PREDICTING BEEF-LONGISSIMUS TENDERNESS FROM VARIOUS BIOCHEMICAL AND HISTOLOGICAL MUSCLE TRAITS[1,2,3]

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ABSTRACT

Our objective was to determine the predictive value of various biochemical and histological traits for tenderness of the longissimus muscle. Data collected from 27 crossbred cattle included longissimus pH, temperature, sarcomere length, total and percentage of soluble collagen, muscle-fiber type and area, cathepsin B and B + L activities, calcium-dependent protease (CDP)-I, -II and inhibitor activities, myofibril fragmentation indices (MFI), Warner-Bratzler shear (WBS) force, sensory-panel tenderness (SPT) ratings and carcass traits. Stepwise regression analyses were performed among breeds or pooled within breeds with WBS and SPT as dependent variables. When MFI were included in the analysis, MFI at d 7 explained 50% of the variation in WBS and SPT at d 14. An additional 19% of SPT was accounted for by the addition of CDP inhibitor d 1 activity and percentage-area of αR fibers to the model. However, because variation in MFI was not significant within breed subclasses and MFI could be classified more as a dependent variable, it was removed from the model. This resulted in CDP inhibitor d 1 activity explaining 44% of the variation in WBS and SPT at d 14. Also, percentage-area of βR fibers, 6 h pH and cathepsin B + L d 14 activity appeared in the model. In addition, CDP inhibitor activity was the only variable to be significant within breed groups. These data suggest that d 7 MFI could be used as a single predictor of d 14 longissimus muscle tenderness; however, CDP inhibitor d 1 activity (a biological event) also may be useful in predicting tenderness.

(Key Words: Bovidae, Tenderness, Proteases, Regression Analysis.)

J. Anim. Sci. 1990. 68:4193–4199

Introduction

Tenderness is the major palatability trait affecting consumer acceptance of beef (Norris et al., 1971). Many studies have been conducted to determine the biological causes of variation in tenderness. Numerous variables have been related to tenderness, such as amount of intramuscular fat (Campion et al., 1975), sarcomere length (Harris, 1976), collagen content (Burson and Hunt, 1986), size and type of muscle fibers (Calkins et al., 1981; Seideman and Crouse, 1986), and enzymatic activity involved in postmortem aging (Calkins and Seideman, 1988; Koohmaraie, 1988; Koohmaraie et al., 1988). Researchers also have conducted regression analyses using some of these traits to predict tenderness. Davis et al. (1979) included percentage of expressible juice, fragmentation index, sarcomere length, cooking loss, and percentage of soluble collagen as variables to predict tenderness and was able to explain 68% of the variation. Calkins et al. (1980) used carcass traits, fragmentation indices, sarcomere length

[1]Contribution no. 90-59-J from the Kansas Agric. Exp. Sta., Manhattan.

[2]Authors wish to thank Kay Theer and Pat Tammen of the U.S. Meat Anim. Res. Center for their computer assistance and Carol Grummert of the U.S. Meat Anim. Res. Center for the typing of this manuscript.

[3]Mention of trade names, proprietary products or specific equipment does not constitute a guarantee or warranty of the product by the USDA and does not imply its approval to the exclusion of other products that also may be suitable.

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Received December 5, 1989.

Accepted May 16, 1990.

and other chemical parameters to derive a model R^2 of .68. In an analysis by Hawkins et al. (1987), various muscle traits, such as sarcomere length and percentage of fat and moisture, accounted for 51% of the tenderness variation. Muscle histological traits were used by Calkins et al. (1981) in predicting tenderness (R^2 = .65). However, no published report has included all these variables in the same analysis, nor has anyone included calcium-dependent proteases and their inhibitor activities in their analysis.

