Published December 8, 2014

Effects of postmortem aging and USDA quality grade on Warner-Bratzler shear force values of seventeen individual beef muscles[1]

S. L. Gruber,* J. D. Tatum,* J. A. Scanga,* P. L. Chapman,† G. C. Smith,* and K. E. Belk*[2]

*Department of Animal Sciences, Colorado State University, Fort Collins 80523-1171; and
†Department of Statistics, Colorado State University, Fort Collins 80523-1877

ABSTRACT: Forty USDA Select and 40 upper two-thirds USDA Choice beef carcasses were used to determine the effects of postmortem aging on tenderness of 17 individual beef muscles. Biceps femoris—long head, complexus, gluteus medius, infraspinatus, longissimus dorsi, psoas major, rectus femoris, semimembranosus, semitendinosus, serratus ventralis, spinalis dorsi, supraspinatus, tensor fasciae latae, teres major, triceps brachii—long head, vastus lateralis, and vastus medialis muscles were removed from each carcass. Seven steaks (2.54-cm thick) were cut from every muscle, and each steak was assigned to one of the following postmortem aging periods: 2, 4, 6, 10, 14, 21, or 28 d postmortem. After completion of the designated aging period, steaks were removed from storage (2°C, never frozen), cooked to a peak internal temperature of 71°C, and evaluated using Warner-Bratzler shear force (WBSF). Analysis of WBSF revealed a 3-way interaction ($P = 0.004$) among individual muscle, USDA quality grade, and postmortem aging period. With the exception of the Select teres major, WBSF of all muscles (both quality grades) decreased with increasing time of postmortem storage. Nonlinear regression was used to characterize the extent (aging response) and rate of decrease in WBSF from 2 through 28 d postmortem for each muscle within each quality grade. In general, WBSF of upper two-thirds Choice muscles decreased more rapidly from 2 to 10 d postmortem than did corresponding Select muscles. Muscles that had greater aging responses generally had greater 2-d WBSF values. The upper two-thirds Choice psoas major, serratus ventralis, and vastus lateralis muscles required similar aging times to complete a majority of the aging response (≤0.1 kg of aging response remaining) compared with analogous Select muscles. The upper two-thirds Choice complexus, gluteus medius, semitendinosus, triceps brachii—long head, and vastus medialis muscles required 4 to 6 d less time to complete a majority of the aging response than did comparable Select muscles. Aging times for Select biceps femoris—long head, infraspinatus, longissimus dorsi, rectus femoris, semimembranosus, spinalis dorsi, supraspinatus, and tensor fasciae latae muscles were ≥7 d longer than those for corresponding upper two-thirds Choice muscles. Results from this study suggest that muscle-to-muscle tenderness differences depend on quality grade and aging time and that postmortem aging should be managed with respect to individual muscle and USDA quality grade.

Key words: aging, beef, meat grade, muscle, tenderness

J. Anim. Sci. 2006. 84:3387–3396
doi:10.2527/jas.2006-194

INTRODUCTION

Tenderness is considered to be the single most important factor influencing consumers' perceptions of taste (Savell et al., 1987, 1989), and consumer studies indicate that beef tenderness is the most important palatability trait for determining overall steak acceptance (Huffman et al., 1996; Platter et al., 2003). It is well documented that postmortem aging increases beef tenderness (Smith et al., 1978; Savell et al., 1981; Calkins and Seideman, 1988); however, The National Beef Tenderness Surveys (Morgan et al., 1991; Brooks et al., 2000) revealed substantial variation in the length of postmortem aging time of beef cuts.

Most previous studies documenting effects of postmortem aging on beef tenderness have involved the LM (Koohmaraie et al., 1991; O'Connor et al., 1997). Smith et al. (1978) reported that 11 or more days of postmortem aging would maximize tenderness of the majority of muscles from the chuck, rib, loin, and round of USDA Choice beef carcasses. Weatherly et al. (1998) suggested

[1]This project was funded by beef producers through their $1/head checkoff through the National Cattlemen's Beef Association, Centennial, CO.
[2]Corresponding author: Keith.Belk@colostate.edu
Received March 29, 2006.
Accepted July 19, 2006.

Table 1. Simple means and SD for carcass traits stratified by quality grade

	Upper two-thirds USDA Choice			USDA Select		
Trait	No.[1]	Mean	SD	No.	Mean	SD
Carcass weight, kg	40	375	32.8	40	356	15.3
Adjusted fat thickness, cm	35	1.32	0.34	40	1.06	0.33
Ribeye area, cm[2]	35	91.1	8.66	40	93.8	10.04
KPH, %	35	2.2	0.34	40	2.1	0.33
Calculated USDA yield grade	35	2.8	0.58	40	2.3	0.68
Marbling score[2]	40	575	48.9	40	351	19.1

[1]Values for adjusted fat thickness, ribeye area, and KPH percentage were inadvertently not recorded for 5 of the upper two-thirds USDA Choice carcasses.
[2]300 to 399 = Slight; 400 to 499 = Small; 500 to 599 = Modest.

postmortem aging times of 12, 13, 16, and 12 d for chuck rolls, striploins and shortloins, top rounds, and bottom rounds, respectively. Moreover, most beef aging research has relied on use of shear force data obtained after freezing and thawing of steaks, a method that Shanks et al. (2002) suggested may reduce shear force values.

One of the key strategies employed by the beef industry to increase beef demand has been to increase the utilization of muscles from the chuck and round through value-added and further-processed beef products. Muscle profiling research (NCBA, 2000) identified several individual muscles that possessed desirable tenderness, flavor attributes, or both and has contributed to increased interest in single-muscle beef cuts (Von-Seggern et al., 2005).

Therefore, the current study was conducted to determine the effects of postmortem aging on the tenderness of 17 individual beef muscles differing in USDA quality grade.

MATERIALS AND METHODS

Animal Care and Use Committee approval was not obtained for this study because the data were obtained from materials collected at a packing plant (see the next section).

Product Selection

United States Department of Agriculture Select (n = 40) and upper two-thirds USDA Choice (n = 40) beef carcasses were selected over a 7-mo period from a commercial packing plant (located in northeast Colorado) for use in this study (Table 1). Five carcasses of the same quality grade were selected during each of 16 sampling days. Carcasses traveled through 4 zones of electrical stimulation: 1) 17 V, 60 Hz, 15 s (1 s on, 1 s off); 2) 21 V, 60 Hz, 15 s (1 s on, 1 s off); 3) 25 V, 60 Hz, 20 s (1 s on; 1 s off); 4) 27 V, 60 Hz, 13 s (2 s on, 1 s off), and then were chilled in a cooler with an air temperature of 2°C for 36 h. For the first 8 h of the chill period, carcasses were sprayed intermittently (2 min on, 8 min off) with a fine mist of 2°C water.

Two days postmortem, the following subprimals (USDA, 1996) were removed from the right side of each carcass by in-plant fabrication: knuckle (IMPS 167), top round (IMPS 168), bottom round (IMPS 171 B), eye of round (IMPS 171 C), striploin (IMPS 180), sirloin (IMPS 181), tenderloin (IMPS 189), shoulder clod (IMPS 114), chuck tender (IMPS 116 B), and chuck roll (IMPS 116 C). In addition, the knuckle (IMPS 167), bottom sirloin (IMPS 185), shoulder clod (IMPS 114), chuck tender (IMPS 116 B), and chuck roll (IMPS 116 C) were removed from the left side of each carcass. Subprimals were then transported under refrigeration to the Colorado State University Meat Laboratory for further processing.

