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Thermophysical Properties of Beef Steaks Varying in USDA Quality Grade and Internal Temperature

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Abstract: The objectives of this study were to determine the influence of quality grade and internal temperature on the thermophysical properties of beef strip steaks. Beef strip loins ($n = 24$) were collected from USDA Prime (PR), Low Choice (LC), and Standard (ST) carcasses. Strip loins were fabricated into 2.54 cm steaks at 21 d postmortem and randomly assigned to an internal temperature (4°C, 25°C, 55°C, 60°C, 71°C, 77°C). Steaks were subjected to various thermal and physical property measurements. No quality grade × internal temperature interaction was observed for diffusivity and conductivity ($P > 0.05$). Steaks tempered to 25°C had the greatest conductivity compared with all other internal temperature treatments ($P = 0.021$). A quality grade × internal temperature interaction was observed for center myosin and sarcoplasmic protein enthalpy values ($P < 0.001$). Raw (4°C and 25°C) ST steaks had lower enthalpy values compared with raw PR and LC steaks ($P < 0.05$). Raw steaks had greater surface myosin and both center and surface actin enthalpy values ($P < 0.05$). A quality grade × internal temperature was observed for surface and center viscoelasticity ($P < 0.05$). Raw steaks possessed less elastic behavior compared with cooked steaks, regardless of quality grade ($P < 0.05$). Quality grade and internal temperature impacted expressible moisture and water holding capacity ($P \leq 0.001$). ST steaks possessed increased expressible moisture and water holding capacity compared with LC and PR steaks ($P < 0.05$). A quality grade × internal temperature was observed for Warner-Bratzler shear force and springiness ($P \leq 0.008$). Internal temperature impacted all texture profile analysis attributes ($P < 0.05$). PR steaks were more cohesive than ST steaks ($P = 0.011$). These data show that final internal temperature and USDA quality grade impact thermophysical properties of beef steaks.

Key words: beef, thermophysical properties, texture, quality grade, internal temperature, water-holding capacity
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Introduction

Tenderness, juiciness, and flavor are the 3 primary attributes that comprise beef palatability. Each of these attributes make substantial contributions to overall consumer liking (O'Quinn et al., 2018). USDA quality grades have been used to predict eating experience. The influence of USDA quality grade on subjective and objective measures of palatability are well recorded in the literature (Savell et al., 1987; Lorenzen et al., 1999, 2003; O'Quinn et al., 2012; Lucherk et al., 2016). Steaks with increased intramuscular fat content are more flavorful, more tender, and juicier. In addition, cooking method, rate, and final internal temperature can have considerable influence on beef palatability (Lorenzen et al., 1999; Yancey et al., 2011; Lucherk et al., 2016).

During the cooking process, myofibrillar proteins denature, resulting in textural changes. Muscle fiber shrinkage has been implicated in the increase in shear force values (Christensen et al., 2000; Tornberg, 2005). Beef is a multicomponent material that is directionally dependent, meaning that heat travels through the matrix in one direction. The composition of beef can impact heat transfer, subsequently affecting palatability attributes. It is crucial to understand how the thermodynamics of beef can affect palatability. Gardner et al. (2020) reported that variations in beef fat composition, thickness, and cooking method impacted the microstructure of beef and overall textural measurements.

To our knowledge, no published literature has explored how degree of doneness and USDA quality grade impact the thermophysical properties of beef. Therefore, the objective of this study was to determine the thermodynamic and physical properties of beef strip loin steaks varying in USDA quality grade and final internal temperature.

Materials and Methods

Product selection and fabrication

Paired strip loins (Institutional Meat Purchase Specifications 180) were collected from “A” maturity, USDA Prime (PR), Low Choice (LC), and Standard (ST) beef carcasses ($n = 24$; 8/grade). Carcasses were selected 24 h postmortem. Visual marbling score was evaluated by trained personnel using official USDA marbling photographs (National Cattlemen’s Beef Association, Centennial, CO). Marbling scores (PR [Slightly Abundant$^{\geq 00}$], LC [Small$^{00-100}$], and ST [Traces$^{\leq 100}$]), lean and skeletal maturity (A$^{00-100}$), 12th rib fat thickness (centimeters), ribeye area (square centimeters), hot carcass weight (kilograms), and percentage of kidney, pelvic, and heart fat were collected by trained personnel to determine USDA quality and yield grade. Strip loins were collected off the fabrication line, vacuum packaged, and transported via refrigerated truck (4°C) to Utah State University (Logan, UT). Loins were aged 21 d postmortem at 4°C. After aging, strip loins were fabricated into 2.54 cm steaks using a commercial meat slicer (Globe Food Equipment Co., Model 3600N, Dayton, OH). Steaks possessing *M. gluteus medius* were excluded from the study. Steaks were randomly assigned to an internal temperature treatment (4°C, 24°C, 55°C, 60°C, 71°C, or 77°C), individually vacuum packaged, and frozen at −20°C until subsequent analyses.

