RESPONSE OF SIRE AND FAMILY GROUP TO POST-MORTEM

ELECTRICAL STIMULATION

A Thesis

by

ERIC ALLEN METTEAUER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2008

Major Subject: Animal Science

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Approved by:

Chair of Committee,	Jeffrey W. Savell
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ABSTRACT

Response of Sire and Family Group to Post-Mortem Electrical Stimulation.

(December 2008)

Eric Allen Metteauer, B.S., Texas A&M University;

Chair of Advisory Committee: Dr. Jeffrey W. Savell

Beef carcasses from F_2 Nellore × Angus (n = 181) and half-blood *Bos indicus × Bos taurus* (n = 57) were used to evaluate the responsiveness of sire and family groups nested within sires to post-mortem electrical stimulation (ES). In the F_2 population, biological response to ES was identified for myofibrillar fragmentation index, and 6 h post-mortem pH. The genetic contributions of sire and families nested within sires were found for the average Warner-Bratzler shear force (WBS), location of shear core extraction, post-mortem carcass temperatures, and carcass pH. ES sides had lower WBS values, higher carcass temperatures, and lower carcass pH. In the half-blood population, biological response to ES was found for WBS core location. Sire and families nested within sires significantly affected WBS core location and carcass temperature. The ES sides had lower WBS values, higher carcass temperatures, and lower carcass pH in the half-blood population. From a carcass temperature and pH standpoint, carcass weight and fat thickness were used as covariates in the analysis of variance. This covariate analysis still showed a genetic component to carcass temperature and pH. There are genetic factors that impact how carcasses respond to electrical stimulation, which is the first work to demonstrate this relationship between genetics and a post-mortem tenderization treatment.

DEDICATION

This thesis is dedication to the love of my life, Kori Lee Metteauer, who is not only my wife and best friend but the driving force behind my successes.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

The use of electrical stimulation (ES) in beef harvest is a common practice in today's industry. It is widely established that postmortem ES greatly enhances tenderness attributes in beef steaks (Savell, Smith, Dutson, Carpenter, & Suter, 1977; Savell, Dutson, Smith, & Carpenter, 1978a; Savell, Smith, & Carpenter, 1978b,c; Savell, Smith, Carpenter, & Parrish, 1979). Research has also illustrated that there is a wide use of *Bos indicus* cattle breeds due to their hardiness and ability to maximize heterosis (Cole, Ramsey, Hobbs, & Temple, 1963; Crockett, Baker, Carpenter, & Koger, 1979). However, researchers have also documented that meat from the *Bos indicus* cattle is often less tender than meat from *Bos taurus* cattle (Crouse, Cundiff, Koch, Koohmaraie, & Seideman, 1989; Koch, Dikeman, & Crouse, 1982; McKeith, Savell, Smith, Dutson, Hostetler, & Carpenter, 1985). With tenderness being the most important factor influencing consumer acceptance for beef palatability (Savell et al., 1987, 1989; Smith et al., 1987), there lies a constant need to identify the effects of postmortem tenderization methods, such as electrical stimulation, and the effectiveness of this technology across breeds and breeding systems.

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This thesis follows the style of *Meat Science.*

In evaluating the effectiveness of ES within a controlled genetic environment, we will more likely be able to identify individual animals that conform to today's industry practices, thus ultimately achieving consumer satisfaction. There are many variables that potentially affect beef tenderness, such as animal age at harvest (Davis, Smith, Carpenter, Dutson, & Cross, 1979), nutrition (Dikeman et al., 1985), breed (Koch et al., 1982), days on high-concentration diets (Tatum, Smith, Berry, Murphey, Williams, & Carpenter, 1980), and the use of growth promotants (Unruh, Gray, & Dikeman, 1986). It is the ultimate goal to be able to understand and correct these many factors that contribute to the variation observed in beef tenderness at the retail level.

Many reports have evaluated the effectiveness of ES in an industry setting. Carse (1973) reported that electrical stimulation would increase the rate of postmortem glycolysis and hasten the onset of rigor mortis. Savell et al. (1978a,b,c, 1979) reported the effectiveness of ES in terms of quality-indicating characteristics including USDA quality grade factors, such as lean maturity and tenderness attributes. Davey, Gilbert, and Carse (1976), Savell et al. (1977), and Shaw and Walker (1977) all reported similar findings on the abilities of ES to accelerate pH decline, hasten rigor development, and improve tenderness.

The evolution of breeding systems in today's industry presents other parameters that are potentially responsible for variation in tenderness. There remains a need in the industry today to further decrease the range of tenderness issues observed at the consumer level. However, there is no published work on the responsiveness of genetic groups to the application of postmortem electrical stimulation. With the knowledge of

the general effects of electrical stimulation, the objective of this research is to identify

sire or family group differences in response to the application of electrical stimulation

and how these factors may contribute to our understanding of mechanisms involved in

the efficacy of electrical stimulation.

CHAPTER II

REVIEW OF LITERATURE

The progression of today's beef industry lies in the positive experience of the consumers, and the confidence they maintain in meat products. It has been reported that consumers are willing to pay more for beef of known tenderness levels (Boleman et al., 1997). Morgan et al. (1991) stated problems in the beef segment in terms of consistency for tenderness, particularly in the round and chuck portions. These tenderness problems have been studied for years and attempts to correct or alter these tenderness issues have shown some success. One of the most heavily research tenderization method is postmortem electrical stimulation. Over the years, many theories have evolved as mechanisms responsible for the effects of electrical stimulation; however, there remain several unknown parameters, which are still being investigated today.

Beef cattle harvested in today's industry most likely undergo postmortem electrical stimulation treatment. For several decades now, researchers have studied the results of electrical stimulation and it has become widely established that this application greatly enhances tenderness in beef (Davey et al., 1976; Savell, et al., 1977, 1978a,b,c, 1979; Shaw & Walker, 1977; McKeith, Savell, & Smith, 1981). The application of electrical stimulation has been thoroughly researched, focusing primarily on the *M. longissimus* (McKeith et al., 1981; Savell et al., 1977, 1978b, 1979; Stolowski et al., 2006; Savell, McKeith, Murphey, Smith, and Carpenter, 1982; Takahashi, Lochner, and

Marsh, 1984; Schroeder, Cramer, & Bowling, 1982). These authors reported electrical

stimulation had a positive effect on beef tenderness of the *M. longissimus*. The vast

amount of research of the *M. longissimus* reflects the importance of this muscle in terms

of consumer satisfaction. Beyond the findings on tenderness, authors have reported an

improvement in lean color (Savell et al., 1978b,c, 1979; McKeith et al., 1981), sensory

panel palatability scores (Savell et al., 1978b), and lean firmness and texture (Savell et

al., 1978c).

More specifically, research has been conducted on specific muscle response to

the electrical stimulation application. Recently, Stolowski et al. (2006) studied the

factors influencing the tenderness of seven beef muscles. These authors state that the

effect of electrical stimulation on tenderness was muscle dependent, and thus improved

Warner-Bratzler shear values were observed in the *M. longissimus dorsi* and *M. biceps

femoris*, similar results were reported by McKeith et al. (1981), in that significant

improvements were made in the *M. longissimus*, *M. biceps femoris*, *M. gluteus medius*,

and *M. semimembranosus*.

Savell et al. (1979) stated that electrical stimulation appeared to tenderize

muscles of carcasses that would otherwise be tough, while electrical stimulation does not

appear to tenderize those muscles of carcasses that would otherwise be tender. This

follows observations noted earlier by Savell et al. (1977) that electrical stimulation

effects were not consistent throughout the carcasses observed in that study. Savell et al.

(1982) suggested that the proper combination of high muscle mass, thick subcutaneous

fat cover, and high ambient cooler temperatures will prevent cold shortening and

increase lysosomal enzymatic activity. Under these circumstances, electrical stimulation is not likely to further improve tenderness. The mechanism by which electrical stimulation improves tenderness has been postulated as prevention of cold shortening (Davey et al., 1976), fiber rupture (Savell et al., 1978a; Takahashi, Wang, Lochner, & Marsh 1987), and increase in lysosomal activity (Dutson, Smith, & Carpenter, 1980).

Within the concept of enhancing tenderness, Davey et al., (1976), Savell et al. (1977), and Shaw and Walker (1977) all reported similar findings on the abilities of ES to accelerate pH decline and hasten rigor development, two potential factors relating to tenderness. Moeller, Fields, Dutson, Landmann, and Carpenter (1976) reported that the rapid decrease in muscle pH combined with higher carcass temperatures increased the free activity of β-glucuronidase and cathepsin C (lysosomal enzymes), therefore promoting autolytic proteolysis and probably increasing tenderness. The application of high-voltage electrical simulation to early postmortem beef sides caused rapid muscle glycolysis resulting in rapid acidification of the cellular tissues as reported by Takahashi et al. (1984), thus being responsible for the rapid pH decline. Dutson et al. (1980) investigated the distribution of lysosomal enzymes in electrically stimulated ovine muscle and noted that the lower pH and higher carcass temperatures were conducive for increased activity of these enzymes. This suggests that this action could possibly cause hydrolysis of myofibrilar protein and connective tissue protein, thus having a tenderizing effect.

