12-2002

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Recommended Citation

Wheeler, T.L.; Vote, D.; Leheska, J.M.; Shackelford, S.D.; Belk, K.E.; Wulf, D.M.; Gwartney, B.L.; and Koohmaraie, M., "The Efficacy of Three Objective Systems for Identifying Beef Cuts That Can Be Guaranteed Tender" (2002). *Animal Science Faculty Publications.* Paper 41.
http://openprairie.sdstate.edu/ans_pubs/41

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The efficacy of three objective systems for identifying beef cuts that can be guaranteed tender[1,2]

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ABSTRACT: The objective of this study was to determine the accuracy of three objective systems (prototype BeefCam, colorimeter, and slice shear force) for identifying guaranteed tender beef. In Phase I, 308 carcasses (105 Top Choice, 101 Low Choice, and 102 Select) from two commercial plants were tested. In Phase II, 400 carcasses (200 rolled USDA Select and 200 rolled USDA Choice) from one commercial plant were tested. The three systems were evaluated based on progressive certification of the longissimus as "tender" in 10% increments (the best 10, 20, 30%, etc., certified as "tender" by each technology; 100% certification would mean no sorting for tenderness). In Phase I, the error (percentage of carcasses certified as tender that had Warner-Bratzler shear force of ≥ 5 kg at 14 d postmortem) for 100% certification using all carcasses was 14.1%. All certification levels up to 80% (slice shear force) and up to 70% (colorimeter) had less error ($P < 0.05$) than 100% certification. Errors in all levels of certification by prototype BeefCam (13.8 to 9.7%) were not different ($P > 0.05$) from 100% certification. In Phase I, the error for 100% certification for USDA Select carcasses was 30.7%. For Select carcasses, all slice shear force certification levels up to 60% (0 to 14.8%) had less error ($P < 0.05$) than 100% certification. For Select carcasses, errors in all levels of certification by colorimeter (20.0 to 29.6%) and by BeefCam (27.5 to 31.4%) were not different ($P > 0.05$) from 100% certification. In Phase II, the error for 100% certification for all carcasses was 9.3%. For all levels of slice shear force certification less than 90% (for all carcasses) or less than 80% (Select carcasses), errors in tenderness certification were less than ($P < 0.05$) for 100% certification. In Phase II, for all carcasses or Select carcasses, colorimeter and prototype BeefCam certifications did not significantly reduce errors ($P > 0.05$) compared to 100% certification. Thus, the direct measure of tenderness provided by slice shear force results in more accurate identification of "tender" beef carcasses than either of the indirect technologies, prototype BeefCam, or colorimeter, particularly for USDA Select carcasses. As tested in this study, slice shear force, but not the prototype BeefCam or colorimeter systems, accurately identified "tender" beef.

Key Words: Beef, Classification, Grading, Instrumentation, Quality, Tenderness

J. Anim. Sci. 2002. 80:3315–3327

Introduction

A number of studies have shown that consumers can differentiate beef that varies in tenderness and are willing to pay some level of premium for guaranteed tenderness (Boleman et al., 1997; Lusk et al., 2001; Shackelford et al., 2001). Sorting beef carcasses from young cattle for quality has long been based on the relationship between marbling scores of the 12th rib cross section of the longissimus and cooked beef palatability (USDA, 1997). However, it has been recognized (Wulf et al., 1997) that USDA quality grade does not adequately differentiate longissimus tenderness of the 85% (Bole-

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[1] 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.

[2] The authors express their gratitude to ConAgra Beef Co., RMS Research Management Systems USA, Smart Machine Vision Inc., USDA-AMS, J. Wise, R. Jones, M. O'Connor, P. Hitch, S. Cave, P. Beska, K. Mihm, P. Tammen, M. Martinez, B. Platter, C. Smith, P. Mies, E. Duffy, J. Goddard, L. Warborg, B. Stahl, and J. Geiman for their contributions to this study and to M. Bierman for secretarial assistance.

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Received April 12, 2002.
Accepted July 8, 2002.

man et al., 1998) of fed-beef carcasses grading USDA Select or Low Choice.

An accurate, instrumental method for classifying beef carcasses based on longissimus tenderness has been developed (Shackelford et al., 1999b). However, it appears that industry is reluctant to implement this system because it is perceived as too costly despite data indicating consumers would pay a premium for a "guaranteed tender" product that would more than offset the costs of identifying that product (Boleman et al., 1997; Lusk et al., 2001; Shackelford et al., 2001).

Some promising results have been obtained for indirect methods of predicting beef tenderness based primarily on lean color attributes (Wulf et al.,1997) that may result in a noninvasive, useful predictor of beef tenderness. Image analysis traits using prototype BeefCam (Belk et al., 2000) and a combination of colorimeter, marbling, and hump height traits (Wulf and Page, 2000) may have potential as predictors of beef tenderness. Direct comparisons of these methods have not been made, thus, it is not clear whether the additional accuracy of direct tenderness measurement (slice shear force) warrants its use relative to less accurate noninvasive methods to identify tender beef. Thus, the objective of this study was to determine the accuracy of three objective systems for identifying beef that can be guaranteed tender.

Materials and Methods

Experimental Samples

Phase I. Carcasses (n = 308) from two commercial plants were selected at the grading stand (approximately 36 h postmortem) by USDA-Agricultural Marketing Service (**AMS**) personnel to represent the upper ⅔ of Choice (Top Choice), the lower ⅓ of Choice (Low Choice), and Select, and were railed off onto separate rails by grade. Carcasses that subsequently were determined to fall into one of the other two classes were moved to that class and replaced by another carcass in the original class. Approximately 50 carcasses per grade per plant were selected. Carcasses were from 279 steers and 29 heifers. Three USDA-AMS expert graders collected consensus data for preliminary yield grade, adjusted preliminary yield grade, percentage kidney, pelvic, and heart fat, lean maturity, skeletal maturity, overall maturity, marbling score, and quality grade (USDA, 1997). Hot carcass weight was recorded from plant carcass tags. Longissimus areas were measured with a ribeye grid twice and averaged. Yield grade was calculated according to USDA (1997).

At approximately 48 h postmortem, the IMPS #180 strip loin (longissimus lumborum), IMPS #184 top sirloin (gluteus medius), and the IMPS #168 inside round (semimembranosus) from one side were obtained, vacuum-packaged, boxed, transported to the U.S. Meat Animal Research Center (**MARC**), and stored at 2°C. At 7 to 10 d postmortem, the cuts were unpackaged, trimmed of s.c. fat and minor muscles, crust frozen at –30°C for 60 min to make them firmer, and sliced into 2.54-cm-thick steaks (Biro model 109 PC slicer, Marblehead, OH). The steaks were vacuum-packaged, stored at 2°C until 14 d postmortem, and then frozen at –30°C. Warner-Bratzler shear force, trained descriptive attribute sensory panel, and consumer sensory panel were conducted on longissimus lumborum and gluteus medius. Warner-Bratzler shear force and consumer sensory panel were conducted on semimembranosus.

Phase II. Carcasses (n = 400) from one commercial plant were selected after the grading stand (approximately 36 h postmortem) by Colorado State University personnel experienced in beef carcass grading. On the Tuesday of two consecutive weeks, 100 carcasses rolled Choice (with Small marbling to represent the lower ⅓ of Choice) and 100 carcasses rolled Select were railed off onto separate rails by grade. Carcass grade data were collected as described for Phase I. Carcasses whose expert USDA quality grade was determined to be different from that stamped on them were kept in the experiment as the grade originally assigned by the on-line AMS grader. Carcasses were from 302 steers and 98 heifers.