Cooking procedure

Steaks were tempered at 4°C for approximately 15 h. External fat was removed from the *longissimus*. Raw weight, internal temperature, and steak thickness were recorded. Steaks assigned to 4°C treatments were held at 4°C temperature, and all analyses were conducted in a refrigerated environment. Steaks assigned to 25°C treatments were tempered inside an incubator (140 Series, Model 12-140E, Quincy Lab, Inc., Chicago, IL) before analyses. Internal steak temperature was monitored using a 5TC-series thermocouple wire attached to a benchtop thermometer (Omega Engineering Inc., Stamford, CT).

Steaks assigned to an internal degree of doneness of 55°C, 60°C, 71°C, or 77°C were cooked on a clamshell grill (Griddler Deluxe, Model GR-150, Cuisinart, East Windsor, NJ). Internal temperature was monitored as previously stated. Steaks were removed after reaching assigned internal degree of doneness. Cooked weights were recorded, and cooking loss was calculated as:

$$Cook\ loss, \% = \frac{raw\ weight - cooked\ weight}{raw\ weight} \times 100.$$

Following cooking, steaks were wrapped with food-grade plastic wrap to prevent evaporative losses and allowed to cool to 25°C before subsequent analyses.

Thermal diffusivity and conductivity

Thermal diffusivity and conductivity was measured using modified methods from Gardner et al. (2020). This method follows similar theory to that reported in Huang and Liu (2009). Measurements were collected using a TPS-500 Hot Disk thermal (Hot Disk AB, Gothenburg, Sweden) and Kalpan 10-mm sensor (Omega Engineering, Stamford, CT). An incision was made in the geometric center of the steak to expose the interior of the steak. The sensor was placed in the incision for 40 s at 0.168 W for 5 repetitions with a 10-min delay between each repetition.

Protein denaturation

A differential scanning calorimeter (DSC-TA Instruments, Model Q20, Albuquerque, NM) was used to measure enthalpy of myofibrillar protein denaturation. A slice was removed from raw and cooked samples. Each slice was then divided into surface and center layers of the steak. The amount of 6–8 mg was placed into individual high-volume hermetic aluminum pans and heated to 100°C at a rate of 5°C per minute. Max peaks and areas from the thermograms were used to calculate enthalpy values. Thermogram peaks were used to identify protein groups (myosin, actin, and sarcoplasmic proteins) based on reported denaturation temperatures in the literature (Findlay et al., 1986; Gredell et al., 2018). For statistical analysis and reporting, myosin and sarcoplasmic protein enthalpy values were combined.

Viscoelasticity

Viscoelastic properties were measured using a magnetic-bearing AR-G2 Rheometer (TA Instruments, Albuquerque, NM) fitted with an 8-mm parallel plate geometry and a temperature-controlled Peltier plate. The temperature of the plate was set at 4°C for cold steaks or 25°C for room temperature steaks. An 8-mm corer was used to collect 4 cores close to the geometric center of the steak. Cores were divided into surface and center layers. Elastic modulus (G’) was obtained by a strain sweep test used under oscillatory mode with a constant frequency of 6.26 rad/s and strain values set from 0.0008 to 10%. G’ modulus is a measure of elastic behavior.

Moisture properties

Expressible moisture percent and water holding capacity were measured using the methods of Pietrasik and Janz (2009). Four 5-g samples were cut from each steak and total initial weight (IW) was recorded. Sub-samples were placed in a 50 mL centrifuge tube pre-weighed with 25 g of 4 mm glass beads (KIMAX Solid Borosilicate Glass Beads, Kimble Chase, Radnor, PA) inside. Samples were centrifuged for 10 min at $900 \times g$. Following centrifugation, samples were reweighed, and final weight (FW) was recorded. Expressible moisture was calculated as $\frac{IW-FW}{IW} \times 100$. Water holding capacity was calculated as $\frac{FW}{IW} \times 100$.