Myofibrillar fragmentation index is used as an indicator of post-mortem proteolysis. Parrish, Young, Miner and Andersen (1973) and Olson, Parrish, and

Stromer (1976) documented that myofibril fragmentation index and the 30,000-dalton component are strongly related to meat tenderness. Later, Olson and Parrish (1977) studied the relationship of myofibril fragmentation index to measures of beef-steak tenderness. This study evaluated veal, A-maturity and C-maturity bovine *M. longissimus dorsi* steaks at 1-7 days postmortem. These authors reported that with the increase from 1-7 days postmortem, the myofibril fragmentation index increases significantly ($P < 0.05$) for all three maturity groups. Olson and Parrish (1977) also reported that during the 1-7 days postmortem, there was no significant differences in Warner-Bratzler shear values. However, Olson and Parrish (1977) found a correlation between myofibril fragmentation index and Warner-Bratzler shear-force values ($P < 0.05$), as well as myofibril fragmentation index and sensory panel tenderness ($P < 0.05$). Olson and Parrish (1977) stated that myofibril fragmentation is also a good indicator for cooked muscle tenderness, accounting for about 50% of the variation in tenderness of *M. longissimus* from young beef. The same study suggested the relevance of myofibril fragmentation index as a predictor of beef tenderness and could potentially allow carcass segregation into tenderness groups according to the correlation coefficient between myofibril fragmentation index and Warner-Bratzler shear force values.

However, King, Voges, Hale, Waldron, Taylor, and Savell (2004) studied electrical stimulation of cabrito carcasses and noted that electrical stimulation had no effect on myofibril fragmentation at 1, 3, or 14 d postmortem. Salm, Mills, Reeves, Judge, and Aberle (1981) performed a study on cattle fed a high-energy diet for different time intervals, and reported no effects of electrical stimulation on myofibril

fragmentation index. Savell et al. (1979) reported similar data, showing the application of electrical stimulation had no effects on myofibril fragmentation or sarcomere length, while having significant effects on lean color and pH, and panel-detectable connective tissue. Whether or not electrical stimulation contributes to changes in myofibril fragmentation, the index is strongly correlated to cooked meat tenderness (Olson & Parrish, 1977).

Early research studied the effectiveness of electrical stimulation as a means to prevent toughening of lamb carcasses when chilled or frozen in a pre-rigor state (Cross, 1979). Chrystall and Hagyard, (1976) and Davey et al. (1976) proposed the contribution of electrical stimulation on tenderness is due to the prevention of cold shortening. These researchers studied carcasses that were immediately frozen as compared to chilling as practiced in today's industry. The freezing process when compared to normal chilling conditions would undoubtedly cause increases in the degree of cold shortening (Cross, 1979). However, there are conflicting results on the effectiveness of electrical stimulation actually instigating the prevention of cold-induced shortening when carcasses are rapidly chilled. The concept of prevention of cold shortening would require a difference in sarcomere length between treated and non-treated sides. Several researchers have documented that there are no significant differences in sarcomere length between the stimulated and non-stimulated carcass sides (Savell et al., 1977, 1978a, 1979; Takahashi et al., 1984; Stolowski et al., 2006). These researchers suggested that the meat tenderness improvement associated with electrical stimulation is accomplished by means other than prevention of cold shortening. This leaves room to

hypothesize on many other variables, in the live animal or carcass, which could play a role in the responsiveness of each carcass to electrical stimulation.

With this vast array of evidence that electrical stimulation has many positive effects on carcass quality and palatability, there remains a need to further understand by what means this process is able to increase tenderness without the prevention of cold shortening. Other researchers have identified differences in palatability due to breed types (Koch et al., 1982; McKeith et al., 1985; Crouse et al., 1989), age (Davis et al, 1979), nutrition (Dikeman et al., 1985), days on high-concentration diets (Tatum et al., 1980), and the use of growth promotants (Unruh et al., 1986). All of these authors have found variables in the process that are significant contributors to the end-product eating experience. However, there is no published work on the responsiveness of genetic groups to the application of postmortem electrical stimulation. With the knowledge of the general effects of electrical stimulation, the objective of this research is to identify sire or family group differences in response to the application of electrical stimulation and how these factors may contribute to our understanding of mechanisms involved in the efficacy of electrical stimulation.

CHAPTER III

MATERIALS AND METHODS

3.1 Breeding System Background

This project incorporated F_2 generation steers (n = 181), and half-blood *Bos indicus* × *Bos taurus* steers (n = 57) from a breeding system designed for genomic mapping, which is composed of families (n =17) from F_1 Nellore × Angus. The original family is composed of F_1 Nellore × Angus females (n=10) and F_1 Nellore × Angus sires (n=4). The females were set up in a multiple ovulation embryo transfer program to maximize offspring each season, and donor cows also were naturally serviced by the same F_1 Nellore × Angus sires. The offspring of this breeding system were placed on a grain ration, post-weaning, and harvested at the Rosenthal Meat Science and Technology Center on the Texas A&M University campus.

3.2 Postmortem Electrical Stimulation Treatment

Each animal was harvested in a manner mirroring large-scale industrial harvesting processes. During the harvest process, each carcass was split vertically through the vertebral column and the right side of each carcass was subjected to high-voltage electrical stimulation (ES) leaving the left side as the non-stimulated control (NON). A single electrical probe was inserted into the carcass between the thoracic vertebrae and the scapula with the rail acting as the ground. Each right side received 525

volts (AC), 2 amps, 2 seconds on, 2 seconds off, for 15 impulses. Electrical stimulation was applied within 1 h postmortem. After completion of the harvesting process, both sides were placed in a blast-chill cooler (1-2 °C) for 24 h chilling before being placed in a holding cooler (2-4° C) for 24 h for a combined postmortem chilling time of 48 hr.

3.3 Time, Temperature and pH Data Collection

Time, temperature, and pH data collection for the ES and non-ES sides began at 0 h immediately prior to entering the blast cooler (within 45 minutes of exsanguination), and continued every three hours thereafter until 12 h. From that point forward, time and temperature data collection occurred every 12 h up until 48 h postmortem. Both temperature and pH data were collected from the *M. longissimus lumborum*, in the caudal half, using an IQ pH/temperature instrument (model IQ150, probe pH 57-SS, IQ Scientific Instruments, Inc., Carlsbad, CA). At 48 h postmortem, the carcasses were ribbed at the 12th–13th rib interface and allowed to bloom for approximately 15 min. USDA (1997) yield and quality grade factors were determined by trained Texas A&M University personnel. Additionally, CIE *L**, *a**, and *b** color space values were measured using a Hunter Miniscan XE colorimeter (HunterLabs, Reston, VA; Illuminant A; 10° observer), immediately after grading of each side.

3.4 Loin Steak Removal

Loin steaks were removed 48 hr postmortem immediately after grading and color data were collected. The anterior portion of the *M. longissimus lumborum* was removed

at a point half the length of the strip loin section from ES and NON sides. This allowed

for an adequate number of steaks for shear force, sensory panel, sarcomere length, and

myofibril fragmentation index (MFI) analysis for each side. The strip loin section was

cut into 2.54 cm steaks beginning at the cranial end; the first steak from each side was

assigned to Warner-Bratzler shear force, the second and third to sensory panel, and the

next two steaks for sarcomere length and MFI, respectively; this anatomical pattern held

true for the entire project, to allow for accurate comparison of ES versus non-ES. Once

cut the steaks were trimmed free of external subcutaneous fat and vacuum packaged.

3.5 Warner-Bratzler Shear Force Analysis

Steaks assigned for Warner–Bratzler shear force determinations were cooked to

an internal temperature of 70 °C using Farberware Open Hearth broilers (Farberware

Company, Bronx, NY). Internal temperature was monitored continually using type-K

thermocouples (model KTSS-HH, Omega Engineering, Inc., Stamford CT), inserted into

the geometric center of each steak, and attached to a Thermocouple Input Benchtop

Meter (model BS 6001A, Omega Engineering, Inc., Stamford, CT). Following cooking,

steaks were covered and allowed to chill overnight in refrigeration. Six 1.27-cm cores

were removed from each steak following a pre-set location for each core number, with

cores taken parallel with the muscle fiber orientation. Each core was sheared on a

Universal Testing Machine (model 5STM-500, United Calibration Corp., Huntington

Beach, CA) equipped with a V-notch Warner-Bratzler blade, and a 20 kg compression

load cell with a cross-head speed of 200 mm/min. The peak force (N) needed to shear

each core was recorded. Individual cores were analyzed for location effects, and the average of these cores also was analyzed as the mean shear value for each side.

3.6 Sarcomere Length

Sarcomere lengths of the *M. longissimus lumborum* were determined with the laser method of Cross, West, and Dutson (1981). A Spectra-Physics model 155SL helium-neon laser (0.95mW, $\lambda= 0.6328$) was pre-warmed before taking measurements. Three to five grams of minced loin muscle tissue was removed from each sample designated for sarcomere length determination. The sample was homogenized in 15-20 mL of cold (4° C) buffer solution (85.58 g, 0.25 M sucrose, 0.15 g, 0.02 mM KCl, and 1.4 g, 0.005 M iodoacetate; adjusted to pH 7.0 and brought to 1 liter volume with distilled water) at a low speed until fiber separation was observed (10-15 sec). One drop of homogenate was placed on a glass microscope slide, a cover slip was applied, and the slide was placed on laser stage. The distance from the top of the slide to the baseboard of the laser stand was set at 100 mm. Distance from the origin and the first order diffraction band was recorded. Each steak was divided into lateral, medial and center sections and 10 measurements were recorded for each section, the average length of all sections for each steak was used for analysis. The sarcomere length was calculated, in μm, using the formula of Cross et al. (1981).