Muscle Fabrication and Steak Allocation

The following individual muscles were removed from the subprimal cuts: biceps femoris—long head (**BF**), complexus (**CP**), gluteus medius (**GM**), infraspinatus (**IF**), longissimus dorsi (**LM**), psoas major (**PM**), rectus femoris (**RF**), semimembranosus (**SM**), semitendinosus (**ST**), serratus ventralis (**SV**), spinalis dorsi (**SP**), supraspinatus (**SU**), tensor fasciae latae (**TF**), teres major (**TM**), triceps brachii—long head (**TB**), vastus lateralis (**VL**), and vastus medialis (**VM**; Table 2). For small-sized muscles, 2 muscles were removed from each carcass to obtain an adequate number of steaks (Table 2). Because of size, CP and SP muscles were fabricated as a muscle-group; individual muscle identification was maintained, but muscles remained grouped throughout sampling and cooking.

After fabrication, individual muscles within a carcass were hand-cut into steaks (2.54-cm thick), and 7 steaks obtained from every muscle were randomly assigned to 1 of the following aging periods: 2, 4, 6, 10, 14, 21, or 28 d. Steaks assigned to the 2-d aging period were immediately measured to determine Warner-Bratzler shear force (**WBSF**). The remaining 6 steaks from each muscle were vacuum-packaged and stored at 2°C for the designated aging period.

Warner-Bratzler Shear Force Determination

Upon completion of the designated aging times, the steaks were removed from storage (2°C, never frozen)

Table 2. Individual beef muscles removed from a carcass, the numbers of each muscle excised from a carcass, and the subprimal from which each muscle was removed

Muscle	No.	Subprimal	IMPS[1]
Biceps femoris—long head	1	Bottom round	171 B
Complexus[2]	2	Chuck roll	116 C
Gluteus medius	1	Sirloin	181
Infraspinatus	2	Shoulder clod	114
Longissimus dorsi	1	Striploin	180
Psoas major	1	Tenderloin	189
Rectus femoris	2	Knuckle	167
Semimembranosus	1	Top round	168
Semitendinosus	1	Eye of round	171 C
Serratus ventralis	2	Chuck roll	116 C
Spinalis dorsi[2]	2	Chuck roll	116 C
Supraspinatus	2	Chuck tender	116 B
Tensor fasciae latae[3]	2	Bottom sirloin	185
Teres major	2	Shoulder clod	114
Triceps brachii—long head	2	Shoulder clod	114
Vastus lateralis	2	Knuckle	167
Vastus medialis	2	Knuckle	167

[1]IMPS = Institutional Meat Purchase Specifications (USDA, 1996).
[2]Complexus and spinalis dorsi muscles were fabricated from the chuck roll as a muscle-group; individual muscle identification was maintained, but muscles remained together throughout sampling and cooking.
[3]Tensor fasciae latae was excised from the sirloin (IMPS 181) removed from the right side of each carcass and excised from the bottom sirloin (IMPS 185) from the left side of each carcass.

for shear force determination. Steaks most similar in thickness (small variations in thickness resulted from hand-cutting of the steaks) were cooked in groups of 3 on electric grills (model GGR64, Salton Inc., Lake Forest, IL) that heated the steaks from both sides simultaneously to a peak internal temperature of 71°C. A Type K thermocouple (Omega Engineering Inc., Stamford, CT) was placed in the geometric center of each steak, and the internal temperature was monitored during cooking using a microprocessor thermometer (model HH21, Omega Engineering Inc., Stamford, CT).

After cooking, the steaks were allowed to equilibrate to room temperature (22°C) and up to 10 cores (1.27-cm diam.) were removed from each steak parallel to the muscle fiber. On the same day as cooking, after cooling to room temperature, each core was sheared once, perpendicular to the muscle fiber, with an Instron testing machine (model 4443, Instron Corp., Canton, MA) fitted with a Warner-Bratzler shear head (crosshead speed of 200 mm/min); peak shear force measurements were recorded and averaged to obtain a single shear force value for each steak.

Statistical Methods

Analysis of WBSF was conducted for a repeated measures design using REML in the MIXED procedure (SAS Inst. Inc., Cary, NC); carcass served as the experimental unit. The model included fixed effects of muscle, quality grade (grade), postmortem aging period (age), and the 2- and 3-way interactions. Random effects included carcass nested within grade, and the 2-way interactions of carcass within grade × muscle, and carcass within grade × age. The Satterthwaite approximation was used to calculate denominator degrees of freedom, and peak internal steak temperature served as a covariate. This analysis revealed a 3-way interaction (P = 0.004) among muscle, grade, and age. Fisher's LSD were calculated ($P < 0.05$) for comparisons of least squares means within a muscle × grade subclass, and for comparisons across muscle, quality grade, and aging period (muscle × grade × age).

Nonlinear regression (PROC NLIN, SAS) was used to characterize the change in WBSF during postmortem storage. Within each muscle × grade subclass, least squares means (muscle × grade × age) were fitted to the following exponential decay model: $WBSF = b_2 + b_1 \exp(-b_0 t)$, where b_2 is the distance from zero to the asymptote, b_1 is the distance from the asymptote to the y-intercept, b_0 is a constant rate of change, and t is the time postmortem, in days. Instantaneous rates of change at a given time during postmortem storage were estimated by the first derivative of each model, as $\frac{dWBSF}{dt} = -b_0 b_1 \exp(-b_0 t)$. Coefficients of determination (r^2) were calculated as the ratio of the residual sums of squares to the corrected total sums of squares.

RESULTS AND DISCUSSION

Most previous studies documenting the effects of postmortem aging on beef tenderness have been confined to 1 or only a few individual muscles (Parrish et al., 1973; Calkins and Seideman, 1988; O'Connor et al., 1997). Studies investigating effects of muscle on shear force have been limited to comparisons within a postmortem aging period (Johnson et al., 1988; Shackelford et al., 1995; Belew et al., 2003) or quality grade (Ramsbottom et al., 1945; Smith et al., 1978). Bratcher et al. (2005) examined aging patterns of 9 USDA Select and upper two-thirds USDA Choice beef muscles from 7 through 28 d postmortem and reported that the effect of postmortem aging on beef tenderness was not affected by individual muscle (muscle × age; $P > 0.05$) but was dependent on USDA quality grade (age × grade; $P < 0.05$). Results from the current study do not support the conclusions of Bratcher et al. (2005). In our study, individual muscle, postmortem aging period, and USDA quality grade interacted (muscle × age × grade; P = 0.004) to affect WBSF. The following discussion describes the cumulative effects of these factors on WBSF values of beef.

Effects of Postmortem Aging

Least squares means for WBSF of USDA Select and upper two-thirds USDA Choice (premium Choice) beef muscles at 7 postmortem aging periods are reported in Table 3. With the exception of the Select TM, WBSF values of all muscles (both quality grades) decreased

Table 3. Least squares means ± SEM of Warner-Bratzler shear force (kg) for USDA Select and upper two-thirds USDA Choice beef muscles at 7 postmortem aging periods[1]