At approximately 48 h postmortem, the IMPS #180 strip loin (longissimus lumborum) from one carcass side was obtained and loaded into a plastic-lined, cardboard "combo" unpackaged and transported to MARC. At 72 h postmortem, the cuts were trimmed of s.c. fat and minor muscles, vacuum-packaged, stored at 2°C until 14 d postmortem, and then frozen at –30°C. Frozen strip loins were cut from the anterior end into 2.54-cm-thick steaks with a bandsaw. The second steak from the anterior end was used for Warner-Bratzler shear force value determination.

Tenderness Certification Methods

BeefCam. A portable prototype BeefCam system (calibrated to a white standard prior to use each day) was used to obtain a digital image of the 12th-rib cross section approximately 90 min after ribbing. Care was taken to properly align the camera with the exposed cross section so that no image distortion occurred and so that the entire longissimus cross section was included in the frame. Digital images were later processed using proprietary software to obtain measurements for lean color and fat color for each carcass using the L*, a*, and b* color scale. These color measurements were then used in regression models developed from preliminary experiments (Belk et al., 2000) to predict the first principal component of Warner-Bratzler shear force and consumer ratings for overall palatability.

Slice shear force. A 1-in-thick steak was removed from the anterior end of the loin from each left carcass side with a knife within 90 min after ribbing and transported to MARC for cooking and slice shear force measurement at 72 h postmortem as described by Shackelford et al. (1999b). Briefly, steaks were rapidly cooked with a belt grill (5.5 min), then a 5-cm-long, 1-cm-thick slice was removed from the lateral end of the steak parallel to the muscle fibers. This slice was sheared perpendicular to the fibers with a flat, blunt-end blade at 500 mm/min to obtain a slice shear force value.

Colorimeter. A portable Minolta Chroma Meter CR-310 (Minolta Corp., Ramsey, NJ) with a 50-mm-diameter measurement area and D65 illuminant was used to obtain L*, a*, and b* values on the longissimus cross section at the 12th rib from both sides 90 to 110 min after ribbing, as described by Wulf and Page (2000). Hump height was measured on both sides as the distance from the dorsal edge of the ligamentum nuchae to the maximum dorsal protrusion of the rhomboideus, not including subcutaneous fat. A regression equation including mean colorimeter traits, USDA marbling score, and mean hump height was used to calculate a predicted palatability index as described by Wulf and Page (2000):

$$\text{Palatability index} = (-129.5) + 0.1923(\text{USDA marbling score}) - 1.01(\text{hump height, cm}) + 4.64(L^*) - 0.01085(L^* \times \text{USDA marbling score}) - 0.31(b^*) - 0.1911(b^{*2}) + 0.01347(b^* \times \text{USDA marbling score}).$$

Protocols

Cooking. Steaks were thawed and cooked as described by Wheeler et al. (1998) with the following exceptions. The preheat platen on the belt grill was set at 149°C, rather than disconnected. That change required that cook time be reduced to 5.5 min, rather than 5.7 min.

Warner-Bratzler Shear Force. Shear force was determined at MARC as described by Wheeler et al. (1998).

Trained Sensory Panel Evaluation. Cooked steaks were evaluated by an eight-member trained descriptive attribute panel at MARC as described by Wheeler et al. (1998).

Consumer Sensory Evaluation. A telemarketing firm was hired to randomly recruit consumers from the Fort Collins, CO, area to serve as participants in an untrained beef taste panel. Consumers (n = 582) were selected to represent a cross section of the population in the Fort Collins area. Demographic characteristics of the consumer panel were: gender—51% male, 49% female; age—18 to 29 yr = 27.5%, 30 to 49 yr = 41.3%, 50 to 69 yr = 21.7%, ≥ 70 yr = 9.5%; ethnicity—Caucasian = 93.2%, Hispanic = 2.3%, Asian or Pacific Islander = 1.0%, African-American = 0.9%, American-Indian = 0.9%; and income level—< \$25,000 = 15.5%, \$25,000 to \$34,999 = 15.8%, \$35,000 to \$49,999 = 18.2%, \$50,000 to \$74,999 = 21.9%, ≥ \$75,000 = 18.6%. Consumers were prescreened to ensure that they were at least 18-yr-old and ate beef at least once a week. For each session, six consumers were seated in random fashion in a room with standard fluorescent lighting. Before starting each session, each consumer was asked to read and sign an informed consent form approved by the Colorado State University “Use of Humans in Research” committee, acknowledging that they were participating in a research project.

Frozen steaks were tempered for 24 h at 2°C and cooked (150°C) on a gas Hobart Char Broiler (Model CB 51, Hobart Corp., Troy, OH), with each steak turned every 4 min until reaching a final internal temperature of 70°C as monitored by an Omega type K thermocouple (Omega Engineering Corp., Stamford, CT). After cooking, researchers assigned a visual degree of doneness score to each steak using the National Live Stock and Meat Board Beef Steak Color Guide (AMSA, 1995). The cooked surface of each steak was removed before cutting the steak into 1.0 × 1.0 × 2.5 cm pieces. These pieces were then placed into a warming oven (140°C) until served. Before serving the first sample, consumers were provided oral instructions regarding the questions they would be asked about the samples. In addition, consumers were provided with distilled water and unsalted saltine crackers and reminded to take a bite of cracker and a sip of water between tasting samples.

Muscle was preassigned to sessions with samples within a muscle randomly assigned to a session and to consumers. A total of nine samples was served to each consumer during a session, and consumers were not allowed to participate in more than one session. Consumers rated each sample for tenderness like/dislike using a nine-point, end-anchored hedonic scale where 1 = like extremely and 9 = dislike extremely. The six consumer ratings were averaged for each steak to obtain a single value.

Statistical Analysis

Within certification method (slice shear force, prototype BeefCam, colorimeter), data were ordered from predicted most tender to predicted least tender and assigned to certification levels in 10% increments. Within certification method, all pairwise comparisons of the percentage error in certified as “tender” were made using PROC FREQ and Mantel-Haenszel χ^2 analysis (SAS Inst. Inc., Cary, NC). Certification as “tender” was considered in error if the longissimus Warner-Bratzler shear force at 14 d postmortem was ≥ 5 kg. This criterion, 5 kg, is largely arbitrary but realistic and in this study served only as a basis for comparing the three technologies. Furthermore, commercial implementation of tenderness classification requires consideration of numerous factors that would impact the profitability of the endeavor, including selecting criteria to evaluate the accuracy of the classification. Data were analyzed by a separate ANOVA of a completely randomized design for the main effect of certification (certified tender or not certified tender) within each certification level and each certification method (SAS Inst. Inc.).

Results

The three systems could have been evaluated based on their respective error rates for identifying the pro-

Table 1. Simple statistics for carcass and muscle traits for Phase I

Trait	n	Mean	SD	Minimum	Maximum
Hot carcass weight, kg	308	347	37	250	437
Adj. fat thickness, cm	308	1.28	0.42	0.3	2.2
Longissimus area, cm^2	308	85.5	8.8	66.5	117.4
Kidney, pelvic, and heart fat, %	308	1.8	0.6	0.5	4.0
USDA yield grade	308	2.8	0.8	0.7	4.6
Bone maturity[a]	308	62	16	30	150
Lean maturity[a]	308	50	12	20	100
Overall maturity[a]	308	57	12	30	130
Marbling score[b]	308	444	97	300	690
Hump height, cm[c]	308	2.9	0.5	1.8	6.0
L*	308	41.4	2.0	35.9	48.8
a*	308	25.7	1.2	22.2	29.9
b*	308	12.3	0.9	9.2	15.9
Longissimus, 14 d postmortem					
Warner-Bratzler shear, kg	306	4.0	0.9	2.1	7.4
Trained tenderness rating[d]	306	6.2	1.0	3.2	7.8
Consumer tenderness like[e]	300	3.8	1.1	1.3	7.6
Gluteus medius, 14 d postmortem					
Warner-Bratzler shear, kg	300	4.4	0.7	2.9	7.0
Trained tenderness rating[d]	304	5.3	0.9	2.2	7.5
Consumer tenderness like[e]	298	4.0	1.2	1.3	7.7
Semimembranosus, 14 d postmortem					
Warner-Bratzler shear, kg	305	4.0	0.7	2.6	6.7
Consumer tenderness like[e]	299	4.5	1.2	1.5	7.8

[a] A^{00} = 00, B^{00} = 100.