Texture profile analysis

Texture profile analysis (TPA) was conducted using the methods of Caine et al. (2003). A TSM-Pro texture analyzer (Food Technology Corporation, Sterling, VA) fitted with a 76.2 mm diameter plate and a 500 N load cell. Three 25.4-mm cubes were cut from the medial portion of each steak. Cubes were compressed twice at a crosshead speed of 200 mm/min.

Warner-Bratzler shear force

Warner-Bratzler shear force was conducted according to the American Meat Science Association Sensory Guidelines (AMSA, 2015). Four to seven 1.27-cm cores were removed parallel to the muscle fibers. Core number was dependent on steak surface area. Cores were sheared perpendicular to the muscle fibers using a TSM-Pro texture analyzer (Food Technology Corporation, Sterling, VA) equipped with a 500 N load cell and a V-shaped blade. Crosshead speed was set to 200 mm/min. Measurements were recorded as peak force (kilograms) and averaged across cores.

Statistical analysis

Data were analyzed as a split-plot design in which quality grade served as the whole plot and degree of doneness was the sub-plot. Individual steaks served as the experimental unit. Statistical analyses were conducted using the PROC GLIMMIX procedure of SAS version 9.4 (SAS Institute, Cary, NC) in which quality grade, degree of doneness, and their interaction were main effects. Least-squares means were separated using the PDIFF option. A predetermined alpha of <0.05 was used to determine significance.

Results and Discussion

Cook loss

Results of cooking loss are presented in Figure 1. No quality grade × internal temperature interaction was

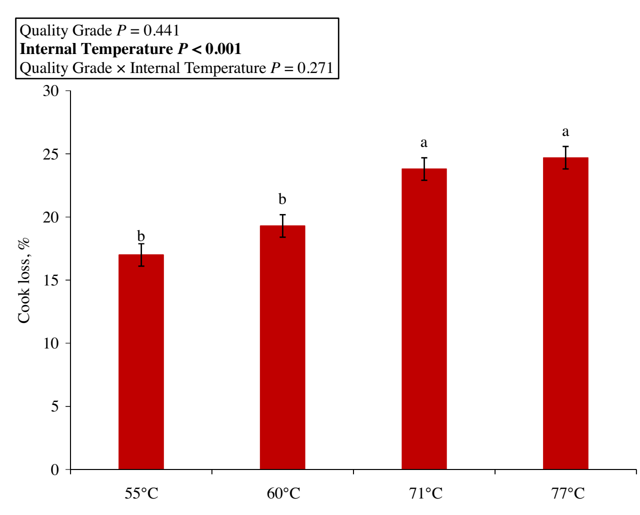

Figure 1. Least-squares means of cooking measurements of beef steaks cooked to 4 degrees of doneness[2].

observed for cook loss ($P = 0.271$). Cook loss was influenced by degree of doneness ($P < 0.001$) but not quality grade ($P = 0.441$). Steaks cooked to an internal temperature of 71°C and 77°C were similar ($P > 0.05$) and produced the greatest cook loss compared with steaks cooked to 55°C and 60°C ($P < 0.05$). These results are expected, because it is known that steaks cooked to higher degrees of doneness are lower yielding (Smith et al., 2011; Yancey et al., 2011). During the cooking process, proteins denature and lose the ability to retain water, resulting in evaporation of moisture (Honikel, 1998). Moisture loss is accepted as the driver of cook loss.

Thermal diffusivity and conductivity

Diffusivity was not impacted by quality grade, internal temperature, or their interaction ($P \geq 0.118$; Table 1). Conductivity was influenced by internal temperature ($P = 0.021$) but not quality grade ($P = 0.886$). Steaks tempered to 25°C possessed the highest conductivity compared with all other treatments ($P = 0.021$).

Table 1. Least-squares means of thermal measurements of beef steaks from 3 USDA quality grades[1] and 6 internal temperatures[2]

Treatment	Diffusivity (W/mK)	Conductivity (mm^2/s)
Quality Grade		
Prime	0.56	0.25
Low Choice	0.56	0.24
Standard	0.54	0.25
SEM[3]	0.027	0.012
P value[4]	0.887	0.886
Internal Temperature		
4°C	0.65	0.22^b
25°C	0.55	0.30^a
55°C	0.51	0.25^b
60°C	0.50	0.25^b
71°C	0.57	0.23^b
77°C	0.55	0.24^b
SEM	0.037	0.018
P value	0.118	0.021
Quality Grade × Temperature		
P value	0.301	0.602

[1]USDA Prime, Low Choice, and Standard.