	Time postmortem, d						
Muscle	2	4	6	10	14	21	28
USDA Select							
Biceps femoris	6.01 ± 0.15	5.67 ± 0.14	5.45 ± 0.14	5.32 ± 0.14	5.47 ± 0.15	4.97 ± 0.14	4.75 ± 0.14
Complexus	6.14 ± 0.15	5.88 ± 0.14	5.58 ± 0.14	5.28 ± 0.14	5.20 ± 0.15	4.87 ± 0.14	4.22 ± 0.14
Gluteus medius	6.12 ± 0.15	6.29 ± 0.14	5.68 ± 0.14	5.48 ± 0.14	5.51 ± 0.15	4.96 ± 0.14	4.58 ± 0.14
Infraspinatus	4.80 ± 0.15	4.52 ± 0.14	4.35 ± 0.15	4.14 ± 0.14	3.79 ± 0.15	3.67 ± 0.14	3.32 ± 0.14
Longissimus dorsi	6.64 ± 0.15	6.37 ± 0.14	5.91 ± 0.14	5.51 ± 0.14	5.02 ± 0.15	4.52 ± 0.14	4.21 ± 0.14
Psoas major	4.50 ± 0.15	4.49 ± 0.14	4.50 ± 0.14	3.96 ± 0.14	3.89 ± 0.15	3.59 ± 0.14	3.22 ± 0.14
Rectus femoris	5.27 ± 0.15	5.22 ± 0.14	4.95 ± 0.14	4.67 ± 0.14	4.46 ± 0.15	4.16 ± 0.14	4.04 ± 0.14
Semimembranosus	7.41 ± 0.15	6.81 ± 0.14	6.21 ± 0.14	5.81 ± 0.14	5.69 ± 0.15	5.08 ± 0.14	4.96 ± 0.14
Semitendinosus	6.41 ± 0.15	5.88 ± 0.14	5.73 ± 0.14	5.43 ± 0.14	5.21 ± 0.15	4.82 ± 0.14	4.74 ± 0.14
Serratus ventralis	4.68 ± 0.15	4.61 ± 0.14	4.43 ± 0.14	4.25 ± 0.14	4.04 ± 0.15	3.91 ± 0.14	3.63 ± 0.14
Spinalis dorsi	4.99 ± 0.15	4.46 ± 0.14	4.23 ± 0.14	4.23 ± 0.15	4.01 ± 0.15	3.70 ± 0.14	3.51 ± 0.14
Supraspinatus	6.01 ± 0.15	5.68 ± 0.14	5.30 ± 0.14	5.09 ± 0.14	4.86 ± 0.15	4.53 ± 0.14	4.35 ± 0.14
Tensor fasciae latae	5.07 ± 0.15	4.74 ± 0.14	4.61 ± 0.14	4.20 ± 0.14	4.30 ± 0.15	4.07 ± 0.14	3.85 ± 0.14
Teres major	4.17 ± 0.15	4.27 ± 0.15	4.38 ± 0.14	4.13 ± 0.14	4.18 ± 0.15	4.20 ± 0.14	3.88 ± 0.15
Triceps brachii	5.77 ± 0.15	5.18 ± 0.14	4.96 ± 0.14	4.57 ± 0.14	4.52 ± 0.15	4.28 ± 0.15	3.94 ± 0.14
Vastus lateralis	6.23 ± 0.15	5.71 ± 0.14	5.49 ± 0.14	4.93 ± 0.14	5.00 ± 0.15	4.79 ± 0.14	4.43 ± 0.14
Vastus medialis	5.76 ± 0.15	5.34 ± 0.15	5.28 ± 0.14	4.64 ± 0.14	4.57 ± 0.15	4.02 ± 0.14	3.89 ± 0.15
Upper two-thirds USDA Choice							
Biceps femoris	5.08 ± 0.15	4.72 ± 0.14	4.65 ± 0.14	4.70 ± 0.14	4.48 ± 0.16	4.56 ± 0.14	4.58 ± 0.14
Complexus	5.48 ± 0.15	4.87 ± 0.14	4.89 ± 0.15	4.63 ± 0.14	4.16 ± 0.15	4.03 ± 0.14	3.92 ± 0.14
Gluteus medius	5.45 ± 0.15	5.04 ± 0.14	4.89 ± 0.14	4.63 ± 0.14	4.53 ± 0.15	4.44 ± 0.14	4.14 ± 0.14
Infraspinatus	4.61 ± 0.15	3.77 ± 0.14	3.89 ± 0.14	3.56 ± 0.14	3.24 ± 0.15	3.25 ± 0.14	2.99 ± 0.14
Longissimus dorsi	5.64 ± 0.15	4.90 ± 0.14	4.30 ± 0.14	3.94 ± 0.14	3.96 ± 0.15	3.66 ± 0.14	3.55 ± 0.14
Psoas major	4.29 ± 0.15	4.09 ± 0.14	3.94 ± 0.14	3.73 ± 0.14	3.57 ± 0.15	3.36 ± 0.14	3.17 ± 0.14
Rectus femoris	5.03 ± 0.15	4.51 ± 0.14	4.25 ± 0.14	4.30 ± 0.14	4.32 ± 0.16	3.81 ± 0.14	3.90 ± 0.14
Semimembranosus	5.93 ± 0.15	5.62 ± 0.15	5.08 ± 0.14	4.82 ± 0.14	4.68 ± 0.15	4.69 ± 0.14	4.45 ± 0.14
Semitendinosus	6.17 ± 0.15	5.62 ± 0.14	5.20 ± 0.14	5.14 ± 0.14	4.94 ± 0.15	4.81 ± 0.14	4.51 ± 0.14
Serratus ventralis	4.10 ± 0.15	4.05 ± 0.14	3.97 ± 0.14	3.68 ± 0.14	3.68 ± 0.15	3.48 ± 0.14	3.20 ± 0.14
Spinalis dorsi	4.58 ± 0.15	4.03 ± 0.14	4.08 ± 0.15	3.67 ± 0.14	3.63 ± 0.16	3.48 ± 0.14	3.55 ± 0.14
Supraspinatus	5.93 ± 0.15	5.04 ± 0.14	5.05 ± 0.14	4.71 ± 0.14	4.59 ± 0.15	4.36 ± 0.14	4.31 ± 0.14
Tensor fasciae latae	4.70 ± 0.15	4.23 ± 0.14	4.05 ± 0.14	3.84 ± 0.14	3.84 ± 0.15	3.77 ± 0.14	3.51 ± 0.14
Teres major	4.18 ± 0.15	4.04 ± 0.14	3.81 ± 0.14	3.91 ± 0.14	3.55 ± 0.16	3.61 ± 0.14	3.45 ± 0.14
Triceps brachii	5.41 ± 0.15	4.59 ± 0.14	4.54 ± 0.14	4.30 ± 0.14	4.19 ± 0.15	3.99 ± 0.14	3.76 ± 0.14
Vastus lateralis	5.75 ± 0.15	5.29 ± 0.14	5.08 ± 0.14	4.72 ± 0.14	4.57 ± 0.15	4.36 ± 0.14	4.17 ± 0.14
Vastus medialis	5.47 ± 0.15	5.37 ± 0.14	4.69 ± 0.14	4.24 ± 0.14	4.03 ± 0.16	3.89 ± 0.14	3.72 ± 0.14

[1]Within a muscle × grade subclass, LSD ($P < 0.05$) = 0.31 kg. Within a muscle × grade × age subclass, LSD = 0.43 kg ($P < 0.05$).

with increasing time of postmortem storage. Difficulties associated with sampling and cooking small muscles and steaks may explain the lack of change in WBSF of the Select TM.

Several studies have reported recommended aging times for individual muscles or beef subprimals based on improvements in shear force (Smith et al., 1978; Weatherly et al., 1998; Bratcher et al., 2005). Smith et al. (1978) found no improvement in shear force past 5 d postmortem for the VM, past 8 d postmortem for the CP and SV, and after 11 d postmortem for the BF, IF, LM, RF, SM, ST, and SP (USDA Choice). More recently, Weatherly et al. (1998) suggested postmortem aging times of 13, 12, 16, and 12 d for striploins and short loins, chuck rolls, top rounds, and bottom rounds, respectively. It was suggested by Bratcher et al. (2005) that CP, IF, SV, TB, and VL muscles be aged for 7 d if removed from upper two-thirds Choice carcasses and for at least 14 d if fabricated from Select carcasses.