[b] 300 = "Slight^{00}," 400 = "Small^{00}," 500 = "Modest,^{00}" 600 = "Moderate^{00}." In Phase I, carcasses whose line-grader quality grade was not confirmed by the USDA expert graders' consensus were replaced.

[c] The distance from the dorsal edge of the ligamentum nuchae to the maximal dorsal protrusion of the rhomboideus, excluding s.c. fat.

[d] 8 = extremely tender, 1 = extremely tough.

[e] 1 = like extremely, 9 = dislike extremely.

portion of the sample that was "tender" based on the preestablished criteria for each individual system (Shackelford et al., 1999b; Belk et al., 2000; Wulf and Page, 2000). However, this approach could have resulted in a biased comparison because each system would be certifying a different proportion of carcasses as "tender" from a relatively small sample of carcasses with a relatively small proportion of the carcasses that were not "tender." In this situation, a few incorrectly classified carcasses can have a large impact on the percentage error rate and give an unfair impression of accuracy. Thus, to ensure valid comparisons, the three systems were evaluated based on progressive certification as "tender" in 10% increments (10 to 90% certified as "tender").

Phase I

Table 1 contains the simple statistics for various carcass and muscle traits to characterize the sample in Phase I. The carcasses sampled were highly variable in all traits. Lean color traits were all slightly less variable and L* and b* mean values were slightly higher than those reported by Page et al. (2001) for 1,000 carcasses selected to represent the U.S. fed beef population.

The error rate for 100% certification using all carcasses was 14.1% (Figure 1). Slice shear force certification levels up to 80% had lower ($P < 0.05$) error rates than did 100% certification. Error rates for slice shear force certification levels of 60% and less were not different ($P > 0.05$) from one another. Colorimeter certification levels up to 70% had lower ($P < 0.05$) error rates than did 100% certification. Error rates for colorimeter certification levels of 60% and less were not different ($P > 0.05$) from one another. Error rates for all levels of certification by prototype BeefCam were not different ($P > 0.05$) from 100% certification.

The error rate for 100% certification for USDA Select carcasses only was 30.7% (Figure 2). Slice shear force certification levels up to 60% had lower ($P < 0.05$) error rates than did 100% certification. Slice shear force certification levels of 70% and lower were not different ($P > 0.05$) from one another. For USDA Select carcasses, error rates for all levels of certification by colorimeter and by prototype BeefCam were not different ($P > 0.05$) from 100% certification.

Regardless of percentage certified, the difference in mean longissimus Warner-Bratzler shear force value between certified "tender" and not certified was significant ($P < 0.05$) for both slice shear force and colorimeter (Table 2). However, the magnitude of the differences in mean longissimus Warner-Bratzler shear force value between certified "tender" and not certified was numerically greater for slice shear force than for colorimeter for all certification levels. For prototype BeefCam, the difference in mean longissimus Warner-Bratzler shear

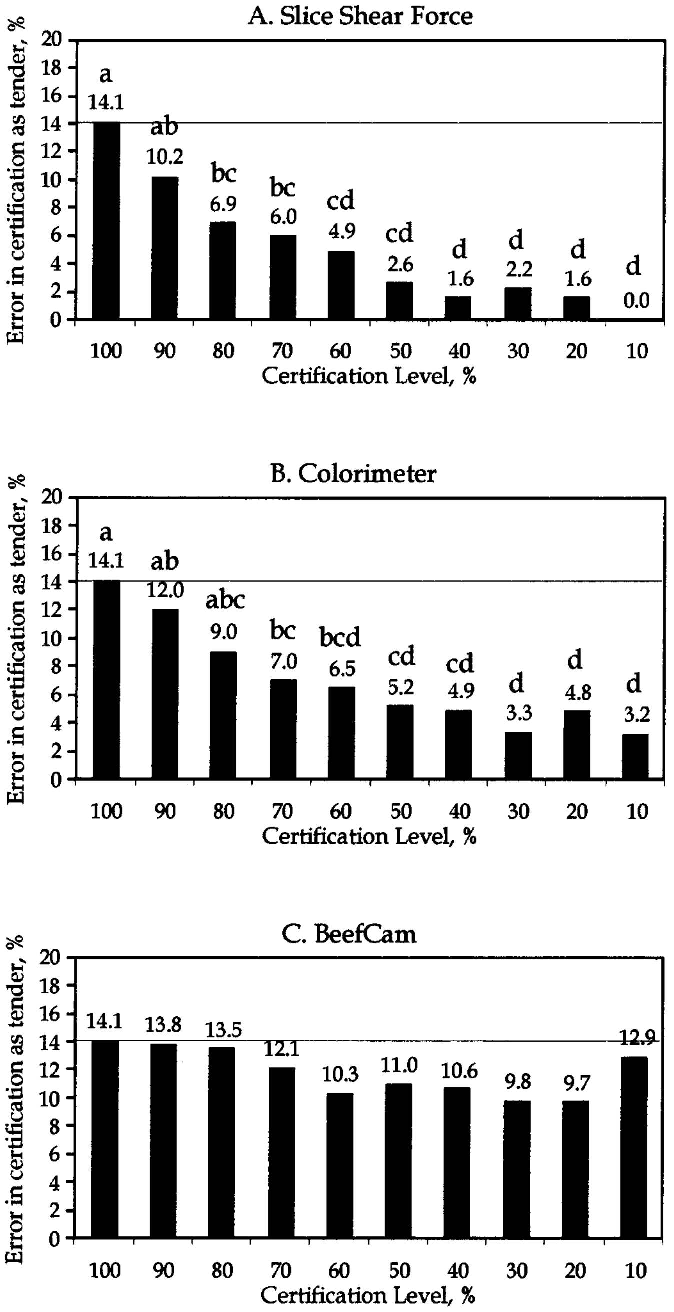

Figure 1. Error rates for certifying all carcasses as "tender" in increments of 10% of the sample (Phase I, n = 308). "Tender" was defined as longissimus Warner-Bratzler shear force of < 5 kg at 14 d postmortem. 100% certification means no tenderness sorting. ^{a,b,c,d}Means across certification levels within certification method lacking a common superscript letter differ ($P < 0.05$).