[2]4°C, 25°C, 55°C, 60°C, 71°C, and 77°C.

[3]Largest standard error of the mean (SEM) within a main effect.

[4]Observed significance level.

[a,b]Means in the same column and main effect without a common superscript differ ($P < 0.05$).

Thermal conductivity is the rate at which heat moves through a substance by conduction (Aberle et al., 2001). Thermal diffusivity is the ratio of a product's thermal conductivity to the heat capacity (Huang and Liu, 2009). Adipose tissue has lower specific heat and thermal conductivity compared with water (Baghe-Khandan et al., 1982). Meat with increased fat content has decreased specific heat, thermal conductivity, and subsequent thermal diffusivity (Aberle et al., 2001). Therefore, we hypothesized that intramuscular fat would have an insulation effect, influencing heat transfer in meat. However, the present study's results are congruent with Gardner et al. (2020) wherein steaks from USDA Select and upper 2/3rds Choice did not differ in diffusivity or conductivity. Despite a larger spread of USDA quality grades compared with those reported in Gardner et al. (2020), no differences in thermal conductivity and diffusivity were observed. Tornberg (2005) reported that beef is more similar to water than fat in its thermodynamic properties. However, results from the present study and previous literature suggests that fat content has no influence on heat transfer in beef steaks. Additionally, cooking steaks to various degrees of doneness did not influence thermal properties. This suggests that beef thermal conductivity and diffusivity remain constant between refrigerated and cooked steaks.

Protein denaturation

A quality grade × internal temperature interaction was observed for center layer myosin and sarcoplasmic proteins ($P = 0.001$; Figure 2). A dramatic decrease in

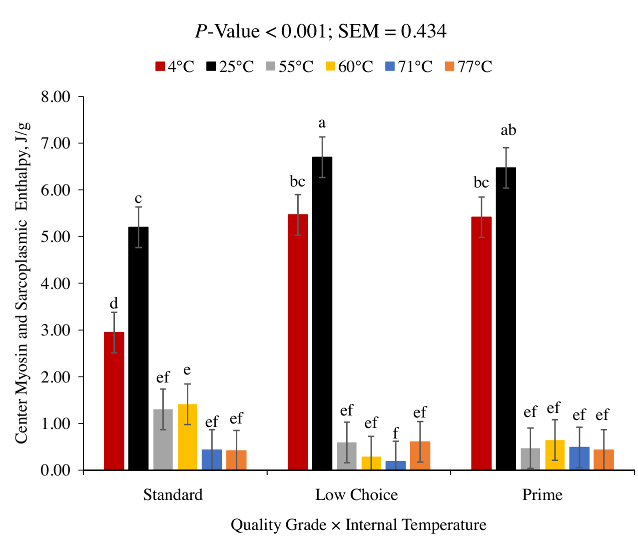

Figure 2. Interaction of center myosin and sarcoplasmic proteins enthalpy (J/g) of beef steaks from 3 USDA quality grades and 6 internal temperatures.

enthalpy was observed between raw and cooked steaks, regardless of quality grade ($P < 0.05$). ST raw steaks possessed decreased enthalpy values ($P < 0.05$) compared with LC and PR raw steaks, which were similar ($P > 0.05$).

Quality grade had no effect on surface layer myosin and sarcoplasmic proteins, surface layer actin, or center layer actin enthalpy values ($P \geq 0.091$; Table 2). Internal temperature influenced surface myosin and sarcoplasmic proteins, surface actin, and center actin ($P < 0.001$). Cooked steaks had the lowest surface layer myosin and sarcoplasmic protein enthalpy compared with raw steaks ($P < 0.05$). Moreover, tempered steaks had greater enthalpy values compared with refrigerated steaks ($P < 0.05$). Similar to surface layer myosin and sarcoplasmic protein, surface actin enthalpy was greatest in raw steaks compared with cooked steaks ($P < 0.05$). Center layer actin enthalpy was greatest in steaks cooked to 55°C and 60°C compared with all other treatments ($P < 0.05$).