Results from the current study (Table 3) showed no improvement ($P > 0.05$) in WBSF (decrease) past 21 d postmortem for 9 of 16 Select muscles (BF, RF, SM, ST, SV, SP, SU, TF, and VM), whereas WBSF of the remaining 7 Select muscles (CP, GM, IF, LM, PM, TB, and VL) improved ($P < 0.05$) up to 28 d postmortem. Of the 17 muscles removed from premium Choice carcasses, 6 muscles (CP, IF, SM, SU, TM, and VM) showed no improvement ($P > 0.05$) in WBSF past 14 d postmortem, and 9 muscles (GM, LM, PM, RF, ST, SV, TF, TB, and VL) showed no improvement ($P > 0.05$) in shear force past 21 d postmortem. Warner-Bratzler shear force of the upper two-thirds Choice BF and SP improved up to 4 and 10 d postmortem, respectively.

Although least squares means of WBSF at distinct postmortem aging periods (Table 3) can aid in determination of appropriate aging times for individual muscles differing in quality grade, a detailed characterization of the extent and rate of postmortem tenderization

Table 4. Coefficients of determination (r^2) and parameter estimates for models fitted to USDA Select beef muscles

Muscle	Parameter estimate[1]			
	r^2	b_2	b_1	b_0
Biceps femoris	0.89	4.2224	1.7756	0.0400
Complexus	0.96	1.7703	4.4266	0.0197
Gluteus medius	0.93	2.2388	4.0956	0.0196
Infraspinatus	0.98	2.9827	1.9880	0.0590
Longissimus dorsi	0.99	3.6024	3.4661	0.0629
Psoas major	0.96	0.5662	4.1254	0.0158
Rectus femoris	0.99	3.7101	1.8391	0.0641
Semimembranosus	0.98	4.9081	3.1205	0.1239
Semitendinosus	0.98	4.6149	2.0793	0.1000
Serratus ventralis	0.99	3.1226	1.6924	0.0409
Spinalis dorsi	0.93	3.4579	1.6558	0.0933
Supraspinatus	0.99	4.2584	2.0725	0.0970
Tensor fasciae latae	0.95	3.8670	1.4597	0.1171
Teres major[2]	—	—	—	—
Triceps brachii	0.96	4.0214	2.1275	0.1288
Vastus lateralis	0.96	4.5494	2.1678	0.1431
Vastus medialis	0.98	3.5104	2.5354	0.0720

[1]Parameter estimates correspond to the following nonlinear regression model: $WBSF = b_2 + b_1 \exp(-b_0 t)$.
[2]Warner-Bratzler shear force (WBSF) of teres major could not be fitted to a nonlinear regression model because no improvement in WBSF occurred with aging to 28 d.

Table 5. Coefficients of determination (r^2) and parameter estimates for models fitted to upper two-thirds USDA Choice beef muscles

Muscle	Parameter estimate[1]			
	r^2	b_2	b_1	b_0
Biceps femoris	0.89	4.5757	1.4024	0.5163
Complexus	0.96	3.8104	1.9448	0.1049
Gluteus medius	0.96	4.2159	1.5025	0.1246
Infraspinatus	0.91	3.1010	1.9420	0.1718
Longissimus dorsi	0.98	3.6626	3.1978	0.2425
Psoas major	0.99	2.9766	1.4902	0.0665
Rectus femoris	0.83	3.9416	1.4036	0.1785
Semimembranosus	0.97	4.5352	2.1006	0.1945
Semitendinosus	0.95	4.6689	2.0348	0.1766
Serratus ventralis	0.97	1.7736	2.4222	0.0182
Spinalis dorsi	0.95	3.5163	1.5595	0.2089
Supraspinatus	0.94	4.3982	2.2824	0.2316
Tensor fasciae latae	0.94	3.6685	1.5747	0.2301
Teres major	0.88	3.4289	0.8864	0.0987
Triceps brachii	0.92	3.9272	2.0345	0.2000
Vastus lateralis	0.99	4.1714	1.9635	0.1244
Vastus medialis	0.97	3.7059	2.4892	0.1376

[1]Parameter estimates correspond to the following nonlinear regression model: $WBSF = b_2 + b_1 \exp(-b_0 t)$.

may also prove useful in identifying suitable strategies for management of postmortem tenderization. To characterize the extent and rate of change in shear force that occurred during postmortem storage, nonlinear regression models were fitted to least squares means of WBSF for each muscle of both quality grades (Table 3). Parameter estimates and coefficients of determination (r^2) for each nonlinear regression model are displayed in Tables 4 and 5.

Instantaneous rate of change in WBSF was estimated for each muscle of both quality grades by calculating the first derivative of the nonlinear regression model at particular points of interest (Table 6). In general, WBSF of premium Choice muscles decreased more rapidly from 2 to 10 d postmortem than corresponding Select muscles. Exceptions included the Select SM, SV, and VL muscles; WBSF of these Select muscles decreased more rapidly from 2 to 10 d postmortem than analogous upper two-thirds Choice muscles. The 28-d rate of change in WBSF was ≤0.05 kg for Select muscles, and ≤0.03 kg for premium Choice muscles.

Nonlinear regression models were used to calculate predicted WBSF values from 2 through 28 d postmortem (not presented in tabular form). Predicted 2-d WBSF values and the change in shear force between 2 and 28 d postmortem (aging response) are displayed in Tables 7 and 8 for Select and upper two-thirds Choice muscles, respectively. For purposes of discussion, aging responses ($\bar{x}$ = 1.4 kg, SD = 0.4 kg) were categorized as follows: ≥2.2 kg (high); 2.1 to 1.8 kg (moderately high); 1.7 to 1.1 kg (moderate); 1.0 to 0.7 kg (moderately low); and ≤0.6 kg (low). With the exception of the Select SV, muscles within the Select quality grade had high, moderately high, or moderate aging responses. Premium Choice muscles possessed moderately high, moderate, moderately low, and low aging responses. In general, muscles that had greater aging responses had higher 2-d WBSF values; regardless of quality grade, all muscles that had high or moderately high aging responses had 2-d shear force values greater than 5.5 kg, and muscles with moderately low or low aging responses had 2-d WBSF values less than 5.5 kg.

To combine extent (aging response) and rate at which tenderness changed throughout aging, shear force values predicted by the nonlinear regression models were used to determine the percentage of the aging response that was completed following each day of postmortem aging for individual muscles of both quality grades (predicted values for WBSF at 2 and 28 d postmortem considered 0 and 100% of aging response complete, respectively). Tables 7 and 8 display the percentage of aging response completed at each of 6 postmortem aging periods for USDA Select and upper two-thirds USDA Choice muscles, respectively. Inconsistencies in the rate at which aging response was completed were observed within muscle across quality grade (Figure 1). For example, the Select LM achieved only 86.6% of a 2.5 kg aging response after 21 d of aging, whereas the LM from premium Choice carcasses completed 94.7% of a 2.0 kg change by 14 d postmortem. Tensor fasciae latae muscles had an aging response of approximately 1.0 kg, and 79.2 and 93.9% of this response was complete at 14 d postmortem for Select and upper two-thirds Choice carcasses, respectively. The VL had an aging response of approximately 1.5 kg and completed greater than 90% of this change in shear force by 21 d postmortem, regardless of quality grade.