3.7 Myofibril Fragmentation Index

The myofibrillar fragmentation index of thawed steaks were determined following the procedure of Olson, et al. (1976) as modified by Culler, Parrish, Smith, and Cross (1978). Minced muscle (4 g) was added to a Eberbach blender with 40 mL of isolating medium (100 mM KCl, 20 mM KPO_4 (pH 7.0), 1 mM EDTA, 1 mM $MgCl_2$, and 1 mM sodium azide) and blended for 30 sec. The homogenate was sedimented at $1000 \times g$ for 15 min, and then supernatant was decanted. The sediment then was resuspended in 40 mL of isolating medium using a stir rod, sedimented again at $1000 \times g$ for 15 minutes and the supernatant was decanted. The sediment was resuspended in 10 mL of isolating medium and passed through a polyethylene strainer to remove connective tissue and debris, an additional 10 mL of isolating medium was used to facilitate passage of myofibrils through the strainer. Protein assay was conducted by placing 0.25 mL of each suspension into 13×100 mm glass cuvette, along with 0.75 mL isolating medium and 4 mL biuret reagent and vortexed. Sample then was set in a dark room for 30 min while Bovine Serum Albumin (BSA) standards were run to establish a standard curve. Absorbance was read at $\lambda = 540$ nm with a Bausch and Lomb Spectronic 20 colorimeter with a large split width. Absorbance was multiplied by 200 to give the myofibril fragmentation index.

3.8 Statistical Analysis

The effects of electrical stimulation on family groups and sires were analyzed for Warner-Bratzler shear force, myofibrillar fragmentation index, sarcomere length, pH,

and temperature. Analysis of variance was performed using SAS PROC MIXED (SAS

Institute, Cary, NC), and when significant differences were found, means were separated

using the p-diff function at $P < 0.05$. The model included harvest day as a block to

account for seasonal and harvest day effects. Main effects were defined as SIRE, SIDE,

FAMILY(SIRE), FAMILY*SIDE(SIRE) and SLDATE. The interaction

FAMILY*SIDE(SIRE) was removed from the model when $P > 0.25$. To determine if

carcass fat thickness or carcass weight impacted temperature and pH data, for these, two

additional covariate analysis were conducted. The first analysis included ACFATM, fat

thickness at the 12th rib, as a covariate in the aforementioned model. A second analysis

was conducted in the same manner using HCWM, hot carcass weight, as the covariate.

CHAPTER IV

RESULTS AND DISCUSSION

4.1. Simple Statistics

Simple statistics for variables analyzed for the F_2 population are presented in Tables 1-3, by treatment (ES) and control (NON). Table 1 illustrates simple carcass data from the F_2 population. Carcass weights ranged from 195.91 kg to 389.09 kg, and USDA Yield Grades from 1.0 to 4.8. Within this F_2 population, the ES sides (Table 2) had a large variation in initial temperature of 15.20° C to 41.50° C and temperature at 12h of 3.30° C to 20.10° C. These carcasses also had a large variation in MFI from 66.00 to 180.25; pH ranges from 5.10 to 7.10 and WBS averages ranging from 14.4 N-45.5 N. The NON sides (Table 3) from this F_2 group had similar variation in initial temperature of 16.60 °C to 41.60 °C, 12 h temperature ranging from 2.90 °C to 19.30 °C, MFI ranging from 66.00 to 180.25, and the WBS average ranges from 14.4 N to 45.5 N.

Table 1

F$_2$ simple statistics for carcass data

Variable[a]	n	Mean	Standard Deviation	Minimum	Maximum
ACFATM (cm)	181	1.23	0.45	0.25	2.41
ADJFATM (cm)	181	1.42	0.90	0.38	2.54
REAM (cm^2)	181	72.13	8.84	76.11	93.53
HCWM (kg)	181	297.25	40.77	195.91	389.09
YG	181	3.19	0.67	1.0	4.8

[a]ACFATM= actual fat thickness at the 12th rib (cm); ADJFATM= adjusted fat thickness (cm); REAM= ribeye area (cm^2); HCWM= hot carcass weight (kg); YG= USDA Yield Grade

Table 2

ES simple statistics for F$_2$ carcasses

Variable[a]	n	Mean	Standard Deviation	Minimum	Maximum
temp0	178	36.36	5.64	15.20	41.50
pH0	176	6.04	0.29	5.10	7.10
temp3	181	24.08	4.79	12.00	33.80
pH3	181	5.62	1.34	5.07	6.90
temp6	181	16.98	3.35	7.40	25.20
pH6	181	5.59	0.25	5.00	6.60
temp9	180	12.98	2.87	5.60	19.30
pH9	181	5.60	0.24	4.80	7.10
temp12	181	9.91	2.98	3.30	20.10
pH12	181	5.63	0.26	5.20	6.40
temp24	181	5.11	1.66	1.10	9.20
pH24	181	5.61	0.23	3.45	6.04
temp36	158	4.11	1.18	1.10	6.80
pH36	157	5.62	0.19	5.20	6.30
temp48	172	4.09	1.62	0.40	15.00
pH48	172	5.59	0.23	4.40	6.02
SARC	172	1.74	0.07	1.56	1.97
MFI	124	120.36	22.12	66.00	180.25
WBS	172	26.96	5.99	14.43	45.48
shear1[b]	171	27.61	7.64	12.31	56.47
shear2[b]	172	26.95	8.16	11.61	55.42
shear3[b]	172	26.28	7.62	11.87	56.10
shear4[b]	172	27.61	8.45	9.83	63.29
shear5[b]	171	26.94	8.82	12.31	64.85
shear6[b]	161	25.75	7.09	11.96	47.85

[a]temp0 = muscle temperature at 0h postmortem; pH0 = muscle pH at 0h; temp3 = muscle temperature at 3h; pH3 = muscle pH at 3h; temp6 = muscle temperature at 6h; pH6 = muscle pH at 6h; temp9 = muscle temperature at 9h; pH9 = muscle pH at 9h; temp12 = muscle temperature at 12h; pH12 = muscle pH at 12h; temp24 = muscle temperature at 24h; pH24 = muscle pH at 24h; temp48 = muscle temperature at 48h; pH48 = muscle pH at 48h; SARC = sarcomere length; MFI = myfibrillar fragmentation index; WBS = average Warner-Bratzler shear force

[b]Individual shear force measurements by location of core extraction

Table 3
NON simple statistics for F_2 carcasses

Variable[a]	n	Mean	Standard Deviation	Minimum	Maximum
temp0	178	35.79	5.59	16.60	41.60
pH0	176	3.37	0.36	5.14	7.09
temp3	181	23.79	4.48	10.30	33.30
pH3	181	5.98	0.41	4.50	6.92
temp6	181	16.31	2.99	7.50	24.80
pH6	181	5.84	0.31	5.10	6.72
temp9	181	12.79	2.99	6.10	20.80
pH9	181	5.75	0.29	5.10	6.67
temp12	181	9.63	2.91	2.90	19.30
pH12	180	5.78	0.30	5.20	6.78
temp24	181	5.19	1.89	0.30	13.10
pH24	181	5.67	0.22	4.90	6.67
temp36	158	4.09	1.27	0.60	7.90
pH36	157	5.62	0.21	5.10	6.50
temp48	171	4.15	1.77	0.40	16.70
pH48	172	5.58	0.27	4.10	6.06
SARC	178	1.74	0.08	1.46	2.11
MFI	130	114.10	26.57	61.50	185.00
WBS	181	36.57	10.28	16.75	69.20
shear1[b]	181	36.94	13.98	10.44	86.08
shear2[b]	181	37.29	14.27	15.01	93.18
shear3[b]	181	36.29	14.44	4.07	88.45
shear4[b]	181	35.76	12.27	11.74	80.87
shear5[b]	180	36.91	14.36	15.10	79.35
shear6[b]	159	34.85	12.95	0.39	74.15

[a]temp0 = muscle temperature at 0h postmortem; pH0 = muscle pH at 0h; temp3 = muscle temperature at 3h; pH3 = muscle pH at 3h; temp6 = muscle temperature at 6h; pH6 = muscle pH at 6h; temp9 = muscle temperature at 9h; pH9 = muscle pH at 9h; temp12 = muscle temperature at 12h; pH12 = muscle pH at 12h; temp24 = muscle temperature at 24h; pH24 = muscle pH at 24h; temp48 = muscle temperature at 48h; pH48 = muscle pH at 48h; SARC = sarcomere length; MFI = myfibrillar fragmentation index; WBS = average Warner-Bratzler shear force

[b]Individual shear force measurements by location of core extraction

Simple statistics for variables analyzed in the half-blood population are presented in Tables 4 to 6. Table 4 illustrates simple statistics for carcass data in the half-blood population. Carcass weights ranged from 220.45 kg to 371.82 and USDA Yield Grades ranged from 1.5 to 5.4. The half-blood carcasses in this study are represented by a smaller population size, and show less variation in early post-mortem temperatures and pH ranges; however, at 12 h, the temperature range is from 4.00 °C to 18.30 °C. The half-blood ES MFI ranges from 84.50 to 188.50 and WBS average varies from 17.2 N to 40.0 N. Differences among individual shear forces by location vary as well. The NON sides range in MFI values from 80.00 to 199.50 and WBS averages vary from 18.4 N to 61.9 N.