The purpose of our study was to determine the predictive value of carcass traits, muscle pH and temperature, total and percentage of soluble collagen at 1 and 14 d postmortem, sarcomere length, myofibril fragmentation index, muscle fiber type and area percentage, calcium-dependent protease-I, -II and inhibitor activities at 0 and 24 h, and cathepsin B and B + L activities at 1 and 14 d for longissimus muscle tenderness at 14 d postmortem. Also, from this analysis we hoped to further explain the biological basis of tenderness.

Materials and Methods

A detailed discussion of the animals utilized in this study and the laboratory assays conducted has been reported by Whipple et al. (1990). Briefly, Hereford (H) × Angus (A) (n = 10), 5/8 Sahiwal × H, A or H × A (n = 11) and 3/8 Sahiwal × H, A or H × A (n = 6) crosses were slaughtered at 15 to 17 mo of age. Carcass data were collected at 24 h postmortem. Longissimus muscle (LM) pH and temperature were monitored at 3, 6, 9 and 12 h. Samples were removed from the LM for determining sarcomere length; muscle-fiber histochemistry; myofibril fragmentation indices (MFI) at d 1, 3, 7 and 14; calcium-dependent protease (CDP)-I, -II and CDP inhibitor (INH) activities at 0 h and 1 d postmortem; cathepsin B and B + L activities at 1 and 14 d; total and soluble collagen at 1 and 14 d; and Warner-Bratzler shear (WBS) force and sensory-panel tenderness (SPT) scores at d 14.

Stepwise regression analyses were performed using WBS and SPT at 14 d postmortem as dependent variables and biochemical and histological measurements as independent variables. Means and standard deviations of traits used in the regression analyses are given in Table 1. All variables in the model that were not significant ($P > .05$) were omitted. Residual-correlation and -regression coefficients were derived using the General Linear Models procedure (SAS, 1985) with breed and gender of the animal and their interaction as independent variables. Correlation coefficients are reported for those variables that were significant in the regression analysis and for selected related traits. Those omitted were not significantly correlated with WBS or SPT.

Results and Discussion

The average WBS value and SPT score for LM steaks at 14 d postmortem were 6.3 kg and 5.1, respectively (Table 1). There was 25 and 16% variation in WBS and SPT scores, respectively. Campion et al. (1975) found 24 and 11% variations in WBS and SPT values, respectively, among numerous *Bos taurus* breeds. The slightly greater variation found in our study may have been because steaks from both *Bos taurus* and *Bos indicus* crosses were utilized.

Significant residual and simple correlations were observed between WBS and SPT (−.64 and −.88, respectively; Table 2). Residual correlations reflect relationships within breed group by gender subclasses, whereas overall-simple correlations reflect relationship among (ignoring) all breed groups. High simple correlations ($P < .01$) occurred between MFI at 1, 3, 7 and 14 d postmortem and WBS and SPT values. These results agree with numerous reports in which MFI had significant simple correlations with WBS values and SPT scores (MacBride and Parrish, 1977; Olson and Parrish, 1977; Culler et al., 1978). However, in our study no significant residual correlations existed between MFI and WBS or SPT. This may be due to limited variation within subclasses for MFI as revealed by lower residual SD (Table 1).

The only other trait to be significantly correlated with WBS and SPT values was INH activity at d 1. Simple correlations ($P < .01$) between INH activity at d 1 and MFI at 1, 3, 7 and 14 d also were observed. In addition, INH activity was the only trait to have significant residual correlations with WBS and MFI. These data indicate that LM INH activity at d 1 was significantly related to tenderness among breed and gender subclasses and within subclasses. In studies in which the CDP mechanism was activated by infusing $CaCl_2$