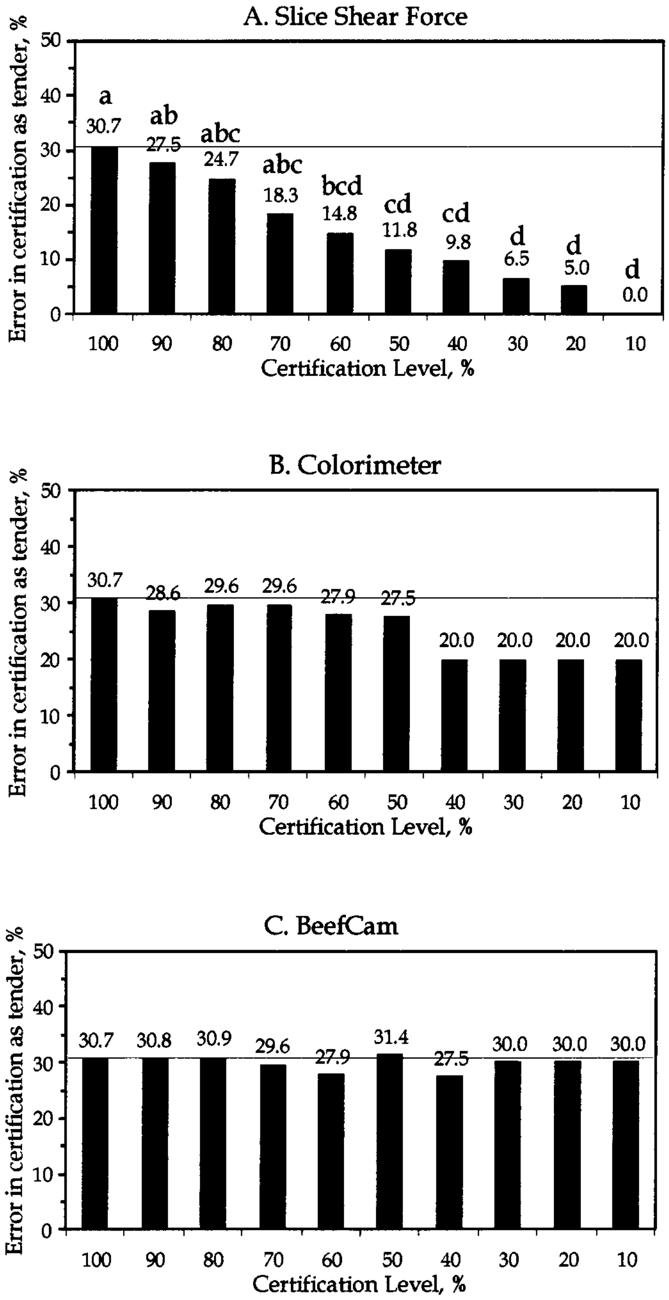

Figure 2. Error rates for certifying USDA Select carcasses as "tender" in increments of 10% of the sample (Phase I, n = 102). "Tender" was defined as longissimus Warner-Bratzler shear force of < 5 kg at 14 d postmortem. 100% certification means no tenderness sorting. ^{a,b,c,d}Means across certification levels within certification method lacking a common superscript letter differ ($P < 0.05$).

force value between certified "tender" and not certified was significant ($P < 0.05$) only for the 60% certification level. Results were similar for longissimus trained sensory tenderness rating, except the mean difference for 90% certification by colorimeter and 60% certification by prototype BeefCam was not ($P > 0.05$) significant (Table 2). Regardless of percentage certified, the difference in mean longissimus consumer tenderness like rating between certified "tender" and not certified was significant ($P < 0.05$) for slice shear force. For all certification levels except for 20, 50, and 90%, the difference in mean longissimus consumer tenderness like rating between certified "tender" and not certified was significant ($P < 0.05$) for colorimeter. The magnitude of the

Table 2. Effect of percentage certified as "tender" on longissimus 14-d Warner-Bratzler shear force, trained sensory panel tenderness rating, and consumer panel tenderness like rating for three tenderness certification methods (Phase I, n = 308)

Percentage certified as "tender"	Slice shear force			Colorimeter			BeefCam		
	Certified "tender"	Not certified	Diff.[a]	Certified "tender"	Not certified	Diff.[a]	Certified "tender"	Not certified	Diff.[a]
	14 d postmortem Warner-Bratzler shear force, kg								
90	3.8	5.0	1.2*	3.9	4.6	0.7*	4.0	3.7	–0.2
80	3.8	4.9	1.0*	3.8	4.6	0.8*	4.0	4.0	0.1
70	3.7	4.6	0.9*	3.7	4.5	0.8*	3.9	4.1	0.2
60	3.6	4.5	0.9*	3.7	4.3	0.6*	3.9	4.1	0.3*
50	3.6	4.3	0.8*	3.7	4.3	0.6*	3.9	4.0	0.2
40	3.5	4.3	0.8*	3.7	4.2	0.5*	3.9	4.0	0.1
30	3.5	4.2	0.7*	3.6	4.1	0.5*	3.9	4.0	0.1
20	3.4	4.1	0.7*	3.6	4.0	0.4*	3.8	4.0	0.2
10	3.2	4.0	0.8*	3.6	4.0	0.4*	3.8	4.0	0.2
	14 d postmortem trained sensory panel tenderness rating[b]								
90	6.3	5.1	–1.2*	6.2	5.9	–0.3	6.1	6.4	0.3
80	6.4	5.3	–1.1*	6.2	5.9	–0.3*	6.2	6.1	–0.1
70	6.5	5.4	–1.0*	6.2	6.0	–0.3*	6.2	6.1	–0.2
60	6.6	5.5	–1.0*	6.2	6.0	–0.2*	6.2	6.0	–0.2
50	6.6	5.7	–0.9*	6.3	6.0	–0.2*	6.2	6.1	–0.1
40	6.7	5.8	–0.8*	6.4	6.0	–0.3*	6.2	6.1	–0.1
30	6.7	5.9	–0.8*	6.5	6.0	–0.4*	6.2	6.2	0.0
20	6.8	6.0	–0.9*	6.5	6.1	–0.4*	6.2	6.1	0.0
10	7.0	6.1	–0.9*	6.6	6.1	–0.5*	6.1	6.2	0.1
	14 d consumer panel tenderness like rating[c]								
90	3.7	5.0	1.3*	3.8	4.2	0.5	3.8	3.7	0.0
80	3.6	4.7	1.1*	3.8	4.1	0.4*	3.8	4.0	0.3
70	3.6	4.4	0.9*	3.7	4.1	0.5*	3.8	4.0	0.3
60	3.5	4.3	0.8*	3.7	4.0	0.3*	3.7	4.0	0.3*
50	3.5	4.2	0.7*	3.7	3.9	0.2	3.8	3.9	0.2
40	3.4	4.1	0.6*	3.6	4.0	0.3*	3.8	3.9	0.0
30	3.5	4.0	0.5*	3.6	3.9	0.3*	3.9	3.8	–0.1
20	3.3	4.0	0.7*	3.7	3.9	0.2	3.9	3.8	–0.1
10	3.4	3.9	0.5*	3.5	3.9	0.3*	3.9	3.8	–0.1

[a] Diff. = The difference between means for not certified "tender" and certified "tender."
[b] 8 = extremely tender, 1 = extremely tough.
[c] 1 = like extremely, 9 = dislike extremely.
*The difference between certified "tender" and not certified "tender" was significant ($P < 0.05$).

differences in mean longissimus trained sensory tenderness rating between certified "tender" and not certified was greater for slice shear force than for colorimeter for all certification levels. For BeefCam, the difference in mean longissimus consumer tenderness like rating between certified "tender" and not certified was significant ($P < 0.05$) only for the 60% certification level.

Regardless of percentage certified, the difference in mean gluteus medius Warner-Bratzler shear force value and trained tenderness rating between certified "tender" and not certified was significant ($P < 0.05$) for slice shear force (Table 3). However, the magnitude of the differences in mean gluteus medius Warner-Bratzler shear force value and trained tenderness rating between certified "tender" and not certified was smaller than the mean difference for longissimus. The difference in mean gluteus medius consumer tenderness like rating between certified "tender" and not certified was significant ($P < 0.05$) for slice shear force for all certification levels except 10, 80, and 90%. For prototype BeefCam, the difference in mean gluteus medius Warner-Bratzler shear force value between certified "tender" and not certified was significant ($P < 0.05$) only for the 10 and 20% certification levels. The mean differences between certified "tender" and not certified for gluteus medius trained tenderness and consumer tenderness like ratings were not significant ($P > 0.05$) for prototype BeefCam regardless of certification level. Regardless of certification level or gluteus medius tenderness measurement, the mean differences between certified "tender" and not certified were not significant ($P > 0.05$) for colorimeter (Table 3).