Table 4
Half-blood simple statistics for carcass data

Variable[a]	n	Mean	Standard Deviation	Minimum	Maximum
ACFATM (cm)	57	1.30	0.45	0.38	2.29
ADJFATM (cm)	57	1.47	0.43	0.64	2.54
REAM (cm^2)	57	75.85	7.76	61.28	96.75
HCWM (kg)	57	313.10	31.42	220.45	371.82
YG	57	3.25	0.68	1.5	5.4

[a]ACFATM= actual fat thickness at the 12th rib (cm); ADJFATM= adjusted fat thickness (cm); REAM= ribeye area (cm^2); HCWM= hot carcass weight (kg); YG= USDA Yield Grade

Table 5
ES simple statistics for half-blood carcasses

Variable[a]	N	Mean	Standard Deviation	Minimum	Maximum
temp0	57	38.46	1.19	33.00	40.30
pH0	55	5.83	0.23	5.30	6.35
temp3	57	26.50	3.14	19.52	34.60
pH3	57	5.42	0.21	4.90	5.87
temp6	57	18.72	2.79	11.70	22.80
pH6	57	5.50	0.22	5.00	6.00
temp9	57	14.06	2.41	9.30	20.40
pH9	57	5.51	0.19	4.80	6.00
temp12	57	11.77	2.99	4.00	18.30
pH12	57	5.55	0.27	5.15	7.00
temp24	57	5.63	1.21	1.60	8.10
pH24	57	5.56	0.17	5.20	6.20
temp36	50	4.74	0.90	2.60	6.30
pH36	50	6.55	6.85	5.10	54.00
temp48	57	4.16	0.97	1.80	6.30
pH48	57	5.56	0.14	5.00	5.90
SARC	56	1.76	0.06	1.62	1.95
MFI	48	126.67	26.23	84.50	188.50
WBS	57	26.72	5.34	17.24	40.03
shear1[b]	57	26.18	6.38	12.98	41.17
shear2[b]	57	26.43	7.43	14.28	48.99
shear3[b]	57	26.82	7.03	15.37	46.92
shear4[b]	57	26.64	8.03	15.90	55.12
shear5[b]	57	27.42	8.16	15.51	50.92
shear6[b]	55	26.69	7.27	15.16	48.08

[a]temp0 = muscle temperature at 0h postmortem; pH0 = muscle pH at 0h; temp3 = muscle temperature at 3h; pH3 = muscle pH at 3h; temp6 = muscle temperature at 6h; pH6 = muscle pH at 6h; temp9 = muscle temperature at 9h; pH9 = muscle pH at 9h; temp12 = muscle temperature at 12h; pH12 = muscle pH at 12h; temp24 = muscle temperature at 24h; pH24 = muscle pH at 24h; temp48 = muscle temperature at 48h; pH48 = muscle pH at 48h; SARC = sarcomere length; MFI = myfibrillar fragmentation index; WBS = average Warner-Bratzler shear force

[b]Individual shear force measurements by location of core extraction

Table 6
NON simple statistics for half-blood carcasses

Variable[a]	N	Mean	Standard Deviation	Minimum	Maximum
temp0	57	37.79	1.30	32.90	40.10
pH0	57	6.22	0.38	5.20	7.01
temp3	57	24.98	2.97	18.70	31.20
pH3	57	5.79	0.40	4.70	6.52
temp6	57	17.61	2.72	12.90	23.50
pH6	57	5.79	0.34	5.00	6.40
temp9	57	12.78	2.49	5.50	16.60
pH9	57	5.70	0.25	5.00	6.28
temp12	57	10.58	3.20	3.30	17.40
pH12	57	5.66	0.29	5.20	6.60
temp24	57	5.13	1.16	2.00	10.30
pH24	57	5.58	0.15	5.20	6.00
temp36	50	4.59	0.83	2.60	5.90
pH36	50	5.58	0.24	5.20	6.30
temp48	57	4.17	0.91	2.10	6.40
pH48	57	5.54	0.14	5.10	5.90
SARC	53	1.76	0.07	1.62	1.95
MFI	48	146.29	29.46	80.00	199.50
WBS	57	32.49	9.09	18.42	61.85
shear1[b]	57	33.39	13.09	16.84	77.61
shear2[b]	57	32.59	11.25	15.89	67.30
shear3[b]	57	33.81	13.08	15.13	71.69
shear4[b]	57	30.67	10.80	16.10	63.73
shear5[b]	57	31.77	10.98	15.27	63.13
shear6[b]	55	32.66	14.08	15.39	76.42

[a]temp0 = muscle temperature at 0h postmortem; pH0 = muscle pH at 0h; temp3 = muscle temperature at 3h; pH3 = muscle pH at 3h; temp6 = muscle temperature at 6h; pH6 = muscle pH at 6h; temp9 = muscle temperature at 9h; pH9 = muscle pH at 9h; temp12 = muscle temperature at 12h; pH12 = muscle pH at 12h; temp24 = muscle temperature at 24h; pH24 = muscle pH at 24h; temp48 = muscle temperature at 48h; pH48 = muscle pH at 48h; SARC = sarcomere length; MFI = myfibrillar fragmentation index; WBS = average Warner-Bratzler shear force

[b]Individual shear force measurements by location of core extraction

4.2. F$_2$ Population

Analysis of variance tables can be found for all fixed effects of the F$_2$ population in Appendix A. Within the F$_2$ population, differences ($P < 0.05$) in sides were found for all six locations of core extraction, and the average of these cores also differed ($P < 0.05$) between sides (ES vs. NON). No differences were found for the interaction of families by side nested within sires, thus this interaction was removed from the model. The location of shear1 extraction is on the medial-ventral side of the *M. longissimus lumborum,* and this location shows particular difference ($P < 0.05$) in family nested within sires. For shear1, shear4, shear5, and shear6, harvest date was found to be significant in the model, thus it should be noted the importance of consistent harvesting conditions on shear force values, and other post-mortem chemical and physical changes in muscle. Differences ($P < 0.05$) were found for the average shear force value for sire and family nested within sire.

Table 7
Least squares means ± standard error for
WBS shear1 by FAMILY(SIRE) for
F_2 carcasses

Sire	FAMILY	shear1
297J		
	70	$30.62^{bc} \pm 2.09$
	71	$34.22^{cd} \pm 2.02$
432H		
	72	$29.80^{bcd} \pm 1.91$
	73	$35.54^{cd} \pm 3.92$
	82	$19.11^{a} \pm 3.59$
437J		
	74	$33.84^{bcd} \pm 4.61$
	75	$28.67^{bc} \pm 2.70$
	81	$31.49^{bcd} \pm 1.70$
	83	$26.09^{ab} \pm 2.54$
551G		
	76	$28.11^{abc} \pm 3.86$
	77	$36.53^{cd} \pm 2.03$
	80	$36.87^{d} \pm 1.91$
	84	$32.80^{bcd} \pm 2.46$

Within a column, means lacking
a common letter (a-d) differ ($P < 0.05$)

Families nested within sires accounted for variation found in WBS at the shear1 location. These differences in least squares means and standard errors are presented in Table 7. Family 82, sired by 432H, produced more tender ($P < 0.05$) shear cores than families 72 and 73 within this same sire for shear1. Families 76 and 80, both sired by 551G, were significantly different with family 76 producing more tender shear cores at this particular location. Sires 437J and 297J presented no significant differences within or across their families at the shear1 location. However, families 75 and 83, sired by 437J, family 82 sired by 432H, and family 70, sired by 297J, were found to be more tender ($P < 0.05$) for shear1 than family 80 from sire 551G.

Differences in least squares means and standard errors for shear location and average shear force values by side are shown in Table 8. The ES sides produced steaks that were more tender ($P < 0.05$) for all shear locations and also for the average of the six values. This data follow the results of earlier researchers in the fact that post-mortem electrical stimulation greatly enhances meat tenderness (Davey et al., 1976; Savell et al., 1977, 1978a, b, c, 1979; and McKeith et al., 1981).

Table 8
Least squares means ± standard error for
WBS location, MFI, and WBS average by side for F_2 carcasses

	ES	NON	P-value
shear1[a]	26.36 ± 0.97	35.72 ± 0.94	<0.0001
shear2[a]	26.92 ± 1.02	37.25 ± 1.09	<0.0001
shear3[a]	24.87 ± 1.03	35.04 ± 1.00	<0.0001
shear4[a]	27.78 ± 0.91	34.82 ± 0.88	<0.0001
shear5[a]	26.09 ± 1.00	36.33 ± 0.97	<0.0001
shear6[a]	24.88 ± 0.93	34.49 ± 0.91	<0.0001
WBS AVG[b]	26.06 ± 0.71	35.73 ± 0.69	<0.0001
MFI	127.01 ± 2.30	118.61 ± 2.22	0.0176

[a]Anatomical location of core extraction from *M. longissimus lumborum*
[b]Average of the six shear core values

Table 9
Least squares means ± standard error for
WBS average by FAMILY(SIRE) for F_2
carcasses

Sire	FAMILY	WBS
297J		
	70	31.20[ab] ± 1.52
	71	32.83[b] ± 1.49
432H		
	72	31.03[ab] ± 1.41
	73	36.36[b] ± 2.76
	82	25.95[a] ± 2.64
437J		
	74	30.31[ab] ± 3.39
	75	26.83[a] ± 1.99
	81	32.54[b] ± 1.27
	83	26.11[a] ± 1.87
551G		
	76	28.90[ab] ± 2.84
	77	33.03[b] ± 1.49
	80	33.60[b] ± 1.40
	84	30.51[ab] ± 1.82

Within a column, means lacking
a common letter (a-b) differ ($P < 0.05$)

The differences in least squares means and standard errors for the average shear values for family nested within sire are presented in Table 9. Steaks from family 82, sired by 432H, had lower (more tender) shear force values ($P < 0.05$) than steaks from family 73, of the same sire. This gives evidence to the contribution of the dam to the tenderness of the carcass. Steaks from family 82 by sire 432H also had lower, more tender shear force values ($P < 0.05$) than steaks from families 77 and 80 sired by 551G, family 81 sired by 437J, and family 71 sired by 297J. Family 81 sired by 437J produced steaks with higher (tougher) shear values ($P < 0.05$) than steaks from families 83 and 75 of the same sire (437J). Differences among families nested within sires 551G and 297J were not found to be significant. Because the model did not find any gentic differences across sires and only differences of families nested within sires, there exists genetic contribution of tenderness from the dams as well as the sires to which they were bred.