TABLE 1. MEANS AND STANDARD DEVIATIONS OF VARIABLES USED IN THE REGRESSION ANALYSIS

Variables	Mean	SD	Residual[e] SD
Day 14 overall tenderness score[a]	5.1	.8	.6
Day 14 shear-force value, kg	6.3	1.6	1.0
Avg daily gain, kg	.9	.1	.1
Slaughter wt, kg	469.3	56.9	46.7
Hot carcass wt, kg	292.6	35.9	29.5
Adjusted fat thickness, cm	1.4	.5	.4
LM area, cm^2	71.6	9.3	8.2
Marbling score[b]	334.3	112.1	118.2
Quality grade[c]	198.1	61.2	63.5
Yield grade	3.3	.7	.6
Heat ring[d]	6.8	1.1	1.0
LM 3 h pH	6.4	.3	.3
LM 6 h pH	6.1	.3	.3
LM 9 h pH	5.9	.3	.3
LM 12 h pH	5.8	.2	.2
LM 3 h temperature, °C	25.9	1.8	1.7
LM 6 temperature, °C	16.5	1.9	1.5
LM 9 h temperature, °C	10.3	1.5	1.3
LH 12 temperature, °C	7.0	1.5	1.3
Day 1, total collagen, mg/g	2.8	.3	.3
Day 1, soluble collagen, %	13.9	1.9	1.9
Day 14, total collagen, mg/g	2.9	.4	.4
Day 14, soluble collagen, %	15.5	3.7	3.5
Sarcomere length, μm	1.8	.2	.2
0 h, CDP-I activity/100 g	108.4	18.8	18.6
0 h, CDP-II activity/100 g	99.4	15.0	15.3
0 h, CDP inhibitor activity/100 g	370.9	77.9	78.7
24 h, CDP-I activity/100 g	37.3	13.8	12.8
24 h, CDP-II activity/100 g	110.9	19.0	15.9
24 h, CDP inhibitor activity/100 g	179.7	58.7	47.2
Day 1, cathepsin B activity, $pmol \cdot mg^{-1} \cdot min^{-1}$	31.9	8.9	9.2
Day 1, cathepsin B + L activity, $pmol \cdot mg^{-1} \cdot min^{-1}$	41.9	8.3	8.6
Day 14, cathepsin B activity, $pmol \cdot mg^{-1} \cdot min^{-1}$	32.1	5.7	5.5
Day 14, cathepsin B + L activity, $pmol \cdot mg^{-1} \cdot min^{-1}$	43.1	10.1	10.0
βR fibers, %	29.5	6.2	7.1
αR fibers, %	18.8	4.5	3.9
αW fibers, %	51.7	6.5	6.6
Area of βR fibers, %	22.9	4.0	4.7
Area of αR fibers, %	30.8	6.2	6.2
Area of αW fibers, %	45.1	8.5	7.9
Day 1, MFI	43.8	14.0	11.8
Day 3, MFI	46.4	19.3	14.2
Day 7, MFI	59.8	17.8	12.3
Day 14, MFI	69.8	13.4	10.7

[a]A score of 6 = moderately tender, 5 = slightly tender.

[b]USDA marbling score: 200–299 = slight, 300–399 = small.

[c]USDA quality grade: 100–199 = Select, 200–299 = Choice.

[d]Presence of heat ring: 1 = severe, . . . 8 = none.

[e]SD after removal of effects of breed, gender and their interaction.

(Koohmaraie et al., 1989, 1990) or inhibited by infusing $ZnCl_2$ (Koohmaraie, 1990), 14 d LM tenderness was improved and not affected ($P > .05$), respectively. Collectively, these studies provide strong evidence for the CDP system's involvement in postmortem tenderization. In our study, residual positive correlation coefficients ($P < .05$) among INH d 1 activity, 3- and 12-h pH and percentage-area of βR fibers also were observed. This indicates that INH d 1 activity may be related in some way to postmortem muscle pH and proportion of muscle area occupied by βR fibers. However, Koohmaraie (1988) found less INH activity in

TABLE 2. SIMPLE AND PARTIAL CORRELATION COEFFICIENTS AMONG WARNER-BRATZLER SHEAR (WBS) FORCE, SENSORY PANEL OVERALL TENDERNESS (SPT) SCORES AT DAY 14, MYOFIBRILLAR FRAGMENTATION INDICES (MFI), ENZYME ACTIVITY, pH AND HISTOCHEMICAL TRAITS OF LONGISSIMUS MUSCLE[a]