Protein denaturation alters the structural integrity of meat, potentially impacting palatability. In particular, myosin shrinks during denaturation, resulting in increased toughness during cooking (Mccormick, 1999). Davey and Gilbert (1974) reported 2 toughening phases during cooking as temperature increased. The first toughening event was attributed to loss of myosin solubility, and the second phase was attributed to collagen shrinking (Davey and Gilbert, 1974). The enthalpy value reported in the present study is the amount of energy required to denature remaining myosin and sarcoplasmic proteins and actin and is indicative of the relative amount of intact protein in their native or varying state of denaturation or aggregation (Gardner et al., 2020). This would explain why cooked steaks required substantially less energy to denature any remaining proteins because the cooking process has denatured myofibrillar proteins. When evaluating myosin and sarcoplasmic protein enthalpy values, no differences were observed in cooked steaks. Myosin has been reported to denature at 55.5°C; therefore, additional denaturation would not be expected (Findlay et al., 1986; Gredell et al., 2018). Actin denatures at approximately 80.9°C (Findlay et al., 1986; Gredell et al., 2018). Actin present in the surface layer of the steak would denature at the same rate regardless of final internal temperature as the surface layers were in direct contact with the clamshell grill. Because steaks were cooked to higher internal temperatures, less energy was required to denature remaining actin. Gredell et al. (2018) reported that change in enthalpy required to denature myofibrillar proteins was related to cooking rate and time exposed to heat.

Table 2. Least-squares means of enthalpy values (J/g) of beef steaks from 3 USDA quality grades[1] and 6 internal temperatures[2]

Treatment	Surface Myosin and Sarcoplasmic Proteins	Surface Actin	Center Actin
Quality Grade			
Prime	2.14	0.72	2.57
Low Choice	2.07	0.80	2.04
Standard	1.67	0.73	2.23
SEM[3]	0.162	0.041	0.279
P value[4]	0.091	0.296	0.403
Internal Temperature			
4°C	4.93[b]	2.00[a]	2.06[b]
25°C	6.01[a]	2.02[a]	2.06[b]
55°C	0.16[c]	0.16[b]	3.20[a]
60°C	0.24[c]	0.15[b]	4.03[a]
71°C	0.15[c]	0.09[b]	1.23[b]
77°C	0.27[c]	0.08[b]	1.07[b]
SEM	0.229	0.058	0.394
P value	<0.001	<0.001	<0.001
Quality Grade × Internal Temperature			
P value	0.069	0.729	0.597

[1]USDA Prime, Low Choice, and Standard.

[2]4°C, 25°C, 55°C, 60°C, 71°C, and 77°C.

[3]Largest standard error of the mean (SEM) within a main effect.

[4]Observed significance level.

[a–c]Means in the same column and main effect without a common superscript differ ($P < 0.05$).

Viscoelasticity

A quality grade × internal temperature interaction was observed for the elastic behavior (G' modulus) of both surface and center steak layers ($P \leq 0.023$; Figures 3 and 4). LC steaks cooked to 77°C were the most elastic at the surface steak layer compared with all other treatments ($P < 0.05$). Moreover, refrigerated ST and LC steaks were less elastic than those cooked to 55°C and 77°C ($P < 0.05$). Similar to the elastic behavior of the surface steak layer, LC steaks cooked to 77°C were the most elastic at the center steak layer ($P < 0.05$). Furthermore, refrigerated ST and LC steaks were less elastic than those cooked to 55°C and 77°C ($P < 0.05$).

Literature reporting the contribution of rheological properties to meat texture in whole muscle beef is very limited. Elasticity in food products is the ability for a material to return to its resting shape after being altered by an applied stressor (Vilgis, 2015). Palka

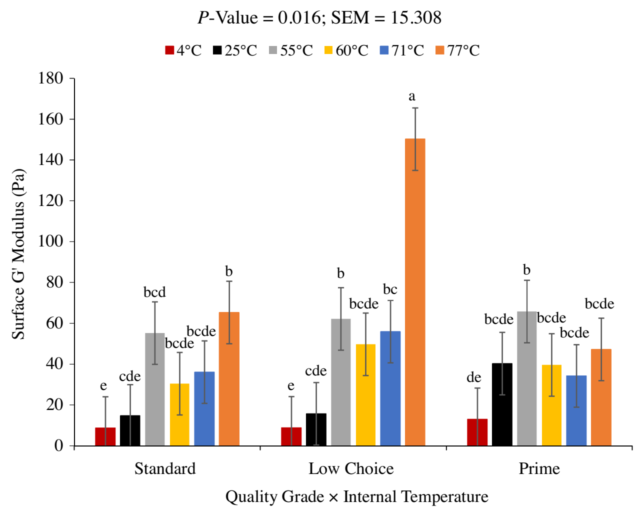

Figure 3. Interaction of surface G' modulus (Pa) of beef steaks from 3 USDA quality grades and 6 internal temperatures.