Table 6. Rate of change in Warner-Bratzler shear force (WBSF; kg/instantaneous unit of time) at 12 postmortem aging periods, as estimated by nonlinear regression models[1] fitted to USDA Select and upper two-thirds USDA Choice beef muscles

		Time postmortem, d											
Muscle	Quality grade	2	3	4	5	6	7	8	9	10	14	21	28
Biceps femoris	Select	−0.07	−0.06	−0.06	−0.06	−0.06	−0.05	−0.05	−0.05	−0.05	−0.04	−0.03	−0.02
Biceps femoris	Upper two-thirds Choice	−0.26	−0.15	−0.09	−0.05	−0.03	−0.02	−0.01	−0.01	0.00	0.00	0.00	0.00
Complexus	Select	−0.08	−0.08	−0.08	−0.08	−0.08	−0.08	−0.07	−0.07	−0.07	−0.07	−0.06	−0.05
Complexus	Upper two-thirds Choice	−0.17	−0.15	−0.13	−0.12	−0.11	−0.10	−0.09	−0.08	−0.07	−0.05	−0.02	−0.01
Gluteus medius	Select	−0.08	−0.08	−0.07	−0.07	−0.07	−0.07	−0.07	−0.07	−0.07	−0.06	−0.05	−0.05
Gluteus medius	Upper two-thirds Choice	−0.15	−0.13	−0.11	−0.10	−0.09	−0.08	−0.07	−0.06	−0.05	−0.03	−0.01	−0.01
Infraspinatus	Select	−0.10	−0.10	−0.09	−0.09	−0.08	−0.08	−0.07	−0.07	−0.07	−0.05	−0.03	−0.02
Infraspinatus	Upper two-thirds Choice	−0.24	−0.20	−0.17	−0.14	−0.12	−0.10	−0.08	−0.07	−0.06	−0.03	−0.01	0.00
Longissimus dorsi	Select	−0.19	−0.18	−0.17	−0.16	−0.15	−0.14	−0.13	−0.12	−0.12	−0.09	−0.06	−0.04
Longissimus dorsi	Upper two-thirds Choice	−0.48	−0.37	−0.29	−0.23	−0.18	−0.14	−0.11	−0.09	−0.07	−0.03	0.00	0.00
Psoas major	Select	−0.06	−0.06	−0.06	−0.06	−0.06	−0.06	−0.06	−0.06	−0.06	−0.05	−0.05	−0.04
Psoas major	Upper two-thirds Choice	−0.09	−0.08	−0.08	−0.07	−0.07	−0.06	−0.06	−0.05	−0.05	−0.04	−0.02	−0.02
Rectus femoris	Select	−0.10	−0.10	−0.09	−0.09	−0.08	−0.08	−0.07	−0.07	−0.06	−0.05	−0.03	−0.02
Rectus femoris	Upper two-thirds Choice	−0.18	−0.15	−0.12	−0.10	−0.09	−0.07	−0.06	−0.05	−0.04	−0.02	−0.01	0.00
Semimembranosus	Select	−0.30	−0.27	−0.24	−0.21	−0.18	−0.16	−0.14	−0.13	−0.11	−0.07	−0.03	−0.01
Semimembranosus	Upper two-thirds Choice	−0.28	−0.23	−0.19	−0.15	−0.13	−0.10	−0.09	−0.07	−0.06	−0.03	−0.01	0.00
Semitendinosus	Select	−0.17	−0.15	−0.14	−0.13	−0.11	−0.10	−0.09	−0.08	−0.08	−0.05	−0.03	−0.01
Semitendinosus	Upper two-thirds Choice	−0.25	−0.21	−0.18	−0.15	−0.12	−0.10	−0.09	−0.07	−0.06	−0.03	−0.01	0.00
Serratus ventralis	Select	−0.06	−0.06	−0.06	−0.06	−0.05	−0.05	−0.05	−0.05	−0.05	−0.04	−0.03	−0.02
Serratus ventralis	Upper two-thirds Choice	−0.04	−0.04	−0.04	−0.04	−0.04	−0.04	−0.04	−0.04	−0.04	−0.03	−0.03	−0.03
Spinalis dorsi	Select	−0.13	−0.12	−0.11	−0.10	−0.09	−0.08	−0.07	−0.07	−0.06	−0.04	−0.02	−0.01
Spinalis dorsi	Upper two-thirds Choice	−0.21	−0.17	−0.14	−0.11	−0.09	−0.08	−0.06	−0.05	−0.04	−0.02	0.00	0.00
Supraspinatus	Select	−0.17	−0.15	−0.14	−0.12	−0.11	−0.10	−0.09	−0.08	−0.08	−0.05	−0.03	−0.01
Supraspinatus	Upper two-thirds Choice	−0.33	−0.26	−0.21	−0.17	−0.13	−0.10	−0.08	−0.07	−0.05	−0.02	0.00	0.00
Tensor fascia latae	Select	−0.14	−0.12	−0.11	−0.10	−0.08	−0.08	−0.07	−0.06	−0.05	−0.03	−0.01	−0.01
Tensor fascia latae	Upper two-thirds Choice	−0.23	−0.18	−0.14	−0.11	−0.09	−0.07	−0.06	−0.05	−0.04	−0.01	0.00	0.00
Teres major[2]	Select	—	—	—	—	—	—	—	—	—	—	—	—
Teres major	Upper two-thirds Choice	−0.07	−0.07	−0.06	−0.05	−0.05	−0.04	−0.04	−0.04	−0.03	−0.02	−0.01	−0.01
Triceps brachii	Select	−0.21	−0.19	−0.16	−0.14	−0.13	−0.11	−0.10	−0.09	−0.08	−0.05	−0.02	−0.01
Triceps brachii	Upper two-thirds Choice	−0.27	−0.22	−0.18	−0.15	−0.12	−0.10	−0.08	−0.07	−0.06	−0.02	−0.01	0.00
Vastus lateralis	Select	−0.23	−0.20	−0.18	−0.15	−0.13	−0.11	−0.10	−0.09	−0.07	−0.04	−0.02	−0.01
Vastus lateralis	Upper two-thirds Choice	−0.19	−0.17	−0.15	−0.13	−0.12	−0.10	−0.09	−0.08	−0.07	−0.04	−0.02	−0.01
Vastus medialis	Select	−0.16	−0.15	−0.14	−0.13	−0.12	−0.11	−0.10	−0.10	−0.09	−0.07	−0.04	−0.02
Vastus medialis	Upper two-thirds Choice	−0.26	−0.23	−0.20	−0.17	−0.15	−0.13	−0.11	−0.10	−0.09	−0.05	−0.02	−0.01

[1]Nonlinear regression model: $WBSF = b_2 + b_1 \exp(-b_0 t)$. Rate of change calculated by first derivative: $\frac{dWBSF}{dt} = -b_0 b_1 \exp(-b_0 t)$.

[2]Warner-Bratzler shear force of Select teres major could not be fitted to a nonlinear regression model because no improvement in WBSF occurred with aging to 28 d.

Comparisons among muscles within quality grades also revealed inconsistent rates of postmortem tenderization. The Select GM and VL muscles had similar 2-d WBSF values (6.18 kg) and aging responses (1.6 kg); however, after 14 and 21 d of postmortem storage, the GM completed 52.5 and 77.9% of the aging response, respectively, whereas the VL achieved 84.1 and 95.7% of the aging response, respectively. Similarly, the upper two-thirds Choice SV and SP had equivalent aging responses (0.9 vs. 1.0 kg) but varying rates of change in shear force. Following 10 and 21 d of postmortem aging, the upper two-thirds Choice SV accomplished 35.9 and 77.5% of the aging response, respectively, and the upper two-thirds Choice SP muscle had completed 81.6 and 98.5% of the aging response, respectively.