These data showed there were no significant differences for genetic contributions or ES treatment in sarcomere length. Harvest day was the only variable that accounted for variation in sarcomere length ($P < 0.05$) in this study. This could be due to the harvesting environment and chilling environment fluctuations. The lack of variation found in sarcomere length from electrical stimulation follows past studies (Savell et al., 1977, 1978a, 1979; Takahashi et al., 1984; Stolowski et al., 2006), in that sarcomere length was not affected by the post-mortem application of electrical stimulation, and thus electrical stimulation does not prevent cold shortening.

MFI was measured as an indicator of post-mortem proteolysis. Sire, family nested within sire, side, and family by side nested within sire accounted for the variation

in MFI. The differences in least square means and standard errors for MFI by sire are presented in Table 10. Sire 551G had the lowest (least post-mortem proteolysis) ($P <$ 0.05) MFI value of all sires. Sire 437J had a lower MFI value ($P < 0.05$) than 432H, whereas sire 432H also was higher ($P < 0.05$) than sires 437J and 551G. Table 11 presents the differences in least squares means in MFI of family nested within sire. Family 80 sired by 551G did not differ from other families within that sire, but was lower ($P < 0.05$) in MFI than all other families across sires, which follows the results found in Table 10. Family 82 sired by 432H had a higher ($P < 0.05$) MFI value than family 72 of the same sire. This family 82, by sire 432H, was higher ($P < 0.05$) than all other families within sires except, family 70 of sire 297J.

Table 10
Least square means ± standard error for
MFI by sire for F_2 carcasses

SIRE	MFI
297J	$126.42^{bc} \pm 3.39$
432H	$131.26^{c} \pm 4.38$
437J	$121.51^{b} \pm 2.96$
551G	$112.05^{a} \pm 2.75$
P-value	<0.0001

Within a column, means lacking a
common letter (a-c) differ ($P < 0.05$)

Table 11
Least square means ± standard error for MFI by FAMILY(SIRE)
for F_2 carcasses

Sire	Family	MFI
297J		
	70	$131.86^{cd} \pm 4.89$
	71	$120.97^{bc} \pm 4.39$
432H		
	72	$119.34^{b} \pm 4.33$
	82	$143.18^{d} \pm 6.89$
437J		
	75	$121.68^{bc} \pm 6.83$
	81	$119.82^{b} \pm 4.78$
	83	$123.04^{bc} \pm 3.23$
551G		
	77	$115.31^{ab} \pm 5.11$
	80	$106.56^{a} \pm 4.43$
	84	$114.29^{ab} \pm 4.72$

Within a column, means lacking a
common letter (a-c) differ ($P < 0.05$)

Table 12
MFI least square means ± standard error by FAMILY*SIDE(SIRE) for F_2 carcasses

Sire	FAMILY	SIDE	MFI
297J			
	70	ES	$141.66^{fg} \pm 6.59$
		NON	$122.07^{abcde} \pm 6.59$
	71	ES	$124.48^{def} \pm 6.18$
		NON	$117.47^{abcde} \pm 5.92$
432H			
	72	ES	$123.79^{cde} \pm 5.84$
		NON	$114.89^{abcde} \pm 5.84$
	82	ES	$157.30^{g} \pm 9.12$
		NON	$129.05^{ef} \pm 9.12$
437J			
	75	ES	$112.57^{abcde} \pm 9.73$
		NON	$130.79^{ef} \pm 8.85$
	81	ES	$127.29^{ef} \pm 4.29$
		NON	$112.35^{abcd} \pm 4.41$
	83	ES	$117.15^{abcde} \pm 6.51$
		NON	$128.93^{ef} \pm 6.51$
551G			
	77	ES	$115.72^{abcde} \pm 6.43$
		NON	$114.90^{abcde} \pm 6.74$
	80	ES	$107.55^{abc} \pm 5.96$
		NON	$105.56^{ab} \pm 5.49$
	84	ES	$123.04^{bcde} \pm 6.57$
		NON	$105.54^{a} \pm 6.24$

Within a column, means lacking a common letter (a-e) differ ($P < 0.05$)

Families by sides within sire also accounted for variation in MFI values, and differences in those least squares means and standard errors are presented in Table 12. The ES side from family 70, sired by 297J, was higher ($P < 0.05$) in MFI than NON sides within this sire. ES sides from family 70, sired by 297J; family82, sired by 432H; family 81, sired by 437J; and family 84, sired by 551G; all had higher MFI values than their corresponding NON sides. Sire 297J had similar values for ES across both families. Sired by 297J, families 70 and 71 had variation that is contributed to the family on the responsiveness to the ES treatment, since differences between sides were seen for family 70 and not for family 71. The ES sides in family 82, sired by 432H had higher ($P < 0.05$) MFI values than the NON sides, as well as a higher ($P < 0.05$) MFI values than the ES sides from family 72, sired by 432H. ES responsiveness was seen for family 82, sired by 432H as the MFI value for ES sides was higher ($P < 0.05$) than that of the NON, where family 72, sired by 432H did not show responsiveness. Family 81, sired by 437J, showed ES had a higher ($P < 0.05$) value than that of NON. All three families within sire 437J had similar values, and the family 81 NON sides were lower ($P < 0.05$) than the NON sides from families 75 and 83. The ES side from family 84, sired by 551G had higher ($P < 0.05$) MFI values than the NON sides within this family and sire. ES improved post-mortem proteolysis in family 70, sired by 297J, family 82, sired by 432H, and family 84, sired by 551G. These data showed responsiveness to electrical stimulation in that post-mortem proteolysis improved MFI values for the ES sides when compared to NON sides of the same family. This responsiveness is contributed to the dam effects in this model.

Side accounted for early post-mortem temperature differences ($P < 0.05$), while sires and families within sires accounted for differences ($P < 0.05$) found in the later hours post-mortem. Harvest day was found to be significant at all time periods. Side differences accounted for the variation in carcass temperatures early post-mortem at 0 h and 6 h. Sire contributions are noted as significant, at time periods 6 h, 9 h, 12 h, 24 h, and 36 h. Families nested within sires were accountable for variation ($P < 0.05$) at time periods 9 h, 12 h, 24 h, and 48 h. Table 13 illustrates the least squares means and standard errors for sire effects at the corresponding time periods. Sire 297J had a higher ($P < 0.05$) carcass temperatures than all other sires at the 6 h, 12 h, and 24 h time period, 297J also had higher ($P < 0.05$) carcasss temperatures than 432H at 24 h. Sire 437J had lower ($P < 0.05$) temperatures at 36 h than sire 437J. The remaining three sires did not differ at these time periods. Table 14 presents the differences in least squares means and standard errors for carcass temperatures at 0 and 6 h. The ES sides had higher ($P < 0.05$) temperatures that the NON sides. These data represent the increased metabolic rates and thus temperatures from the application of electrical stimulation.

Table 13
Least square means ± standard errors for carcass temperature at times 6, 9, 12, 24, and 36 h by sire for F_2 carcasses

SIRE	6h	9h	12h	24h	36h
297J	$18.13^b \pm 0.33$	$14.03^b \pm 0.34$	$10.98^b \pm 0.33$	$5.72^b \pm 0.20$	$4.64^b \pm 0.12$
432H	$16.62^a \pm 0.55$	$12.81^a \pm 0.58$	$9.51^a \pm 0.56$	$4.64^a \pm 0.34$	$4.22^a \pm 0.17$
437J	$16.10^a \pm 0.34$	$12.02^a \pm 0.35$	$9.04^a \pm 0.34$	$4.74^a \pm 0.21$	$3.97^a \pm 0.11$
551G	$16.72^a \pm 0.29$	$12.53^a \pm 0.31$	$9.36^a \pm 0.30$	$4.90^a \pm 0.18$	$4.11^a \pm 0.09$
P-value	0.0004	0.0011	0.0004	0.0012	0.0005

Within a column, means lacking a common letter (a-b) differ ($P < 0.05$)

Table 14
Least square means ± standard error for carcass temperature at times 0 and 6 h by side for F_2 carcasses

Time	ES	NON	*P*-value
0h	37.22 ± 0.15	36.65 ± 0.15	0.0005
6h	17.21 ± 0.23	16.57 ± 0.23	0.0099

Table 15
Least square means ± standard errors for carcass temperature at times 9, 12, 24, and 48 h by FAMLY(SIRE) for F_2 carcasses