Regardless of percentage certified, the difference in mean semimembranosus Warner-Bratzler shear force value and consumer tenderness like rating between certified "tender" and not certified was significant ($P < 0.05$) for slice shear force (Table 4). The difference in mean semimembranosus Warner-Bratzler shear force value between certified "tender" and not certified was significant ($P < 0.05$) for colorimeter only for 80, 70,

Table 3. Effect of percentage certified as "tender" on gluteus medius 14-d Warner-Bratzler shear force, trained sensory panel tenderness rating, and consumer panel tenderness like rating for three certification methods (Phase I, n = 308)

Percentage certified as "tender"	Slice shear force			Colorimeter			BeefCam		
	Certified "tender"	Not certified	Diff.[a]	Certified "tender"	Not certified	Diff.[a]	Certified "tender"	Not certified	Diff.[a]
	14 d postmortem Warner-Bratzler shear force, kg								
90	4.4	4.7	0.4*	4.4	4.5	0.1	4.4	4.3	–0.1
80	4.3	4.8	0.5*	4.4	4.5	0.1	4.4	4.4	0.0
70	4.3	4.8	0.5*	4.4	4.4	0.0	4.4	4.4	0.0
60	4.2	4.7	0.5*	4.4	4.3	–0.1	4.4	4.4	0.0
50	4.2	4.6	0.5*	4.4	4.4	0.0	4.4	4.4	0.0
40	4.1	4.6	0.5*	4.4	4.4	0.0	4.4	4.4	0.0
30	4.1	4.5	0.4*	4.4	4.4	0.0	4.5	4.4	–0.2
20	4.2	4.5	0.3*	4.4	4.4	0.0	4.6	4.4	–0.3*
10	4.2	4.4	0.2	4.4	4.4	0.0	4.7	4.4	–0.3*
	14 d postmortem trained sensory panel tenderness rating[b]								
90	5.3	4.8	–0.6*	5.3	5.3	0.0	5.3	5.5	0.2
80	5.4	4.7	–0.7*	5.3	5.3	0.0	5.3	5.3	0.0
70	5.5	4.8	–0.7*	5.3	5.3	0.0	5.3	5.2	–0.1
60	5.6	4.9	–0.7*	5.3	5.3	0.0	5.3	5.2	–0.1
50	5.6	5.0	–0.6*	5.3	5.2	–0.1	5.3	5.3	0.0
40	5.6	5.0	–0.6*	5.3	5.3	0.0	5.2	5.3	0.1
30	5.6	5.1	–0.4*	5.3	5.3	0.0	5.2	5.3	0.2
20	5.7	5.2	–0.5*	5.3	5.3	0.0	5.1	5.3	0.2
10	5.6	5.2	–0.4*	5.5	5.3	–0.2	5.1	5.3	0.2
	14 d consumer panel tenderness like rating[c]								
90	4.0	4.0	0.0	3.9	4.2	0.3	4.0	4.0	0.0
80	4.0	4.1	0.1	3.9	4.2	0.3	4.0	4.0	0.0
70	3.9	4.2	0.3*	3.9	4.1	0.2	4.0	4.0	0.0
60	3.8	4.2	0.4*	3.9	4.0	0.1	4.0	3.9	–0.1
50	3.8	4.2	0.4*	3.9	4.0	0.1	4.0	3.9	–0.1
40	3.7	4.2	0.5*	4.0	4.0	0.0	4.0	4.0	0.0
30	3.7	4.1	0.4*	4.0	4.0	0.0	4.1	3.9	–0.2
20	3.7	4.1	0.4*	3.9	4.0	0.1	4.2	3.9	–0.3
10	3.7	4.0	0.3	3.9	4.0	0.1	4.0	4.0	0.0

[a] Diff. = The difference between means for not certified "tender" and certified "tender."
[b] 8 = extremely tender, 1 = extremely tough.
[c] 1 = like extremely, 9 = dislike extremely.
*The difference between certified "tender" and not certified "tender" was significant ($P < 0.05$).

and 10% certification levels and was not significant ($P > 0.05$) at any certification level for consumer tenderness like rating. The difference in mean semimembranosus Warner-Bratzler shear force value between certified "tender" and not certified was significant ($P < 0.05$) for prototype BeefCam only for the 30% certification level and was not significant ($P > 0.05$) at any certification level for consumer tenderness like rating.

Phase II.

Table 5 contains the simple statistics for various carcass and muscle traits to characterize the sample in Phase II. Most traits in Phase II had a similar level of variability as in Phase I. Phase II was conducted to verify the results of Phase I.

The error rate for 100% certification using all carcasses was 9.3% (Figure 3). Slice shear force certification levels up to 80% had lower ($P < 0.05$) error rates than did 100% certification. Error rates for slice shear force certification levels of 80% and lower were not different ($P < 0.05$) from one another. Error rates for all levels of certification by colorimeter and prototype BeefCam were not different ($P > 0.05$) from 100% certification.

The error rate for 100% certification for USDA Select carcasses only was 12.0% (Figure 4). Slice shear force certification levels up to 70% had lower ($P < 0.05$) error rates than did 100% certification. Error rates for slice shear force certification levels of 70% and lower were not different ($P < 0.05$) from one another. For USDA Select carcasses, error rates for all levels of certification by colorimeter and by prototype BeefCam were not different ($P > 0.05$) from 100% certification.

When all Phase II carcasses were included, regardless of percentage certified, the difference in mean longissimus Warner-Bratzler shear force value between certified "tender" and not certified was significant ($P < 0.05$) for all three systems (Table 6). However, the magnitude of the difference in mean longissimus War-

Table 4. Effect of percentage certified as "tender" on semimembranosus 14-d Warner-Bratzler shear force and consumer panel tenderness like rating for three certification methods (Phase I, n = 308)

Percentage certified as "tender"	Slice shear force Certified "tender"	Not certified	Diff.[a]	Colorimeter Certified "tender"	Not certified	Diff.[a]	BeefCam Certified "tender"	Not certified	Diff.[a]
	14 d -postmortem Warner-Bratzler shear force, kg								
90	3.9	4.5	0.7*	3.9	4.1	0.2	4.0	3.8	–0.1
80	3.8	4.6	0.8*	3.9	4.1	0.2*	4.0	4.0	0.0
70	3.8	4.4	0.6*	3.9	4.1	0.2*	4.0	3.9	0.0
60	3.7	4.3	0.6*	3.9	4.0	0.1	3.9	4.0	0.1
50	3.7	4.2	0.5*	3.9	4.0	0.2	3.9	4.0	0.0
40	3.7	4.1	0.5*	3.9	4.0	0.1	4.0	3.9	–0.1
30	3.7	4.1	0.4*	3.9	4.0	0.0	4.1	3.9	–0.2*
20	3.7	4.0	0.3*	3.9	4.0	0.1	4.1	3.9	–0.2
10	3.6	4.0	0.3*	3.9	4.0	0.3*	4.2	3.9	–0.2
	14 d consumer panel tenderness like rating[c]								
90	4.4	5.3	0.9*	4.5	4.6	0.1	4.5	4.3	–0.2
80	4.4	4.9	0.5*	4.4	4.7	0.3	4.5	4.5	0.0
70	4.3	4.8	0.5*	4.4	4.6	0.2	4.5	4.5	0.0
60	4.3	4.8	0.5*	4.4	4.6	0.2	4.5	4.5	0.0
50	4.3	4.7	0.4*	4.4	4.6	0.2	4.5	4.5	0.0
40	4.3	4.6	0.3*	4.3	4.6	0.3	4.6	4.4	–0.2
30	4.2	4.6	0.4*	4.3	4.6	0.3	4.6	4.4	–0.2
20	4.1	4.6	0.5*	4.3	4.5	0.2	4.7	4.4	–0.3
10	4.0	4.5	0.5*	4.2	4.5	0.3	4.8	4.5	–0.3

[a] Diff. = The difference between means for not certified "tender" and certified "tender."