The length of postmortem aging required for a muscle of each quality grade to complete a majority of its respective aging response is listed in Table 9. Aging times (d postmortem) for muscles with high, moderately high, moderate, moderately low, and low aging responses correspond to the day that at least 96, 95, 94, 90, and 85% of the aging response was completed, respectively. Aging periods longer than those listed (up to 28 d) in Table 9 resulted in an additional decrease in WBSF of ≤0.1 kg. In general, Select muscles required 20 d or longer of postmortem aging to achieve a majority of their respective aging response. Premium Choice PM, SV, and VL muscles required similar aging times to complete a majority of the aging response when compared with analogous Select muscles. A majority of the aging response was completed by upper two-thirds Choice CP, GM, ST, TB, and VM muscles 4 to 6 d sooner than for comparable Select muscles. Aging times for Select BF, IF, LM, RF, SM, SP, and TF muscles were 7 d or longer than aging times for corresponding premium Choice muscles.

Table 7. Warner-Bratzler shear force (WBSF) of USDA Select muscles at 2 d postmortem (kg), the change in shear force through 28 d postmortem (aging response), and the percentage (%) of that change completed at each of 6 postmortem aging periods

Muscle	2-d WBSF[1]	Aging response,[2] kg	Time postmortem, d					
			4	6	10	14	21	28
Biceps femoris	5.86	1.1	11.9	22.9	42.4	59.0	82.3	100.0
Complexus	6.03	1.7	9.6	18.9	36.4	52.5	77.9	100.0
Gluteus medius	6.18	1.6	9.6	18.9	36.3	52.5	77.9	100.0
Infraspinatus	4.75	1.4	14.2	26.8	48.0	64.7	85.9	100.0
Longissimus dorsi	6.66	2.5	14.7	27.6	49.1	65.8	86.6	100.0
Psoas major	4.56	1.3	9.2	18.2	35.2	51.3	77.0	100.0
Rectus femoris	5.33	1.3	14.8	27.9	49.5	66.2	86.8	100.0
Semimembranosus	7.34	2.3	22.9	40.7	65.5	80.6	94.3	100.0
Semitendinosus	6.32	1.6	19.6	35.6	59.5	75.5	91.9	100.0
Serratus ventralis	4.68	1.0	12.0	23.1	42.6	59.2	82.5	100.0
Spinalis dorsi	4.83	1.3	18.7	34.2	57.7	73.9	91.1	100.0
Supraspinatus	5.97	1.6	19.2	35.0	58.7	74.8	91.5	100.0
Tensor fasciae latae	5.02	1.1	21.9	39.3	63.9	79.2	93.7	100.0
Teres major[3]	—	—	—	—	—	—	—	—
Triceps brachii	5.67	1.6	23.5	41.7	66.7	81.5	94.7	100.0
Vastus lateralis	6.18	1.6	25.5	44.7	69.9	84.1	95.7	100.0
Vastus medialis	5.71	1.9	15.8	29.6	51.7	68.4	88.1	100.0

[1]WBSF at 2 d postmortem predicted by a nonlinear regression model.
[2]Aging response equal to predicted 2-d WBSF minus predicted 28-d WBSF.
[3]Warner-Bratzler shear force of teres major could not be fitted to a nonlinear regression model because no improvement in WBSF occurred with aging to 28 d.

Individual Muscle Tenderness

Warner-Bratzler shear force of individual muscles varied greatly. At 2 d postmortem, the range in shear force across all muscles of both quality grades was 3.30 kg; the range in 2-d WBSF of Select muscles was greater than that of premium Choice muscles (3.24 vs. 2.07 kg). The range in WBSF among muscles decreased with increased aging time, across and within quality grades. The range in WBSF among 28-d muscles across both quality grades was 1.97 kg (Select 1.74 kg; upper two-thirds Choice 1.59 kg).

Because of differences in extent and rate of postmortem tenderization, the rank of muscles by WBSF within

Table 8. Warner-Bratzler shear force (WBSF) of upper two-thirds USDA Choice muscles at 2 d postmortem (kg), the change in shear force through 28 d postmortem (aging response), and the percentage (%) of that change completed at each of 6 postmortem aging periods

Muscle	2-d WBSF[1]	Aging response,[2] kg	Time postmortem, d					
			4	6	10	14	21	28
Biceps femoris	5.08	0.5	64.4	87.3	98.4	99.8	99.9	100.0
Complexus	5.39	1.5	20.2	36.7	60.8	76.6	92.4	100.0
Gluteus medius	5.39	1.1	23.0	40.9	65.7	80.7	94.3	100.0
Infraspinatus	4.48	1.4	29.4	50.3	75.6	88.3	97.3	100.0
Longissimus dorsi	5.63	2.0	38.5	62.2	85.8	94.7	99.2	100.0
Psoas major	4.28	1.1	15.1	28.4	50.1	66.8	87.2	100.0
Rectus femoris	4.92	1.0	30.3	51.5	76.8	89.1	97.6	100.0
Semimembranosus	5.96	1.4	32.4	54.4	79.4	90.9	98.1	100.0
Semitendinosus	6.10	1.4	30.1	51.2	76.4	88.9	97.5	100.0
Serratus ventralis	4.11	0.9	9.5	18.6	35.9	52.0	77.5	100.0
Spinalis dorsi	4.54	1.0	34.3	56.9	81.6	92.3	98.5	100.0
Supraspinatus	5.83	1.4	37.2	60.5	84.5	94.0	99.0	100.0
Tensor fasciae latae	4.67	1.0	37.0	60.3	84.3	93.9	99.0	100.0
Teres major	4.16	0.7	19.4	35.3	59.1	75.2	91.7	100.0
Triceps brachii	5.29	1.4	33.2	55.4	80.3	91.4	98.3	100.0
Vastus lateralis	5.70	1.5	22.9	40.8	65.6	80.7	94.0	100.0
Vastus medialis	5.60	1.8	24.7	43.5	68.7	83.1	95.3	100.0

[1]WBSF at 2 d postmortem predicted by a nonlinear regression model.
[2]Aging response equal to predicted 2-d WBSF minus predicted 28-d WBSF.