Sire	FAMILY	9h	12h	24h	48h
297J					
	70	$14.16^d \pm 0.48$	$11.07^c \pm 0.46$	$5.84^d \pm 0.28$	$3.59^a \pm 0.21$
	71	$13.89^d \pm 0.46$	$10.88^c \pm 0.44$	$5.60^{cd} \pm 0.27$	$4.08^{ab} \pm 0.19$
432H					
	72	$12.64^{abcd} \pm 0.44$	$9.72^{abc} \pm 0.43$	$4.66^{abc} \pm 0.25$	$3.94^a \pm 0.18$
	73	$14.08^d \pm 0.86$	$10.73^c \pm 0.84$	$5.45^{bcd} \pm 0.50$	$4.06^{ab} \pm 0.35$
	82	$11.73^{ab} \pm 0.82$	$8.06^a \pm 0.80$	$3.82^a \pm 0.48$	$3.41^a \pm 0.33$
437J					
	74	$11.24^{ab} \pm 1.05$	$7.79^a \pm 1.03$	$3.89^{ab} \pm 0.61$	$3.78^a \pm 0.42$
	75	$11.99^{ab} \pm 0.60$	$8.55^a \pm 0.58$	$4.71^{abc} \pm 0.35$	$4.07^{ab} \pm 0.24$
	81	$13.62^{cd} \pm 0.39$	$10.65^c \pm 0.28$	$5.68^{cd} \pm 0.23$	$3.81^a \pm 0.16$
	83	$11.23^a \pm 0.58$	$9.16^{ab} \pm 0.57$	$4.67^{abc} \pm 0.34$	$3.93^a \pm 0.24$
551G					
	76	$11.25^{ab} \pm 0.89$	$8.55^{ab} \pm 0.86$	$4.56^{abc} \pm 0.52$	$3.83^a \pm 0.41$
	77	$13.17^{bcd} \pm 0.46$	$9.32^{ab} \pm 0.45$	$4.58^{abc} \pm 0.27$	$4.04^{ab} \pm 0.19$
	80	$13.34^{bcd} \pm 0.42$	$10.20^{bc} \pm 0.41$	$5.17^{bcd} \pm 0.24$	$3.62^a \pm 0.19$
	84	$12.38^{abc} \pm 0.55$	$9.37^{ab} \pm 0.54$	$5.27^{bcd} \pm 0.32$	$4.57^b \pm 0.22$

Within a column, means lacking a common letter (a-d) differ ($P < 0.05$)

Differences in least square means and standard errors of temperature and time periods for families nested within sires are presented in Table 15. Family 82, sired by 432H had lower carcass temperatures ($P < 0.05$) than family 73 from this sire, at 9 h, 12 h, and 24 h. Family 73 sired by 432H had higher carcass temperatures at 9 h than families 70 and 71 from sire 297J, families 74, 75, and 83 sired by 437J, and families 76 and 84 sired by 551G. Family 81, sired by 437J, had a higher ($P < 0.05$) temperature at 9 h than all other families within this sire, leading to the conclusion that progeny from this genetic group would maintain higher temperatures for an extended period of time. This conclusion follows the hypothesis given by Moeller et al. (1976), who stated that these higher temperatures combined with a lower pH would promote increased enzymatic activity within the muscles. At 12 h time period, family 81, sired by 437J was higher than other families within this sire, thus contributing more evidence of dam contributions to response of electrical stimulation. Family 76, sired by 551G had lower temperatures than family 84 from the same sire at the 48 h time period. This family, 84, sired by 551G, had higher ($P < 0.05$) carcass temperatures than family 82, sired by 432H, family 70, sired by 297J, and families 74, 81 and 83 sired by 551G. Schroeder et al., (1982), stated that lighter weight carcasses chilled faster than heavier, fatter carcasses. In order to effectively account for all the variation present in carcass temperature and isolate the contributing factors, fat thickness and hot carcass weight were individually added to the model as covariates. Fat thickness, as a covariate was significant for all time periods for temperature. The significance of the fixed effects were not found to changed except for 9 h at which sire effects became not significant in the model and at 36 h where

FAMILY(SIRE) became significant in the model. Hot carcass mass was then used as an individual covariant, and showed to be significant for all time periods. Fixed effects remained unchanged except for 36 h at which FAMILY(SIRE) became significant in the model. These results support the conclusion that at the specified time periods where fixed effects remain unaffected by the individual covariate, variability accounted for by genetic contribution is due to the metabolic activity differences between sires and families nested within sires.

Harvest day accounted for variation in carcass pH at all time periods, while side differences were found to be significant from the initial time period (0 h) to 24 h. Variation for pH 6 h also was accounted for by family nested within sire and the interaction family by side nested within sire. Variation present at the 36 h time period was not found to be significant for biological or treatment effects. While family nested within sire accounted for the variation of the final 48 h pH. Least squares means and standard errors for time periods by side are presented in Table 16. From 0 h to 24 h post-mortem, ES sides had a lower ($P < 0.05$) carcass pH across all time periods when compared to NON. The ES sides had a small rise in pH from 9 h to 12 h and the NON sides show a small rise at from 9 h to 12 h as well. From these data it is shown that ES sides reached a final pH range at 3-6 h, while pH in NON sides were still differing out to 24 h.

Table 16
Least squares means ± standard error for
carcass pH 0, 3, 6, 9,12, and 24 h by side for F_2 carcasses

Time	ES	NON	P-value
0h	6.01 ± 0.02	6.34 ± 0.02	<0.0001
3h	5.55 ± 0.03	5.96 ± 0.03	<0.0001
6h	5.55 ± 0.02	5.83 ± 0.02	<0.0001
9h	5.59 ± 0.02	5.74 ± 0.02	<0.0001
12h	5.60 ± 0.02	5.76 ± 0.02	<0.0001
24h	5.58 ± 0.02	5.64 ± 0.02	<0.0001

Table 17
Least square means ± standard error for pH at 6 h and
48 h by FAMILY(SIRE) for F_2 carcasses

Sire	FAMILY	6h	48h
297J			
	70	$5.66^{ab} \pm 0.04$	$5.59^{bcd} \pm 0.03$
	71	$5.76^{bcd} \pm 0.03$	$5.60^{bcd} \pm 0.03$
432H			
	72	$5.70^{abcd} \pm 0.03$	$5.54^{abc} \pm 0.03$
	73	$5.78^{cd} \pm 0.07$	$5.64^{cd} \pm 0.06$
	82	$5.69^{abcd} \pm 0.07$	$5.53^{abc} \pm 0.05$
437J			
	74	$5.53^{a} \pm 0.09$	$5.57^{abcd} \pm 0.07$
	75	$5.67^{abc} \pm 0.05$	$5.62^{cd} \pm 0.04$
	81	$5.67^{abc} \pm 0.03$	$5.53^{ab} \pm 0.03$
	83	$5.74^{bcd} \pm 0.05$	$5.59^{bcd} \pm 0.03$
551G			
	76	$5.80^{cd} \pm 0.07$	$5.73^{d} \pm 0.06$
	77	$5.77^{cd} \pm 0.04$	$5.59^{bcd} \pm 0.03$
	80	$5.61^{a} \pm 0.04$	$5.64^{cd} \pm 0.03$
	84	$5.84^{d} \pm 0.02$	$5.46^{a} \pm 0.03$

Within a column, means lacking a common letter (a-d) differ ($P < 0.05$)

Differences of least squares means for carcass pH at 6 and 48 h, by family nested within sire are displayed in Table 17. At 6 h, family 74 had a lower pH than family 83 both sired by 437J. Family 80 sired by 551G had the lowest ($P < 0.05$) pH recorded for this time period (6 h) for families nested within this sire. Within sire 437J, family 81 had a lower ($P < 0.05$) pH than family 75 for 48 h. Sire 551G had variation between families; family 80 had a lower ($P < 0.05$) pH than the other three families within this sire. Family 84, sired by 551G, also had a higher pH than families 74, 75 and 81, sired by 437J; and family 70, sired by 297J. At 48 h family 84, sired by 551G, had a lower

($P < 0.05$) pH than other families within this sire, while also being lower than families 83 and 75 sired by 437J, family 73 sired by 432H and both families 70 and 71 sired by 297J. Within sire 437J, family 81 was lower ($P < 0.05$) pH than family 75.

The differences of least squares means and standard errors for 6 h pH for family by side nested within sire are displayed in Table 18. The NON sides from family 76, sired by 551G, had a higher ($P < 0.05$) pH values than the NON sides from families 77 and 80, both sired by 551G; families 74 and 75, sired by 437J; families 82 and 72 all sired by 432H, and family 70, sired by 297J. Family 76, sired by 551G, produced NON sides which were higher ($P < 0.05$) than all ES sides in families within sires. Family 71, sired by 297J, families 72 and 73, sired by 432H, families 81 and 83, sired by 437J, and family 76, sired by 551 all show response to ES treatment by having a lower ($P < 0.05$) pH for the ES sides. These pH data were also suspected of being influenced by carcass mass and fat thickness, thus these covariates were used here as well. Fat thickness, as a covariate, was found to be significant for time period 6 h for pH. At the 6 h time period, covariate fat thickness ($P = 0.0098$), sire effects became significant while family nested within sire remained significant. Thus further emphasizing the biological contribution of the sire and dam to the metabolic activity of the post-mortem muscle. Hot carcass mass, as a covariate, was found not to be significant for any time period for pH.

Table 18
Least square means ± standard errors for
pH at 6 h by FAMILY*SIDE(SIRE) for F_2 carcasses

Sire	Family	Side	pH 6h
297J			
	70	ES	5.49^{ab} ± 0.05
		NON	5.82^{bc} ± 0.05
	71	ES	5.60^{ab} ± 0.05
		NON	5.92^{cde} ± 0.05
432H			
	72	ES	5.53^{ab} ± 0.05
		NON	5.88^{cd} ± 0.05
	73	ES	5.49^{ab} ± 0.10
		NON	6.08^{de} ± 0.10
	82	ES	5.65^{ab} ± 0.09
		NON	5.74^{abc} ± 0.09
437J			
	74	ES	5.38^{a} ± 0.02
		NON	5.68^{abc} ± 0.02
	75	ES	5.57^{ab} ± 0.07
		NON	5.76^{abc} ± 0.07
	81	ES	5.55^{ab} ± 0.04
		NON	5.80^{cde} ± 0.04
	83	ES	5.61^{ab} ± 0.07
		NON	5.89^{cde} ± 0.07
551G			
	76	ES	5.50^{ab} ± 0.10
		NON	6.11^{e} ± 0.10
	77	ES	5.69^{abc} ± 0.05
		NON	5.85^{bc} ± 0.05
	80	ES	5.55^{ab} ± 0.05
		NON	5.68^{ab} ± 0.05
	84	ES	5.76^{abc} ± 0.06
		NON	5.92^{cde} ± 0.06

Within a column, means lacking a
common letter (a-e) differ ($P < 0.05$)

4.3. Half-blood Population

Analysis of variance tables can be found for all fixed effects of the half-blood population in Appendix B. Within the half-blood population, side accounted for variation in WBS at all six shear locations. For shear1, the data once again found genetic contributions to the variability of these values. Since this population had only one family within each sire, the sire effect is corresponding with the results we saw with the F_2 population of family nested within sire. Variation in shear4 also was accounted for with the interaction of family by side within sire.