[b] 1 = like extremely, 9 = dislike extremely.

*The difference between certified "tender" and not certified "tender" was significant (P < 0.05).

ner-Bratzler shear force value between certified "tender" and not certified for slice shear force was double that for colorimeter or prototype BeefCam for almost all certification levels. For USDA Select carcasses, slice shear force certification was as effective as for all carcasses. However, the difference in mean longissimus Warner-Bratzler shear force value between certified "tender" and not certified was significant ($P < 0.05$) only for 80 and 90% certification levels for colorimeter and was significant ($P < 0.05$) only for 60 to 90% certification levels for prototype BeefCam.

In Phase I, quality grade was relatively effective for identifying a more tender group (Table 7). Mean longissimus Warner-Bratzler shear force value was lowest ($P < 0.05$) for Top Choice and highest ($P < 0.05$) for Select. Carcasses qualified for Top Choice or Low Choice had

Table 5. Simple statistics for carcass and muscle traits for Phase II

Trait	n	Mean	SD	Minimum	Maximum
Hot carcass weight, kg	400	363	40	266	460
Adj. fat thickness, cm	400	1.3	0.45	0.4	2.8
Longissimus area, cm^2	400	86.2	10.8	62.6	119.0
Kidney, pelvic, and heart fat, %	400	2.3	0.4	1.0	3.5
USDA yield grade	400	3.0	0.7	1.0	5.0
Bone maturity[a]	400	69	20	30	300
Lean maturity[a]	397	60	16	20	130
Overall maturity[a]	400	65	14	30	200
Marbling score[b]	400	416	77	300	680
Hump height, cm[c]	400	2.5	0.4	1.4	4.2
L*	400	41.0	2.0	35.8	46.3
a*	400	25.3	1.4	19.5	29.5
b*	400	11.4	1.1	7.6	14.6
Longissimus Warner-Bratzler shear force, kg	400	3.82	0.86	2.18	7.10

[a] A^{00} = 00, B^{00} = 100, C^{00} = 200, D^{00} = 300.

[b] 300 = "Slight^{00}," 400 = "Small^{00}," 500 = "Modest^{00}," 600 = "Moderate^{00}." In Phase II, carcasses whose line-grader quality grade was not confirmed by the USDA expert graders' consensus remained in the study at the originally assigned grade.

[c] The distance from the dorsal edge of the ligamentum nuchae to the maximum dorsal protrusion of the rhomboideus, not including subcutaneous fat.

a lower ($P < 0.05$) percentage of their longissimus with Warner-Bratzler shear force values that were at least 5 kg than did Select carcasses. In Phase II, mean Warner-Bratzler shear force value also was higher ($P < 0.05$) for longissimus from Select rather than from Low Choice carcasses. However, there was no difference ($P > 0.05$)

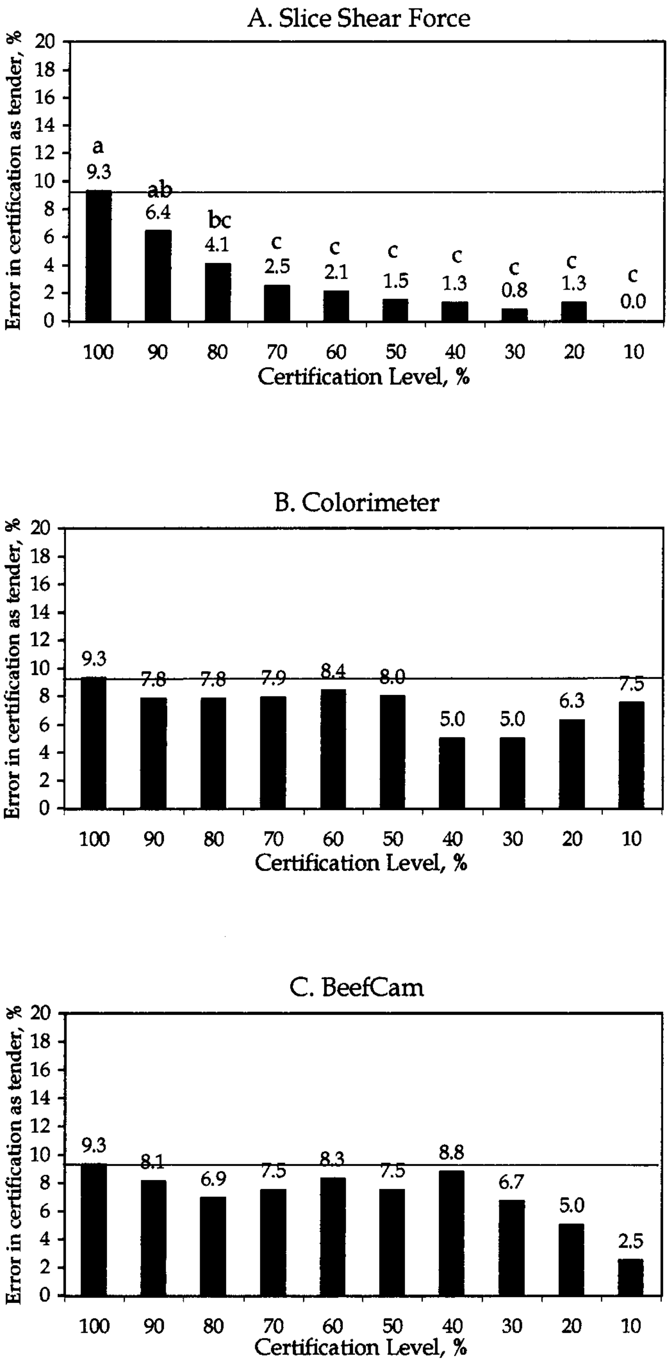

Figure 3. Error rates for certifying all carcasses as "tender" in increments of 10% of the sample (Phase II, n = 400). "Tender" was defined as longissimus Warner-Bratzler shear force of < 5 kg at 14 d postmortem. 100% certification means no tenderness sorting. ^{a,b,c,d}Means across certification levels within certification method lacking a common superscript letter differ ($P < 0.05$).