Variables for simple correlation coefficients	Variables for partial correlation coefficients																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1. WBS		−.64	−.26	.03	−.23	−.31	−.07	−.10	.43	−.09	−.20	.17	.07	.02	−.17	.09	.20	−.27	.01	.26	.05	.01	.08
2. SPT	−.88		.19	−.05	.27	.26	−.11	.12	−.36	.08	.05	−.17	.11	−.09	.12	−.09	−.19	.21	.01	−.21	.12	.35	.40
3. MFI, d 1	−.51	.53		.72	.54	.53	−.12	−.26	−.65	−.29	−.13	−.48	−.07	−.22	−.41	−.37	−.55	.12	.24	−.03	−.22	−.31	−.11
4. MFI, d 3	−.51	.52	.79		.18	.11	−.03	−.21	−.43	−.16	−.06	−.50	−.09	−.14	−.34	−.23	−.34	−.36	.47	.07	−.42	−.48	−.19
5. MFI, d 7	−.72	.69	.63	.42		.61	−.18	−.02	−.54	−.18	−.22	−.19	−.06	−.20	−.38	−.21	−.18	−.19	−.12	.26	−.36	−.32	−.22
6. MFI, d 14	−.66	.65	.72	.52	.76		−.02	−.19	−.60	−.37	−.39	−.08	−.08	−.27	−.18	−.12	−.47	.03	−.16	.06	−.34	−.19	−.12
7. CDP-I[b]	−.08	−.07	−.16	−.01	−.06	.02		−.32	.33	.14	.36	.01	−.13	.59	.58	.58	.39	−.07	−.04	.09	.05	.07	.19
8. CDP-II[b]	.01	−.06	−.19	−.34	−.05	−.20	−.02		−.15	.41	.04	.34	.40	.07	.26	.20	.34	−.21	.00	.21	−.32	.19	.14
9. CDP inhibitor[b]	.66	−.66	−.79	−.70	−.68	−.70	.28	.15		.07	.23	.14	−.24	.46	.38	.20	.42	−.12	−.12	.19	.48	.28	−.01
10. Cathepsin B[b]	−.01	−.01	−.26	−.10	−.19	−.42	.10	.31	.05		.67	.28	.31	.22	.43	.30	.61	.09	.05	−.12	−.12	.11	.09
11. Cathepsin B+L[b]	.03	−.07	−.48	−.42	−.55	−.36	.08	−.10	.17	.61		.27	.23	.58	.52	.26	.38	−.04	.33	−.15	−.01	−.05	−.03
12. Cathepsin B[c]	.36	−.36	−.08	.14	.38	−.39	.09	.24	.27	.38	.44		.67	.22	.43	.30	.61	.09	.05	−.12	−.12	.11	.09
13. Cathepsin B+L[c]	.21	−.12	−.14	.11	.28	−.18	−.22	.17	−.11	.38	.36	.67		.19	.23	.32	.22	−.05	.21	−.08	−.14	.27	.48
14. pH, 3 h	−.09	.01	−.16	−.46	−.32	−.55	.59	.15	.31	.21	.28	.41	.14		.64	.69	.57	−.36	.16	.25	.15	.17	.16
15. pH, 6 h	−.02	−.05	.15	−.08	−.10	−.30	.62	.32	.38	.37	.30	.35	.21	.64		.69	.51	−.07	−.02	.08	.01	.41	.27
16. pH, 9 h	.13	−.17	−.03	−.25	−.12	−.30	.60	.19	.18	.36	.45	.14	.32	.64	.65		.77	−.16	−.06	.19	−.02	.33	.42
17. pH, 12 h	.36	−.37	−.10	−.17	−.24	−.64	.36	.26	.42	.59	.51	.32	.32	.49	.51	.78		−.15	−.15	.24	.01	.20	.22
18. βR fibers, %	−.19	.19	.00	−.20	−.15	.02	−.21	−.25	−.17	.15	.08	.16	−.01	−.37	−.18	−.19	−.18		−.26	−.82	.34	.32	.22
19. αR fibers, %	.20	−.21	.00	.03	−.25	−.35	.19	.16	.13	.08	.22	−.04	.09	.14	−.05	.07	−.02	−.25		−.35	−.22	−.08	.00
20. αW fibers, %	.06	−.05	.00	.17	.30	.19	.15	.14	.08	−.19	−.21	−.14	−.05	.27	.14	.15	.18	−.81	−.37		−.20	−.26	−.21
21. βR%-area	−.09	.12	−.27	−.33	−.08	−.13	.19	−.01	.37	−.07	−.13	−.16	−.20	.24	.10	.01	−.03	.24	−.13	−.16		.51	.36
22. αR%-area	.13	.05	−.37	−.49	−.35	−.27	.04	.31	.36	.12	−.01	.18	.16	.14	.34	.22	.14	.33	.04	−.34	.50		.80
23. αW%-area	.34	−.15	−.37	−.45	−.40	−.39	.25	.35	.35	.09	−.06	.21	.28	.14	.30	.38	.26	.12	.24	−.26	.37	.79	