The average of the six WBS individual cores is presented as the WBS average. These data found that variation was accounted for by side. Least squares means and standard errors for WBS average are presented in Table 19 by side. These data show this population also responded to application of electrical stimulation with the ES sides more tender ($P < 0.05$) than NON sides.

Differences in least squares means for WBS location by side are presented in Table 19. ES shear cores were more tender ($P < 0.05$) than the cores from NON sides for all locations. This response shows the effectiveness of ES within this population is similar to that seen in the F_2 generation. Table 20 illustrates the differences of least squares means and standard errors for the shear1, as influenced by sire. Sire 432H produced steaks with a lower ($P < 0.05$) shear force value (more tender) for this location than that of sires 297J and 437J. Since we did not see this in the F_2 population, this could be related to the individual dams that are nested within the sires on this portion of the project. This effect is presented in Table 21 by differences in least squares means

and standard errors for shear 4 as families by sides nested within sires. Table 21

illustrates that the ES sides from sire 297J were more tender than the NON sides from

the same sire. Other differences within individual sires and families were not found.

This leads to the assumption that sire 297J fits the criteria presented by Savell et al.

(1979), in that tougher carcasses are more readily affected by the application of electrical

stimulation than those carcasses less needy of improvement in tenderness.

Differences in sarcomere length within this population were not found, which

corresponds to data presented in the F_2 population. This portion of the study found only

side effects for variation in MFI values. Differences of least squares means and standard

errors for MFI by side are presented in Table 19. ES sides had lower ($P < 0.05$) MFI

values than the ES sides (Table 19).

Table 19
Least squares means ± standard error for
WBS location, MFI and WBS average by side for half-blood carcasses

Effect	ES	NON	P-value
shear1[a]	26.48 ± 1.45	33.24 ± 1.44	0.0004
shear2 [a]	27.16 ± 1.40	33.12 ± 1.40	0.0012
shear3 [a]	27.44 ± 1.55	34.28 ± 1.55	0.0008
shear4 [a]	27.14 ± 1.33	31.15 ± 1.33	0.0257
shear5 [a]	27.64 ± 1.41	31.97 ± 1.41	0.0236
shear6 [a]	27.51 ± 1.67	33.24 ± 1.67	0.0088
WBS AVG[b]	27.19 ± 1.11	32.91 ± 1.11	0.0002
MFI	123.42 ± 4.15	143.04 ± 4.15	0.0002

[a]Anatomical location of core extraction from *M. longissimus lumborum*
[b]Average of the six shear core values

Table 20
Least square means and standard errors for shear1
for half-blood carcasses

SIRE	shear1
297J	$33.27^b \pm 2.10$
432H	$25.43^a \pm 1.92$
437J	$32.28^b \pm 2.00$
551G	$28.45^{ab} \pm 3.05$
P-value	0.0392

Within a column, means lacking a
common letter (a-b) differ ($P < 0.05$)

Table 21
Least squares means ± standard error for
WBS shear4 by FAMILY*SIDE(SIRE) for half-blood carcasses

Sire	Family	Side	shear4
297J			
	95	ES	$26.47^{ab} \pm 2.47$
	95	NON	$38.95^c \pm 2.47$
432H			
	96	ES	$29.86^{ab} \pm 2.23$
	96	NON	$27.46^{ab} \pm 2.23$
437J			
	97	ES	$27.46^{ab} \pm 2.37$
	97	NON	$33.69^{bc} \pm 2.37$
551G			
	98	ES	$24.76^{ab} \pm 3.59$
	98	NON	$23.80^a \pm 3.59$

Within a column, means lacking a common letter (a-c) differ ($P < 0.05$)

Carcass temperature variations were accounted for by the differences in sides for 0, 3, 6, 9, 12, and 24 h, and no significance was found for the 36 h and 48 h time periods. Sire accounted for variation at time period 6 h, which is one of the same time periods discussed in the F_2 population. Differences in least squares means for temperature time period 6 h by sire are presented in Table 22, and times 0, 3, 6, 9, 12, and 24 h by side are presented in Table 23. Harvest day was also significant for all temperature time periods. For the 6 h time period, sire 297J had the highest temperature ($P < 0.05$), which mirrors the results found in the F_2 population for this sire. Differences among other sires were not found. The covariates, fat thickness and hot carcass weight, were once again used in this population to aid in the explanation of differences found. Fat thickness was found to be significant for time periods 0 to 36 h. Fixed effects were unchanged except for the time period at 6 h where sire became not significant with the covariate in the model. This further illustrates that differences in temperature at this point were not biologically affected. Hot carcass weight also was added to the model and was found to be significant for 0 to 36 h. This covariate had no effect on the fixed effects significance.

Table 22

Least square means ± standard errors for sire effects for 6 h temperature for half-blood carcasses

SIRE	temp 6h
297J	$19.08^b \pm 0.45$
432H	$17.61^a \pm 0.41$
437J	$17.98^a \pm 0.43$
551G	$16.63^a \pm 0.65$
P-value	0.0196

Within a column, means lacking a common letter (a-b) differ ($P < 0.05$)

Table 23

Least square means ± standard errors for carcass temperature at 0, 3, 6, 9, and 12 h by side for half-blood carcasses

Time	ES	NON	P-value
0h	38.53 ± 0.16	37.84 ± 0.16	0.0011
3h	26.21 ± 0.38	24.83 ± 0.38	0.0058
6h	18.40 ± 0.31	17.24 ± 0.31	0.0038
9h	13.79 ± 0.28	12.52 ± 0.28	0.0006
12h	11.66 ± 0.32	10.39 ± 0.32	0.0024
24h	5.71 ± 0.16	5.20 ± 0.16	0.0133

Results of pH data were found to be similar for the half-blood population to that of the F_2 population. Side accounted for differences in pH for 0, 3, 6, 9, and 12h, while harvest day accounted for variation in times other than 36 h, which at this time period differences were not found in this model. Table 24 illustrates similar data as the F_2 population in that ES sides had a lower ($P < 0.05$) pH than NON sides. These data also illustrate the rise in pH for the ES sides, whereas the NON sides showed a more steady decline across time intervals. The covariate fat thickness, once added to the model for pH data, was found to be significant for 0, 36, and 48 h pH. The significance of this covariate had no effect on the other fixed variables. Hot carcass mass, as a covariate,

was found to be significant at 0 and 48 h. At 48 h, covariate hot carcass mass ($P =$

0.0024), sire effects became significant in the model. This places more biological

relationship to the metabolic activities that effect pH. However, at 12 h, where the

covariate was not significant ($P = 0.1035$), sire effects become significant.

Table 24
Least square means ± standard errors for carcass pH at 0, 3, 6, 9, and 12 h by side for half-blood carcasses

Time	ES	NON	P-value
0h	5.86 ± 0.04	6.25 ± 0.04	<0.0001
3h	5.43 ± 0.04	5.83 ± 0.04	<0.0001
6h	5.51 ± 0.03	5.83 ± 0.03	<0.0001
9h	5.51 ± 0.03	5.70 ± 0.03	<0.0001
12h	5.56 ± 0.03	5.66 ± 0.03	0.0070

CHAPTER V

SUMMARY

In the F_2 population, biological response to ES was identified for myofibrillar fragmentation index, and 6 h post-mortem pH. In the half-blood population, biological response to ES was found for WBS core location. Further analysis of the carcass temperature and pH data using the covariates, carcass weight and fat thickness, showed the response effects found were solely due to genetic differences.

In the search of genetic responsiveness, other carcass traits were identified in each population as being genetically influenced, or influenced by electrical stimulation. The F_2 population data found genetic contributions, of sire and families nested within sires, for the average Warner-Bratzler shear force (WBS), location of shear core extraction, post-mortem carcass temperatures, and carcass pH. ES sides had lower WBS values, higher carcass temperatures, and lower carcass pH. Genetic contributions in the half-blood population were identified as sires and families nested within sire affects on WBS core location and carcass temperature. The ES sides had lower WBS values, higher carcass temperatures, and lower carcass pH in the half-blood population. The results of this study are the first to identify genetic factors in their responsiveness of post-mortem electrical stimulation.