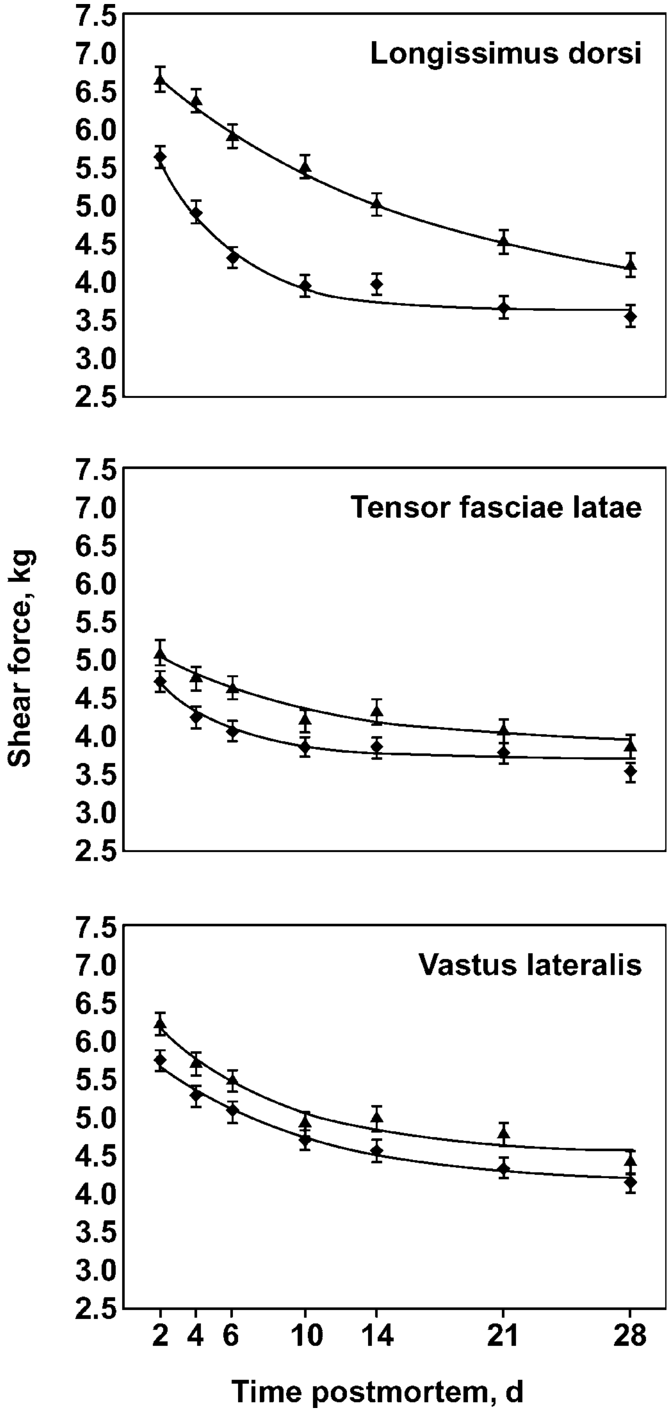

Figure 1. Least squares means ± SEM for Warner-Bratzler shear force of USDA Select (▲) and upper two-thirds USDA Choice (◆) longissimus dorsi, tensor fasciae latae, and vastus lateralis muscles at 7 postmortem aging periods, and the nonlinear regression models ($WBSF = b_2 + b_1 \exp(-b_0 t)$ fitted to these points.

and across quality grades changed with increasing time of postmortem storage (Table 10). Postmortem aging improved WBSF values (Table 3) of virtually all muscles (except for the Select TM). However, when muscles of both quality grades were ranked by WBSF within

Table 9. Change in shear force from 2 through 28 d postmortem (aging response, kg) and the length of postmortem aging (d) needed for the majority of this change to occur for USDA Select and upper two-thirds Choice beef muscles

	USDA Select		Upper two-thirds USDA Choice	
Muscle	Aging response	Aging time[1]	Aging response	Aging time[1]
Biceps femoris	1.1	26	0.5	6
Complexus	1.7	27	1.5	23
Gluteus medius	1.6	27	1.1	21
Infraspinatus	1.4	25	1.4	18
Longissimus dorsi	2.5	26	2.0	15
Psoas major	1.3	27	1.1	25
Rectus femoris	1.3	25	1.0	15
Semimembranosus	2.3	23	1.4	16
Semitendinosus	1.6	23	1.4	18
Serratus ventralis	1.0	24	0.9	25
Spinalis dorsi	1.3	23	1.0	13
Supraspinatus	1.6	23	1.4	14
Tensor fasciae latae	1.1	22	1.0	12
Teres major[2]	—	—	0.7	21
Triceps brachii	1.6	21	1.4	16
Vastus lateralis	1.6	20	1.5	21
Vastus medialis	1.9	25	1.8	21

[1]Aging times for muscles with aging responses ≥2.2 kg (high), 2.1 to 1.8 kg (moderately high), 1.7 to 1.1 kg (moderate), 1.0 to 0.7 kg (moderately low), and ≤0.6 kg (low) correspond to the day that at least 96, 95, 94, 90, and 85% of the aging response was completed, respectively.

[2]Warner-Bratzler shear force of Select teres major did not decrease with increasing time of postmortem storage.

each aging period, several muscles were continually ranked within the toughest one-third: Select BF, CP, GM, SM, ST, SU, and VL, as well as the premium Choice SM and ST muscles. Likewise, within each of the 7 aging periods, the premium Choice IF, PM, SV, SP, TF, and TM muscles and Select IF were consistently ranked within the most tender one-third of all muscles.

Nelson et al. (2004) found that steaks from 14-d premium Choice BF, GM, LM, and TB muscles were more tender ($P < 0.05$) than steaks from analogous Select muscles and that WBSF values for upper two-thirds Choice SM muscles were similar ($P > 0.05$) to those of the Select SM. Our results generally agreed with those of Nelson et al. (2004); however, no difference ($P > 0.05$) in 14-d WBSF was detected between upper two-thirds Choice and Select TB steaks, and upper two-thirds Choice SM steaks were more tender ($P < 0.05$) than steaks from Select SM muscles.

Although 14-d within-muscle comparisons of WBSF values showed that steaks from premium Choice GM muscles were more tender ($P < 0.05$) than steaks from Select GM muscles, WBSF values for 14-d upper two-thirds Choice GM muscles were similar ($P > 0.05$) to those of 28-d Select GM muscles (4.53 ± 0.15 vs. 4.58 ± 0.14 kg). Comparisons such as this suggest that if postmortem aging is managed with respect to individual muscle and quality grade, certain Select muscles

Table 10. Rank of USDA Select (Se) and upper two-thirds USDA Choice (Ch) muscles from the lowest Warner-Bratzler shear force (WBSF) to the greatest WBSF at 4 postmortem aging periods

	Time postmortem, d			
Rank	6	14	21	28
1	Ch Teres major	Ch Infraspinatus	Ch Infraspinatus	Ch Infraspinatus
2	Ch Infraspinatus	Ch Teres major	Ch Psoas major	Ch Psoas major
3	Ch Psoas major	Ch Psoas major	Ch Serratus ventralis	Ch Serratus ventralis
4	Ch Serratus ventralis	Ch Spinalis dorsi	Ch Spinalis dorsi	Se Psoas major
5	Ch Tensor fasciae latae	Ch Serratus ventralis	Se Psoas major	Se Infraspinatus
6	Ch Spinalis dorsi	Se Infraspinatus	Ch Teres major	Ch Teres major
7	Se Spinalis dorsi	Ch Tensor fasciae latae	Ch Longissimus dorsi	Ch Tensor fasciae latae
8	Ch Rectus femoris	Se Psoas major	Se Infraspinatus	Se Spinalis dorsi
9	Ch Longissimus dorsi	Ch Longissimus dorsi	Se Spinalis dorsi	Ch Longissimus dorsi
10	Se Infraspinatus	Se Spinalis dorsi	Ch Tensor fasciae latae	Ch Spinalis dorsi
11	Se Teres major	Ch Vastus medialis	Ch Rectus femoris	Se Serratus ventralis
12	Se Serratus ventralis	Se Serratus ventralis	Ch Vastus medialis	Ch Vastus medialis
13	Se Psoas major	Ch Complexus	Se Serratus ventralis	Ch Triceps brachii
14	Ch Triceps brachii	Se Teres major	Ch Triceps brachii	Se Tensor fasciae latae
15	Se Tensor fasciae latae	Ch Triceps brachii	Se Vastus medialis	Se Teres major
16	Ch Biceps femoris	Se Tensor fasciae latae	Ch Complexus	Se Vastus medialis
17	Ch Vastus medialis	Ch Rectus femoris	Se Tensor fasciae latae	Ch Rectus femoris
18	Ch Gluteus medius	Se Rectus femoris	Se Rectus femoris	Ch Complexus
19	Ch Complexus	Ch Biceps femoris	Se Teres major	Se Triceps brachii
20	Se Rectus femoris	Se Triceps brachii	Se Triceps brachii	Se Rectus femoris
21	Se Triceps brachii	Ch Gluteus medius	Ch Vastus lateralis	Ch Gluteus medius
22	Ch Supraspinatus	Ch Vastus lateralis	Ch Supraspinatus	Ch Vastus lateralis
23	Ch Vastus lateralis	Se Vastus medialis	Ch Gluteus medius	Se Longissimus dorsi
24	Ch Semimembranosus	Ch Supraspinatus	Se Longissimus dorsi	Se Complexus
25	Ch Semitendinosus	Ch Semimembranosus	Se Supraspinatus	Ch Supraspinatus
26	Se Vastus medialis	Se Supraspinatus	Ch Biceps femoris	Se Supraspinatus
27	Se Supraspinatus	Ch Semitendinosus	Ch Semimembranosus	Se Vastus lateralis
28	Se Biceps femoris	Se Vastus lateralis	Se Vastus lateralis	Ch Semimembranosus
29	Se Vastus lateralis	Se Longissimus dorsi	Ch Semitendinosus	Ch Semitendinosus
30	Se Complexus	Se Complexus	Se Semitendinosus	Ch Biceps femoris
31	Se Gluteus medius	Se Semitendinosus	Se Complexus	Se Gluteus medius
32	Se Semitendinosus	Se Biceps femoris	Se Gluteus medius	Se Semitendinosus
33	Se Longissimus dorsi	Se Gluteus medius	Se Biceps femoris	Se Biceps femoris
34	Se Semimembranosus	Se Semimembranosus	Se Semimembranosus	Se Semimembranosus

may be able to be substituted for analogous premium Choice muscles in commercial merchandizing systems.