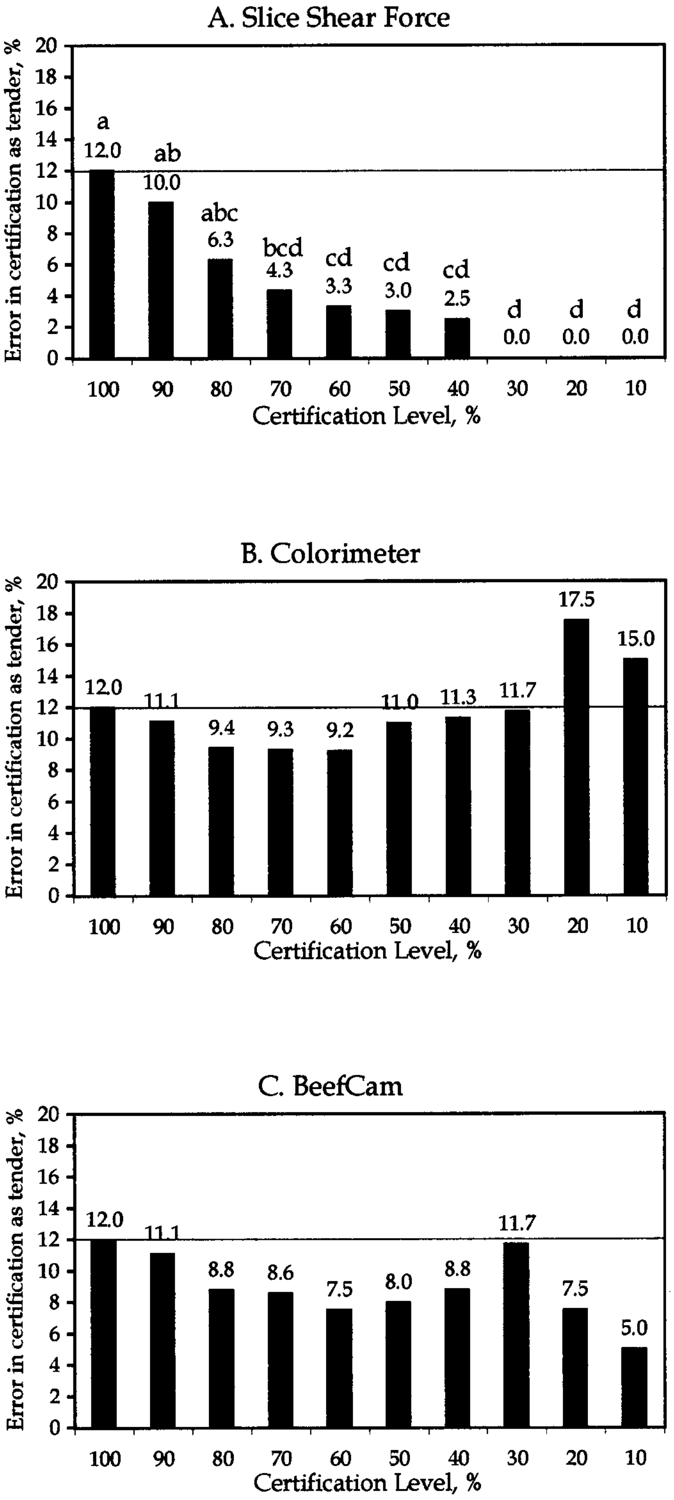

Figure 4. Error rates for certifying USDA Select carcasses as "tender" in increments of 10% of the sample (Phase II, n = 200). "Tender" was defined as longissimus Warner-Bratzler shear force of < 5 kg at 14 d postmortem. 100% certification means no tenderness sorting. ^{a,b,c,d}Means across certification levels within certification method lacking a common superscript letter differ ($P < 0.05$).

Table 6. Effect of percentage certified as "tender" on longissimus 14-d Warner-Bratzler shear force for three certification methods (Phase II)

Percentage certified as "tender"	Slice shear force			Colorimeter			BeefCam		
	Certified "tender"	Not certified	Diff.[a]	Certified "tender"	Not certified	Diff.[a]	Certified "tender"	Not certified	Diff.[a]
	All carcasses, n = 400								
90	3.7	4.7	1.0*	3.8	4.3	0.5*	3.8	4.3	0.6*
80	3.6	4.5	0.9*	3.8	4.1	0.3*	3.7	4.2	0.4*
70	3.6	4.4	0.8*	3.7	4.0	0.3*	3.8	4.0	0.2*
60	3.5	4.3	0.8*	3.7	4.0	0.2*	3.7	3.9	0.2*
50	3.4	4.2	0.8*	3.7	3.9	0.2*	3.7	3.9	0.2*
40	3.4	4.1	0.7*	3.6	4.0	0.3*	3.7	3.9	0.2*
30	3.3	4.0	0.7*	3.7	3.9	0.2*	3.6	3.9	0.3*
20	3.4	3.9	0.6*	3.6	3.9	0.2*	3.5	3.9	0.4*
10	3.4	3.9	0.5*	3.6	3.9	0.3*	3.5	3.9	0.4*
	USDA Select carcasses, n = 200								
90	3.9	4.9	1.0*	3.9	4.3	0.4	3.9	4.4	0.5*
80	3.8	4.7	1.0*	3.9	4.4	0.5*	3.8	4.4	0.6*
70	3.7	4.6	0.9*	3.9	4.2	0.3*	3.8	4.3	0.5*
60	3.6	4.5	0.8*	3.9	4.1	0.2	3.8	4.1	0.3*
50	3.5	4.4	0.9*	3.9	4.0	0.1	3.9	4.0	0.2
40	3.5	4.3	0.8*	3.9	4.0	0.0	3.9	4.0	0.2
30	3.4	4.2	0.8*	3.9	4.0	0.1	3.9	4.0	0.1
20	3.4	4.1	0.7*	3.9	4.0	0.0	3.8	4.0	0.2
10	3.5	4.0	0.5*	3.8	4.0	0.1	3.7	4.0	0.3

[a] Diff. = The difference between means for not certified "tender" and certified "tender."

*The difference between certified "tender" and not certified "tender" was significant ($P < 0.05$).

between Select and Low Choice carcasses for percentage with at least a 5-kg longissimus Warner-Bratzler shear force value. Quality grade was more effective than prototype BeefCam or colorimeter for identifying tender beef. However, slice shear force could identify a subset of Select beef that would be similar in tenderness to Top Choice beef.

Discussion

To meet consumer expectations, the beef industry has become increasingly interested in implementing strategies for improving and reducing variation in beef quality. It has been suggested by industry leaders that sorting and marketing beef based on tenderness would result in increased consumer satisfaction with beef by enabling the industry to manage and reduce the variation in tenderness. Toward that goal, the beef industry has placed a high priority on the development of instrumentation for carcass measurements that accurately predict cooked meat tenderness.

Additional incentive for the beef industry to identify and market beef based on accurate prediction of tenderness is provided by the increased proportion of branded beef products offered by both small and large companies, as well as data indicating that a segment of consumers is willing to pay a premium for guaranteed tender beef. Historically, the correlation between price and tenderness of beef cuts has been high (Savell and Shackelford, 1992). Boleman et al. (1997) were the first to demonstrate that consumers could detect differences in beef tenderness and were willing to pay a premium of at least $1.10/kg ($0.50/lb) for more tender steaks. In a willingness-to-pay experiment, Lusk et al. (2001) found that 69% of consumers preferred a low slice shear force steak to a high slice shear force steak based solely on their eating experience from the two steaks, and that percentage increased to 84% when the consumers were informed they were evaluating a "guaranteed tender" and a "probably tough" steak. Furthermore, 36% of consumers were willing to pay an average premium of $2.71/kg ($1.23/lb) for a "tender" vs a "tough" steak, and that percentage in-

Table 7. Least squares means and percentages ≥ 5 kg for longissimus 14-d Warner-Bratzler shear force within expert USDA quality grade

Phase/quality grade[a]	N	Mean, kg	SEM	≥ 5 kg, %
Phase I				
Select	101	4.53^{c}	0.08	30.7^{f}
Low Choice	101	3.82^{d}	0.08	7.9^{g}
Top Choice	104	3.55^{e}	0.08	3.9^{g}
Phase II				
Select	190^{b}	3.98^{c}	0.06	11.1
Low Choice	146^{b}	3.77^{d}	0.07	8.9

[a] Consensus quality grade of three USDA-AMS expert graders.

[b] Carcasses whose consensus quality grade according to USDA-AMS expert graders was not Select or Low Choice were excluded.

[c,d,e] Means within a phase lacking a common superscript differ ($P < 0.05$).