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APPENDIX A

Analysis of variance for WBS shear1 fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	2.52	0.0084
SIRE	2.21	0.0869
Side	65.14	<0.0001
SLDATE[a]	2.46	0.0004

[a]Harvest day

Analysis of variance for WBS shear2 fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	1.35	0.2116
SIRE	1.29	0.2769
Side	71.24	<0.0001
SLDATE[a]	1.51	0.0723

[a]Harvest day

Analysis of variance for WBS shear3 fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	1.69	0.0902
SIRE	1.08	0.3593
Side	67.06	<0.0001
SLDATE[a]	1.13	0.3082

[a]Harvest day

Analysis of variance for WBS shear4 fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	1.77	0.0737
SIRE	1.01	0.3875
Side	54.40	<0.0001
SLDATE[a]	2.25	0.0013

[a]Harvest day

Analysis of variance for WBS shear5 fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	1.27	0.2515
SIRE	1.62	0.1840
Side	72.18	<0.0001
SLDATE[a]	3.04	<0.0001

[a]Harvest day

Analysis of variance for WBS shear6 fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	1.83	0.0619
SIRE	0.70	0.5555
Side	71.60	<0.0001
SLDATE[a]	2.18	0.0021

[a]Harvest day

Analysis of variance for mean WBS force fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	2.28	0.0137
SIRE	1.22	0.3027
Side	126.73	<0.0001
SLDATE[a]	2.86	<0.0001

[a]Harvest day

Analysis of variance for sarcomere length fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	0.76	0.6495
SIRE	1.15	0.3298
Side	0.41	0.5201
SLDATE[a]	2.67	<0.0001

[a]Harvest day

Analysis of variance for MFI fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	2.47	0.0248
SIRE	5.84	0.0007
Side	5.72	0.0176
FAMILY*Side(SIRE)	2.00	0.0406
SLDATE[a]	5.24	<0.0001

[a]Harvest day

Analysis of variance for carcass temperature 0 h fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	1.01	0.4326
SIRE	0.69	0.5585
Side	12.30	0.0005
SLDATE[a]	143.52	<0.0001

[a]Harvest day

Analysis of variance for carcass temperature 3 h fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	1.68	0.0929
SIRE	1.90	0.1297
Side	1.34	0.2484
SLDATE[a]	24.27	<0.0001

[a]Harvest day

Analysis of variance for carcass temperature 6 h fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	1.77	0.0729
SIRE	6.16	0.0004
Side	6.74	0.0099
SLDATE[a]	10.66	<0.0001

[a]Harvest day

Analysis of variance for carcass temperature 9 h fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	2.76	0.0040
SIRE	5.51	0.0011
Side	0.46	0.4968
SLDATE[a]	5.31	<0.0001

[a]Harvest day

Analysis of variance for carcass temperature 12 h fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	2.56	0.0074
SIRE	6.19	0.0004
Side	0.96	0.3290
SLDATE[a]	5.90	<0.0001

[a]Harvest day

Analysis of variance for carcass temperature 24 h fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	2.64	0.0058
SIRE	5.44	0.0012
Side	0.27	0.6067
SLDATE[a]	8.43	<0.0001

[a]Harvest day

Analysis of variance for carcass temperature 36 h fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	1.14	0.3324
SIRE	6.03	0.0005
Side	0.03	0.8561
SLDATE[a]	23.39	<0.0001

[a]Harvest day

Analysis of variance for carcass temperature 48h fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	2.08	0.0309
SIRE	0.42	0.7380
Side	0.18	0.6676
SLDATE[a]	23.34	<0.0001

[a]Harvest day

Analysis of variance for carcass pH 0h fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	0.28	0.9791
SIRE	0.26	0.7605
Side	128.48	<0.0001
SLDATE[a]	7.72	<0.0001

[a]Harvest day

Analysis of variance for carcass pH 3h fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	0.81	0.6060
SIRE	0.60	0.6162
Side	115.21	<0.0001
FAMILY*Side(SIRE)	1.60	0.0896
SLDATE[a]	10.95	<0.0001

[a]Harvest day

Analysis of variance for carcass pH 6h fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	3.16	0.0011
SIRE	2.07	0.1042
Side	112.40	<0.0001
FAMILY*Side(SIRE)	2.27	0.0091
SLDATE[a]	13.20	<0.0001

[a]Harvest day

Analysis of variance for carcass pH 9h fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	1.73	0.0810
SIRE	2.15	0.0940
Side	35.81	<0.0001
SLDATE[a]	6.00	<0.0001

[a]Harvest day

Analysis of variance for carcass pH 12h fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	1.23	0.2755
SIRE	0.22	0.8838
Side	51.43	<0.0001
SLDATE[a]	13.34	<0.0001

[a]Harvest day

Analysis of variance for carcass pH 24h fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	0.95	0.4816
SIRE	0.04	0.9877
Side	8.22	0.0040
SLDATE[a]	8.17	<0.0001

[a]Harvest day

Analysis of variance for carcass pH 36h fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	1.32	0.2256
SIRE	0.46	0.7083
Side	0.06	0.8123
SLDATE[a]	12.64	<0.0001

[a]Harvest day

Analysis of variance for carcass pH 48h fixed effects for F_2 carcasses

Effect	F Value	P-value
FAMILY(SIRE)	3.17	0.0011
SIRE	0.45	0.7193
Side	0.06	0.8112
SLDATE[a]	18.12	<0.0001

[a]Harvest day

APPENDIX B

Analysis of variance for WBS shear1 fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	2.95	0.0365
Side	13.51	0.0004
SLDATE[a]	1.76	0.0663

[a]Harvest day

Analysis of variance for WBS shear2 fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	1.43	0.2386
Side	11.13	0.0012
SLDATE[a]	0.90	0.5544

[a]Harvest day

Analysis of variance for WBS shear3 fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	0.39	0.7627
Side	12.03	0.0008
SLDATE[a]	0.86	0.5847

[a]Harvest day

Analysis of variance for WBS shear4 fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	2.05	0.1115
Side	5.14	0.0257
FAMILY*SIDE(SIRE)	4.26	0.0072
SLDATE[a]	1.97	0.0353

[a]Harvest day

Analysis of variance for WBS shear5 fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	2.05	0.1116
Side	5.29	0.0236
FAMILY*SIDE(SIRE)	2.54	0.0610
SLDATE[a]	1.10	0.3727

[a]Harvest day

Analysis of variance for WBS shear6 fixed effects for half-blood carcasses

Effect	F Value	*P*-value
SIRE	1.59	0.1966
Side	7.16	0.0088
SLDATE[a]	0.82	0.6328

[a]Harvest day

Analysis of variance for WBS average fixed effects for half-blood carcasses

Effect	F Value	*P*-value
SIRE	2.32	0.0797
Side	15.48	0.0002
FAMILY*SIDE(SIRE)	2.31	0.0816
SLDATE[a]	1.24	0.2701

[a]Harvest day

Analysis of variance for sarcomere length fixed effects for half-blood carcasses

Effect	F Value	*P*-value
SIRE	0.48	0.6954
Side	0.22	0.6426
FAMILY*SIDE(SIRE)	2.66	0.0529
SLDATE[a]	0.71	0.7336

[a]Harvest day

Analysis of variance for MFI fixed effects for half-blood carcasses

Effect	F Value	*P*-value
SIRE	2.44	0.0700
Side	15.51	0.0002
SLDATE[a]	3.23	0.0021

[a]Harvest day

Analysis of variance for carcass temperature 0 h fixed effects for half-blood carcasses

Effect	F Value	*P*-value
SIRE	1.08	0.3661
Side	11.33	0.0011
SLDATE[a]	3.27	0.0005

[a]Harvest day

Analysis of variance for carcass temperature 3 h fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	0.61	0.6092
Side	7.97	0.0058
SLDATE[a]	4.90	<0.0001

[a]Harvest day

Analysis of variance for carcass temperature 6 h fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	3.52	0.0180
Side	8.77	0.0038
SLDATE[a]	4.18	<0.0001

[a]Harvest day

Analysis of variance for carcass temperature 9 h fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	0.14	0.9385
Side	12.50	0.0006
SLDATE[a]	5.73	<0.0001

[a]Harvest day

Analysis of variance for carcass temperature 12 h fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	0.66	0.5795
Side	9.70	0.0024
SLDATE[a]	8.83	<0.0001

[a]Harvest day

Analysis of variance for carcass temperature 24 h fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	0.43	0.7323
Side	6.35	0.0133
SLDATE[a]	2.94	0.0016

[a]Harvest day

Analysis of variance for carcass temperature 36 h fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	0.14	0.9368
Side	1.74	0.1977
SLDATE[a]	11.66	<0.0001

[a]Harvest day

Analysis of variance for carcass temperature 48 h fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	0.15	0.9285
Side	0.02	0.8924
SLDATE[a]	31.74	<0.0001

[a]Harvest day

Analysis of variance for carcass pH 0 h fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	0.64	0.5937
Side	69.41	<0.0001
SLDATE[a]	4.66	<0.0001

[a]Harvest day

Analysis of variance for carcass pH 3 h fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	1.38	0.2536
Side	58.55	<0.0001
FAMILY*SIDE(SIRE)	1.75	0.1629
SLDATE[a]	4.03	<0.0001

[a]Harvest day

Analysis of variance for carcass pH 6 h fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	0.65	0.5821
Side	63.57	<0.0001
FAMILY*SIDE(SIRE)	2.43	0.0700
SLDATE[a]	10.59	<0.0001

[a]Harvest day

Analysis of variance for carcass pH 9 h fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	1.83	0.1475
Side	32.91	<0.0001
SLDATE[a]	5.99	<0.0001

[a]Harvest day

Analysis of variance for carcass pH 12 h fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	2.37	0.0755
Side	7.60	0.0070
FAMILY*SIDE(SIRE)	1.80	0.1532
SLDATE[a]	12.76	<0.0001

[a]Harvest day

Analysis of variance for carcass pH 24 h fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	1.95	0.1318
Side	0.83	0.3658
SLDATE[a]	4.90	<0.0001

[a]Harvest day

Analysis of variance for varcass pH 36 h fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	0.87	0.4592
Side	0.94	0.3348
SLDATE[a]	0.43	0.9298

[a]Harvest day

Analysis of variance for carcass pH 48 h fixed effects for half-blood carcasses

Effect	F Value	P-value
SIRE	1.86	0.1398
Side	0.36	0.5512
SLDATE[a]	8.46	<0.0001

[a]Harvest day

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