear force measurements was higher for four out of five institutions using the standardized protocol compared to Exp. 1 using institution-specific procedures. Repeatability of shear force for Institutions B and E was dramatically higher. Institutions A and D had moderately higher repeata-

Table 3. Historical repeatability of longissimus Warner-Bratzler shear force and tenderness rating for Institution A

Trait	n	Mean	SD	Minimum	Maximum	Repeatability
Shear force[a]	383	5.7	1.9	2.1	13.0	.78
Shear force[b]	299	5.1	1.2	2.7	7.6	.69
Shear force[c]	368	5.6	1.7	2.7	10.6	.78
Tenderness rating (before)[d]	397	4.8	.8	2.3	6.6	.75
Tenderness rating (after)[d]	103	4.6	1.0	1.5	7.2	.85

[a]Historical data from all available duplicate measurements obtained using standard procedures.
[b]Data set above that has been edited to produce an amount of variation in shear force similar to that Institution A had in Exp. 1.
[c]Data set above that has been edited to produce an amount of variation in shear force similar to that Institution A had in Exp. 2.
[d]Data from all available duplicate measurements obtained using standard procedures before (before) and after (after) extensive panel retraining.

bility of shear force and Institution C had a similar level of repeatability compared to Exp. 1. Thus, it would seem that following the standardized protocol resulted in improved measurement of shear force. However, because the protocols were not greatly different in Exp. 1, it is likely that two other factors contributed significantly to the increased repeatability in Exp. 2. First, the measure of repeatability is somewhat sensitive to the amount of variation in the data set. Thus, more variation would tend to result in higher repeatability, as occurred in Exp. 2 relative to Exp. 1. However, measurements can be highly repeatable with low variation, and vice versa. Second, empirically it would seem likely that for some institutions the results from Exp. 1 provided great incentive for improved technique in Exp. 2, resulting in greater attention to how the experiment was conducted. This latter effect on repeatability of shear force may have been greater than standardizing the protocol.

Standard procedures have been published for instrumental measurement of meat tenderness (Chrystall et al., 1994; Savell et al., 1994; AMSA, 1995; Wheeler et al., 1995). Contrary to statements by Chrystall et al. (1994), procedures for Warner-Bratzler shear force measurement have been defined and standardized (Bratzler, 1932, 1949; Savell et al., 1994; AMSA, 1995; Wheeler et al., 1995; Tennison Collins, personal communication, G-R Electric, Manhattan, KS). However, numerous deviations from and modifications to the standard protocol have been reported and erroneously called Warner-Bratzler shear force. Assessment of meat tenderness using Warner-Bratzler shear force should be conducted as outlined by Wheeler et al. (1995). This standard protocol should facilitate comparison and interpretation of data among institutions.

Historical Repeatability of Tenderness Measurements

The repeatabilities of two measures of tenderness for Institution A on data collected over a period of 10 yr are shown in Table 3. These data were collected on longissimus cooked on Farberware electric broilers. Repeatability of shear force on 383 animals was slightly higher than repeatability for Institution A in Exp. 1, possibly due to the greater variation in the data set. Thus, this data set was edited twice to produce two additional data sets with an amount of variation similar to that in Exp. 1 and 2, respectively (Table 3). The historical shear force data had only slightly more variation than the data in Exp. 2 for Institution A; thus, the editing had little effect and did not change the repeatability of shear force. However, the editing to produce variation similar to that Institution A had in Exp. 1 resulted in a repeatability slightly lower than Institution A had in Exp. 1. These data indicate that the historical repeatability of shear force from Institution A was slightly higher than that from Exp. 1 (using its usual protocol) and slightly lower than that from Exp. 2 (using a standardized protocol). However, when the amount of variation in the historical data set was standardized to the same level as Exp. 1, shear force repeatability was reduced (Table 3).

Historical repeatability of sensory tenderness ratings also was provided for comparison to shear force repeatability. Tenderness ratings from the trained sensory panel were divided into data collected before and after an extensive refresher training of the panel. Repeatability of tenderness rating on 397 animals before retraining was similar (.75) to that obtained for shear force. However, after retraining, repeatability of tenderness rating increased to .85. A portion of the increase can be attributed to greater variation in the data set, but the rest of the increase was likely due to increased performance of the panel due to retraining and possibly more consistent initial internal temperature (thawing protocol also was improved in this data set). These historical data indicate that it is possible for both shear force and tenderness rating to be measured with a high degree of repeatability; however, proper execution of appropriate protocols and a well-trained sensory panel are required to achieve high repeatabilities. Although trained sensory tenderness rating is generally considered the ideal measure

Table 4. Effects of crosshead speed and full scale load setting on Instron Warner-Bratzler shear force

Setting	n	Shear force, kg
Exp. 4		
Crosshead speed, mm/min		
5	20	4.6[a]
10	20	4.4[a]
20	20	3.8[b]
50	20	3.6[b]
SEM		.20
Full scale load, kg		
10	40	4.2
20	40	4.1
SEM		.15
Warner-Bratzler[c]	10	3.7
Exp. 5		
Crosshead speed, mm/min		
50	100	5.9[a]
200	100	5.4[b]
SEM		.15

[a,b]Means in a column within main effect with a common superscript are not different ($P > .05$).
[c]Warner-Bratzler shear machine.

of tenderness to which other measurements should be compared, low correlations between shear force and tenderness rating do not automatically mean that shear force was not an accurate measurement. Errors in either one or both measurements could result in low correlations to one another. This fact has long been known (but frequently overlooked) since Khan et al. (1973) stated that insufficient precision in experimental technique seems to cause the conflicting and poor correlations between shear force and taste panel scores in the literature. It also is possible that low correlations between shear force and sensory tenderness in the literature could have resulted from comparison of multiple muscles (Shackelford et al., 1995), many of which may have little repeatable variation in tenderness (Shackelford et al., 1997).