[a]Values > .41 but < .51 ($P < .05$) and values > .51 ($P \leq .01$).

[b]Activity at d 1 postmortem.

[c]Activity at d 14 postmortem.

the psoas major, a predominantly red muscle, when compared to the LM. Ducastaing et al. (1985) found that the activities of CDP-I and INH at 4 h postmortem may be related to the postmortem muscle pH fall as manipulated by electrical stimulation.

A negative relationship also appears to exist between MFI and muscle fiber percentage-area, as indicated by simple correlations ($P < .05$) among percentage area of αR and αW fibers and MFI at d 3. Within-subclass residual correlations ($P < .05$) also were observed among MFI at d 3, αR fiber percentage (positive) and percentage area of βR and αR fibers (negative). However, no significant relationship existed between WBS force and muscle fiber traits. In contrast, Seideman and Crouse (1986) found percentage and percentage-area of red and white fibers to be significantly correlated with WBS force. Also, Seideman et al. (1986) reported αR and αW fiber percentage and percentage-area to be related to WBS force. Therefore, LM fiber characteristics may have some influence on tenderness.

Postmortem muscle pH at either 3, 6, 9 or 12 h was positively correlated with in vitro activities of CDP-I and cathepsin B and B + L. A relationship between pH and enzyme activity in vivo might be expected because the maximum activity of these enzymes in vitro is pH-dependent (Etherington, 1984; Koohmaraie et al., 1986).

Regression Analysis. Regression equations with standard errors and model coefficients of determination (R^2) for d 14 LM tenderness that were computed overall (ignoring breed group and gender subclasses) are given in Table 3. Independent variables presented are those that were significant ($P < .05$). When MFI values were included in the analyses (Equations 1 and 3), MFI at d 7 explained almost 50% of the variation observed in SPT scores and WBS values among breeds. Others have reported that either MFI or fragmentation index accounts for approximately 50% of the variation observed in LM tenderness at 10 to 14 d postmortem (Culler et al., 1978; Davis et al., 1980) and at 1 and 7 d postmortem (Olson and Parrish, 1977). This evidence indicates that MFI or fragmentation index may be the most important currently known objective indicator of LM tenderness other than WBS force.