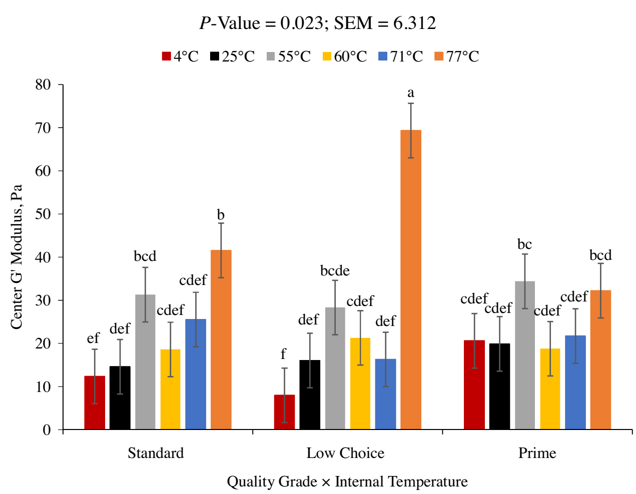

Figure 4. Interaction of center G' modulus (Pa) of beef steaks from 3 USDA quality grades and 6 final temperatures.

and Daun (1999) reported a linear increase in elasticity in beef *semitendinosus* steaks cooked from 50°C to 80°C. The results of the present study do not follow the linear increase observed in Palka and Daun (1999). Within the LC steaks, the increase in elastic behavior was observed at 77°C. ST and PR steaks did not follow this trend. Discrepancies between the present study and Palka and Daun (1999) could be the use of different muscles (*longissimus* vs. *semitendinosus*, respectively) and the method in which elastic modulus was collected (rheometer vs. texture analyzer, respectively). Brunton et al. (2006) reported that rheological parameters of beef are related to protein denaturation. Gardner et al. (2020) reported a moderate, negative correlation between steak surface G' modulus and WBSF values ($r = -0.41$; $P < 0.05$). Moreover, Mathoniere et al. (2000) reported a strong, negative correlation between G' modulus and overall tenderness determined by a trained panel ($r = -0.71$; $P < 0.05$). Based on these studies, it could be speculated that a greater G' modulus, or elasticity, results in less tender product.

Moisture properties

Results of expressible moisture and water holding capacity are presented in Table 3. No quality grade × internal temperature interactions were observed ($P \geq 0.411$). Quality grade influenced expressible moisture and water holding capacity ($P = 0.001$). PR steaks had the lowest expressible moisture percentage ($P < 0.05$) compared with LC and ST, which were similar ($P > 0.05$). ST steaks had the greatest water holding capacity ($P < 0.05$) compared with LC and PR steaks, which were similar ($P > 0.05$).

Internal temperature influenced expressible moisture and water holding capacity ($P < 0.001$). Steaks cooked to 55°C and 60°C had the greatest expressible moisture percentage, followed by steaks cooked to 71°C and 77°C ($P < 0.05$). Raw steaks had less

Table 3. Least-squares means of moisture properties of beef steaks from 3 quality grades[1] and 6 internal temperatures[2]

Treatment	Expressible Moisture, %	Water Holding Capacity, %
Quality Grade		
Prime	14.9^{b}	83.2^{b}
Low Choice	16.9^{a}	83.1^{b}
Standard	16.8^{a}	85.1^{a}
SEM[3]	0.42	0.43
P value[4]	0.001	0.001
Internal Temperature		
4°C	13.2^{c}	86.8^{b}
25°C	11.5^{d}	88.5^{a}
55°C	19.7^{a}	80.3^{d}
60°C	19.1^{a}	80.9^{d}
71°C	16.7^{b}	83.4^{c}
77°C	17.0^{b}	81.0^{c}
SEM	0.60	0.60
P value	<0.001	<0.001
Quality Grade × Internal Temperature		
P value	0.405	0.411

[1]USDA Prime, Low Choice, and Standard.