Instron Crosshead Speed

In Exp. 4, shear force was affected ($P < .05$) by crosshead speed, but not ($P > .05$) by full scale load setting (Table 4). Shear force decreased as crosshead speed increased; crosshead speeds of 50 and 100 mm/min resulted in greater ($P < .05$) shear force than speeds of 200 and 500 mm/min. In Exp. 5, the difference in shear force between 5 and 20 cm/min crosshead speed was confirmed ($P < .05$), although the magnitude of the difference was slightly lower than in Exp. 4 (Table 4). In addition, samples from Exp. 4 also were sheared with a Warner-Bratzler machine and had a mean shear force similar to that of the Instron at 200 cm/min crosshead speed (Table 4).

The Warner-Bratzler shear machine was designed to operate at 229 mm/min shearing speed after it was determined to produce the most reproducible shear values (Bratzler, 1932). Given the evidence in Table 4, it would seem logical that a Warner-Bratzler machine shearing at 229 mm/min and an Instron at 5 cm/min crosshead speed would provide different shear force values. However, it was reported by Wheeler et al. (1994) that there was no difference in shear force values between an Instron using a 50 mm/min shear speed and a Warner-Bratzler machine. Further study of the data reported by Wheeler et al. (1994) revealed that the offsetting effects of initial internal temperature (Berry and Leddy, 1990; Wheeler et al., 1996) and shear speed resulted in similar shear force values for Instron and Warner-Bratzler machines despite the shearing speed difference. Thus, based on the data in Table 4, shear force from a Warner-Bratzler machine and an Instron should be the same as long as the Instron is used at 200 mm/min crosshead speed.

Instrument Variation

Mean shear force among institutions varied ($P < .05$) even though all steaks were cooked by one institution (Table 5). There were no differences ($P > .05$) in shear force among Institutions A, F, and G using Instrons with the same crosshead speed (50 mm/min). However, the two measurements obtained by Warner-Bratzler machines were lower ($P < .05$) than the Instron measurements. The Instron measurements were obtained at 50 mm/min crosshead speed. Data in Table 4 indicate that difference in shearing

Table 5. Effect of institution's shearing instrument on Warner-Bratzler shear force values[a]

Institution[b]	n	Mean	SD	Minimum	Maximum
A	10	4.0[c]	.5	3.2	4.7
E	10	2.5[e]	.3	2.2	3.0
F	10	4.1[c]	.4	3.6	4.9
G	10	3.9[c]	.6	3.0	4.9
A1	10	3.3[d]	.4	2.6	3.8

[a]Institution A cooked all steaks and shipped them to each institution chilled.
[b]Institutions A, F, and G used an Instron with 50 mm/min crosshead speed; Institutions E and A1 used a Warner-Bratzler machine.
[c,d,e]Means lacking a common superscript are different ($P < .05$).

speed (50 vs 200 mm/min) could account for .5 to .8 kg of shear force. That would explain the shear force difference between Institutions A1 and A. In addition, it also would explain the higher shear force of Institution A relative to the other institutions in Exp. 2 (Table 2) using the standard protocol. However, only half of the 1.5-kg difference between Institutions A and E (Table 5) could be accounted for by shearing speed. Furthermore, Institution E's shear force from Exp. 2 also was .7 kg below the mean of the shear force reported by the other institutions (Table 2). The only sources of variation for these differences were the instruments used to measure shear force and the accuracy of obtaining uniform diameter cores parallel to the fiber orientation. It seems unlikely that errors in obtaining cores would result in more than .2 or .3 kg of shear force. Thus, these data imply that there may be differences in instruments used to measure shear force. Shear force from older Warner-Bratzler shear machines may vary over time due to changes in the tension of the spring.

Summary

Shear force values of beef longissimus can vary considerably within and among institutions. The sources of this variation may include protocol, execution of the protocol, and instrument variation. A standardized protocol, increased variation in tenderness, and incentive to properly conduct the shear force assessment resulted in improved repeatability of shear force measurement. If the mean shear force values from Exp. 2 (Table 2) are adjusted for these additional factors (Institution A decreased .7 kg to adjust for crosshead speed too low and Institution E increased .7 kg for instrument difference), the resulting shear force means would be 4.4, 4.3, 4.6, 4.2, and 4.3 kg, respectively, for Institutions A, B, C, D, and E. Thus, it is possible for institutions to obtain the same mean shear force and have high repeatability if a standard protocol is properly executed with calibrated equipment.

Implications

Proper execution of a standardized protocol is imperative for obtaining accurate and repeatable shear force measurement. Thus, until a standardized protocol is uniformly adopted, it is not valid to compare Warner-Bratzler shear force values among institutions or use shear force thresholds developed at other institutions.

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