In Equation 3, an additional 20% of the variation in SPT scores that was not explained by MFI was explained by INH activity at d 1 (partial $R^2 = .10$) and percentage-area of αR fibers (partial $R^2 = .10$). For Equation 1, percentage of βR fibers explained an additional 9% of the variation in tenderness. Calkins et al. (1981) performed regression analyses to determine the accuracy of using muscle fiber-type characteristics to predict SPT scores and WBS values at 10 to 14 d postmortem. Nine

TABLE 3. REGRESSION EQUATIONS WITH AND WITHOUT MYOFIBRIL FRAGMENTATION INDEX (MFI) FOR PREDICTING LONGISSIMUS MUSCLE, WARNER-BRATZLER SHEAR (WBS) FORCE VALUES AND SENSORY PANEL OVERALL TENDERNESS SCORES (SPT) AT DAY 14

Equation	Independent variables	Intercept	β-value	Partial R^2	Model R^2	SE
1: WBS with MFI						
	MFI, d 7	12.650	−.068	.49		
	βR fibers, %		−.079	.09	.58	1.1
2: WBS without MFI						
	INH activity, d 1[a]	14.984	.027	.44		
	βR fibers, % area		−.129	.13		
	pH, 6 h		−2.116	.09		
	Cathepsins B + L activity, d 14[b]		.054	.10	.76	.86
3: SPT with MFI						
	MFI, d 7	3.089	.025	.48		
	INH activity, d 1[a]		−.006	.10		
	αR fibers, % area		.052	.10	.68	.51
4: SPT without MFI						
	INH activity, d 1[a]	5.386	−.012	.44		
	βR fibers, % area		.079	.16	.60	.56

[a]INH = calcium-dependent protease inhibitor. Activity expressed/100 g muscle.

[b]Cathepsin B + L activity expressed as $pmol \cdot mg^{-1} \cdot min^{-1}$.

characteristics appeared ($P < .10$) in the backward-stepwise analysis to account for 30% of the variation in SPT and three characteristics accounted for 19% of the variation in WBS force values. In our Equation 4, percentage-area of βR fibers had a partial R^2 of .16. Therefore, it appears that LM fiber characteristics may be important in predicting WBS and SPT.

Because MFI had insignificant residual correlation coefficients (Table 2) and they are more of a response to aging than a predictor of tenderness, we felt justified in removing MFI from the analyses to examine the predictive value of other biological traits for LM tenderness. When MFI were deleted from the analysis (Equations 2 and 4), INH activity at d 1 accounted for 44% of the variation in SPT scores and WBS values, which is more variation in tenderness accounted for than by any other variable. The linear regression coefficient of INH on WBS revealed that for every 50 units increase in INH d 1 activity, WBS increased 1 kg. No published research reports regression analyses that include CDP and INH activities, and those that are published report regression models that usually contain several variables. Our regression model for WBS force (Equation 2) excluding MFI had the largest R^2, .76, which included only four variables: INH 24 h, d 1 activity, cathepsin B + L activity at d 14, 6 h pH and percentage-area of βR fibers. However, the magnitude of the standard partial regression coefficients clearly indicates that INH d 1 activity was the most important contributor to the model, whereas 6 h pH and cathepsin B + L 14 d activity were the least important. Calkins et al. (1987) found that total and specific activities of cathepsin B and H and β-glucoronidase within 1 h after exsanguination accounted for 37 to 59% of the variation in tenderness at 7 d postmortem. In our study, no significant correlations of catheptic enzyme activity to WBS or SPT were observed (Table 2). Therefore, the predictive value of cathepsins in postmortem tenderization still is not clearly defined.

Implications

Of the various biochemical and histological traits studied, myofibril fragmentation indices can be utilized among breed groups to accurately predict longissimus muscle tenderness at 14 d postmortem. Calcium-dependent protease inhibitor was an important trait to predicting longissimus muscle tenderness, when comparing breeds or variation within breeds and gender. However, myofibril fragmentation indices require less time and are less expensive to determine than calcium-dependent protease inhibitor activity. If a method could be refined to measure myofibril fragmentation index on a muscle biopsy, it probably could be implemented to determine the genetic potential of sires to produce progeny with tender meat.

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