Warner-Bratzler shear force values obtained in this study were higher than those reported previously (Shackelford et al., 1995; Belew et al., 2003; Rhee et al., 2004). Shanks et al. (2002) reported that freezing LM steaks before shear force determination resulted in lower WBSF values compared with those for LM steaks that had never been frozen and recommended that research trials utilizing several or very short aging periods should assess WBSF without freezing. All product used in our study was never frozen; this, combined with differences in cooking methods, might have accounted for our comparatively high mean WBSF values. Within quality grade, ranking of muscles by 14-d WBSF was in general agreement with that of earlier reports (Shackelford et al., 1995; Belew et al., 2003; Rhee et al., 2004); the PM and IF muscles were ranked among the most tender, and the SM among the least tender, muscles.

IMPLICATIONS

Individual muscle, length of postmortem aging, and United States Department of Agriculture quality grade affected beef tenderness. Results from this study may assist retail and foodservice operators establish appropriate postmortem aging times for a variety of beef muscles that differ in quality grade, and allow muscle-to-muscle tenderness comparisons for differing quality grades and lengths of postmortem storage.

LITERATURE CITED

Belew, J. B., J. C. Brooks, D. R. McKenna, and J. W. Savell. 2003. Warner-Bratzler shear evaluations of 40 bovine muscles. Meat Sci. 64:507–512.

Bratcher, C. L., D. D. Johnson, R. C. Littell, and B. L. Gwartney. 2005. The effects of quality grade, aging, and location within muscle on Warner-Bratzler shear force in beef muscles of locomotion. Meat Sci. 70:279–284.

Brooks, J. C., J. B. Belew, D. B. Griffin, B. L. Gwartney, D. S. Hale, W. R. Henning, D. D. Johnson, J. B. Morgan, F. C. Parrish, Jr., J. O. Reagan, and J. W. Savell. 2000. National Beef Tenderness Survey - 1998. J. Anim. Sci. 78:1852–1860.

Calkins, C. R., and S. C. Seideman. 1988. Relationships among calcium-dependent protease, cathepsins B and H, meat tenderness and the response of muscle to aging. J. Anim. Sci. 66:1186–1193.

Huffman, K. L., M. F. Miller, L. C. Hoover, C. K. Wu, H. C. Brittin, and C. B. Ramsey. 1996. Effect of beef tenderness on consumer satisfaction with steaks consumed in the home and restaurant. J. Anim. Sci. 74:91–97.

Johnson, R. C., C. M. Chen, T. S. Muller, W. J. Costello, J. R. Romans, and K. W. Jones. 1988. Characterization of the muscles within the beef forequarter. J. Food Sci. 53:1247–1257.

Koohmaraie, M., G. Whipple, D. H. Kretchmar, J. D. Crouse, and H. J. Mersmann. 1991. Postmortem proteolysis in longissimus muscle from beef, lamb and pork carcasses. J. Anim. Sci. 69:617–624.

Morgan, J. B., J. W. Savell, D. S. Hale, R. K. Miller, D. B. Griffin, H. R. Cross, and S. D. Shackelford. 1991. National Beef Tenderness Survey. J. Anim. Sci. 69:3274–3283.

NCBA. 2000. Muscle Profiling. National Cattlemen's Beef Association, Centennial, CO.

Nelson, J. L., H. G. Dolezal, F. K. Ray, and J. B. Morgan. 2004. Characterization of Certified Angus Beef steaks from the round, loin, and chuck. J. Anim. Sci. 82:1437–1444.

O'Connor, S. F., J. D. Tatum, D. M. Wulf, R. D. Green, and G. C. Smith. 1997. Genetic effects on beef tenderness in *Bos indicus* composite and *Bos taurus* cattle. J. Anim. Sci. 75:1822–1830.

Parrish, F. C., Jr., R. B. Young, B. E. Miner, and L. D. Anderson. 1973. Effect of postmortem conditions on certain chemical, morphological, and organoleptic properties of bovine muscle. J. Food Sci. 38:690–695.

Platter, W. J., J. D. Tatum, K. E. Belk, P. L. Chapman, J. A. Scanga, and G. C. Smith. 2003. Relationships of consumer sensory ratings, marbling score, and shear force value to consumer acceptance of beef strip loin steaks. J. Anim. Sci. 81:2741–2750.

Ramsbottom, J. M., E. J. Strandine, and C. H. Koonz. 1945. Comparative tenderness of representative beef muscles. Food Res. 10:497–509.

Rhee, M. S., T. L. Wheeler, S. D. Shackelford, and M. Koohmaraie. 2004. Variation in palatability and biochemical traits within and among eleven beef muscles. J. Anim. Sci. 82:534–550.

Savell, J. W., R. E. Branson, H. R. Cross, D. M. Stiffler, J. W. Wise, D. B. Griffin, and G. C. Smith. 1987. National Consumer Retail Beef Study: Palatability evaluations of beef loin steaks that differed in marbling. J. Food Sci. 52:517–519, 532.

Savell, J. W., H. R. Cross, J. J. Francis, J. W. Wise, D. S. Hale, D. L. Wilkes, and G. C. Smith. 1989. National Consumer Retail Beef Study: Interaction of trim level, price and grade on consumer acceptance of beef steaks and roasts. J. Food Qual. 12:251–274.

Savell, J. W., F. K. McKeith, and G. C. Smith. 1981. Reducing postmortem aging time of beef with electrical stimulation. J. Food Sci. 46:1777–1781.

Shackelford, S. D., T. L. Wheeler, and M. Koohmaraie. 1995. Relationship between shear force and trained sensory panel tenderness ratings of 10 major muscles from *Bos indicus* and *Bos taurus* cattle. J. Anim. Sci. 73:3333–3340.

Shanks, B. C., D. M. Wulf, and R. J. Maddock. 2002. Technical note: The effect of freezing on Warner-Bratzler shear force values of beef longissimus steaks across several postmortem aging periods. J. Anim. Sci. 80:2122–2125.

Smith, G. C., G. R. Culp, and Z. L. Carpenter. 1978. Postmortem aging of beef carcasses. J. Food Sci. 43:823–826.

USDA. 1996. Institutional Meat Purchase Specifications for Fresh Beef. Agric. Marketing Serv., USDA, Washington, DC.

Von Seggern, D. D., C. R. Calkins, D. D. Johnson, J. E. Brickler, and B. L. Gwartney. 2005. Muscle profiling: Characterizing the muscles of the beef chuck and round. Meat Sci. 71:39–51.

Weatherly, B. H., C. L. Lorenzen, and J. W. Savell. 1998. Determining optimal aging times for beef subprimals. J. Anim. Sci. 76(Suppl. 1):598. (Abstract)