[f,g] Percentages within a phase lacking a common superscript differ ($P < 0.05$).

creased to 51% willing to pay an average premium of \$4.06/kg (\$1.84/lb) when the consumers were informed they were evaluating a "guaranteed tender" and a "probably tough" steak. In a study of Denver metropolitan area consumers, Shackelford et al. (2001) reported that 50% of consumers would be willing to pay a \$1.10/kg (\$0.50/lb) premium for guaranteed tender USDA Select loin steaks. They also found that 65% of consumers indicated that if a store carried a guaranteed tender line of beef, they would buy all their beef at that store (Shackelford et al., 2001). These data clearly indicate that some proportion of steak-eating consumers are willing to pay a premium for guaranteed tender steaks.

There have been many attempts to identify instrumental methods for predicting meat tenderness (reviewed by Pearson, 1963; Szczesniak and Torgeson, 1965). Most of these were intended for laboratory research tools and varied widely in their efficacies. In more recent investigations of objective predictions of meat tenderness, the goal has been to develop on-line systems for grading carcasses based on tenderness. The ideal system would involve an objective, noninvasive, tamper-proof, accurate, and robust technology. Technologies evaluated for their potential as on-line tenderness grading tools include Tendertec (George et al., 1997; Belk et al., 2001), connective tissue probe (Swatland, 1995; Swatland and Findlay, 1997; Swatland et al., 1998), elastography (Berg et al., 1999), near-infrared spectroscopy (Hildrum et al., 1994; Park et al., 1998), ultrasound (Park and Whittaker, 1991; Park et al., 1994), image analysis (Li et al., 1999, 2001), colorimeter (Wulf et al., 1997; Wulf and Page, 2000), and slice shear force (Shackelford et al., 1999a,b, 2001).

In studies investigating the use of color as a palatability indicator, Hodgson et al. (1992) and Hilton et al. (1998) found that lean and fat color scores for mature cow carcasses were related to subsequent cooked beef palatability. Davis et al. (1981) concluded from a comparison of grain- and forage-finished cattle that fat color could be used as an effective predictor of beef palatability. Although the relationship of lean and fat color with palatability in these three studies is likely greater than in A and B maturity grain-finished cattle, there is some indication that these traits also may be useful in youthful carcasses (Hilton et al., 1998). In other studies, lean and fat color of beef carcasses have been shown to be related to traits associated with palatability (our unpublished observations). Wulf et al. (1997) reported that b* values of the exposed longissimus at the 12th rib from a small-aperture colorimeter were correlated with 24-h calpastatin activity ($r = -0.28$) and trained sensory tenderness rating ($r = 0.37$). Furthermore, they found that a regression equation that included L*, a*, b*, and marbling score accounted for 19% of the variation in tenderness rating (Wulf et al., 1997). Li et al. (1999, 2001) have shown that lean color, marbling, and image texture features combined could account for up to 70% of the variation in trained sensory tenderness scores of longissimus lumborum. Collectively, this information led to the development of two noninvasive approaches to identify "tender" beef. One was an image analysis system, prototype BeefCam, used to obtain lean and fat color traits of the exposed surface of the longissimus at the 12th rib using the L*, a*,and b* color scale. The second was a palatability index (colorimeter) based on marbling, hump height, L*, and b* values that was intended as an augmentation system for USDA quality grade by changing the criteria for grading Choice or Select (Wulf and Page, 2000).

The amount a processor can spend on identifying "guaranteed tender" product depends on several factors, such as the amount of premium that product will generate, the proportion of carcasses that will qualify, potential reduction in value of nonqualifying product, and the weight of product (number of cuts) from each carcass that can be marketed as enhanced in tenderness. The method selected to identify "guaranteed tender" must be accurate enough to create a product that is recognizable by consumers as superior in tenderness. Furthermore, it would seem likely that tenderness certification would be applied to USDA Select carcasses because USDA Prime carcasses and most of the carcasses within the upper two thirds of Choice already receive premiums in the market. Thus, USDA Select carcasses would be logical candidates for increased value by identifying those that are "tender."

A preliminary experiment for prototype BeefCam model development on 769 carcasses with 13.8% "tough" resulted in a 7.8% error rate for certification as "tender" with 51.9% of carcasses certified as "tender" (Belk et al., 2000). Validation of that model on an independent data set ($n = 282$) with 7.1% "tough" resulted in a 1.6% error rate for certification as "tender" with 45.7% of carcasses certified as "tender" (our unpublished observations). Although prototype BeefCam performed slightly better in Phase 2 than in Phase 1, it was less accurate at sorting carcasses for tenderness than it had been in preliminary experiments. This may be partly due to the total number of observations and/or because the percentage of "tough" samples was too small in some preliminary data sets to get an accurate evaluation of the technology. In addition, further development of the prototype BeefCam has resulted in a commercial version of the system. Evaluation of the commercial BeefCam system indicates that Warner-Bratzler shear force (4.1 vs 4.6 kg) was not different ($P = 0.058$) between longissimus thoracis steaks from Select carcasses accepted ($n = 48$) and Select carcasses ($n = 50$) rejected by commercial BeefCam, respectively (D. S. Hale, unpublished data). Furthermore, the percentage of Select carcasses with longissimus Warner-Bratzler shear force values greater than 4.5 kg (10 lb) was not different ($P > 0.05$) between commercial BeefCam accepted (27%) and commercial BeefCam rejected (44%) carcasses. That study (D. S. Hale, unpublished data) concluded that commercial BeefCam provided added assurance of acceptable tenderness over USDA quality grade, however, findings indicated that further refinement seems warranted to enhance the ability of BeefCam to segment carcasses that will yield acceptably tender meat. Thus, the prototype BeefCam performed poorly in this study, and after further development, the commercial BeefCam system appears to be only slightly improved.

The initial application of the colorimeter approach on 100 carcasses reduced the percentage of "low palatability" carcasses in Low Choice from 14 to 4% and in Select from 36 to 7% (Wulf and Page, 2000). From tests of its ability to identify "guaranteed tender" beef using an independent sample (Figures 1-4 of the present study), it appears that the "palatability index" from the colorimeter approach to tenderness sorting for carcasses may be useful when used over a broad range of marbling scores, but not within the narrow range of marbling in USDA Select carcasses. However, this approach may be useful to augment quality grade as demonstrated by Wulf and Page (2000), if validated on an independent sample.

The high level of accuracy of slice shear force for sorting carcasses into tenderness groups is in agreement with previous data (Shackelford et al., 1999a,b; 2001). Similar results have been obtained from classification at 2 or 3 d postmortem, as were obtained in this study from 3 d postmortem classification (Shackelford et al., 1999b). In agreement with our current results, it appears that accurate early-postmortem longissimus tenderness classification also would enable one to market sirloin and round cuts based on tenderness (Tatum et al., 1999; Wheeler et al., 2000).

This direct approach to tenderness grading of carcasses (slice shear force) is significantly more accurate than currently available noninvasive methods, allows certification of a greater proportion of carcasses, creates a "guaranteed tender" product that consumers recognize as superior, and enables marketing of multiple muscles, not only the longissimus, as superior in tenderness. When this accuracy is combined with estimates of the level of premium a "guaranteed tender" beef product could command in the marketplace (Boleman et al., 1997; Lusk et al., 2001; Shackelford et al., 2001), it appears that the direct approach of slice shear force would be superior for identifying guaranteed tender beef compared to the noninvasive tenderness sorting methods tested in this study.

Implications

Indirect, noninvasive methods to predict meat tenderness that are based primarily on lean color may not be sufficiently accurate to warrant their use. The prototype BeefCam performed poorly in this study. The colorimeter performed inconsistently, appearing to be useful in Phase I, but not in Phase II, and was of little value when used within USDA Select. Direct methods to predict meat tenderness, such as slice shear force, are currently necessary to obtain accurate identification of beef that can be guaranteed tender.

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