[2]4°C, 25°C, 55°C, 60°C, 71°C, and 77°C.

[3]Largest standard error of the mean (SEM) within a main effect.

[4]Observed significance level.

[a–d]Means in the same column and main effect without a common superscript differ ($P < 0.05$).

expressible moisture compared with cooked steaks, with steaks tempered to 25°C having the lowest expressible moisture percentage compared with all other treatments ($P < 0.05$). Conversely, steaks tempered to 25°C possessed the greatest water holding capacity compared with all other treatments ($P < 0.05$). Raw steaks had greater water holding capacity compared with cooked steaks ($P < 0.05$). Among the cooked steaks, steaks cooked to 55°C and 60°C had the lowest water holding capacity compared with steals cooked to 71°C and 77°C ($P < 0.05$).

These data indicate that expressible moisture and water holding capacity were readily influenced by quality grade and internal temperature. Fat and moisture content have an inverse relationship. This may explain the decrease in expressible moisture and water holding capacity in steaks with greater intramuscular fat content. However, Lucherk et al. (2017) reported no differences in expressible moisture or water holding capacity in raw and cooked beef striploin steaks of varying quality grades. Water in meat is found in between the myofibrils, specifically in between the thick and thin filament (Offer et al., 1989). When heat is applied to meat, myofibrillar proteins denature, resulting in moisture loss (Honikel, 1998). More specifically, as proteins denature, they lose their ability to retain water. Furthermore, the aggregation of proteins during cooking has been suggested to contribute to moisture loss (Tornberg, 2005; Gardner et al., 2020).

Texture profile analysis

A quality grade × internal temperature interaction was observed for springiness ($P < 0.001$; Figure 5). Refrigerated LC and PR steaks had the lowest springiness value compared with all other treatments ($P < 0.05$). Quality grade did not influence hardness, resilience, chewiness, or adhesion ($P \geq 0.120$; Table 4). However, cohesiveness was affected by quality grade ($P = 0.011$). PR steaks were more cohesive compared with ST steaks ($P < 0.05$). Internal temperature influenced hardness, cohesiveness, resilience, chewiness, and adhesion ($P < 0.001$; Table 4). Steaks cooked to 71°C were the hardest compared with all other treatments ($P < 0.05$). Steaks cooked to 60°C were harder than steaks cooked to 55°C ($P < 0.05$). Cooked steaks were harder than raw steaks ($P < 0.05$). Refrigerated steaks were more cohesive compared with all other treatments ($P < 0.05$), followed by tempered steaks. Cooked steaks were similar ($P > 0.05$) and less cohesive than raw steaks ($P < 0.05$). Steaks cooked to

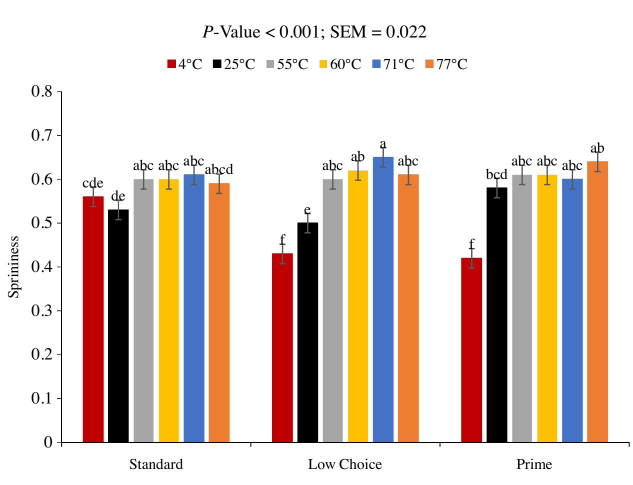

Figure 5. Interaction of springiness of beef steaks from 3 USDA quality grades and 6 final temperatures.

Table 4. Least-squares means of texture profile analysis attributes[1] of beef steaks from 3 USDA quality grades[2] and 6 internal temperatures[3]

Treatment	Hardness (kg)	Cohesiveness	Resilience	Chewiness (kg)	Adhesion
Quality Grade					
Prime	6.14	2.37^{a}	5.38	8.11	0.11
Low Choice	6.39	2.25^{ab}	5.05	8.05	0.13
Standard	6.25	2.18^{b}	4.80	7.59	0.09
SEM[4]	0.343	0.045	0.330	0.424	0.015
P value[5]	0.881	0.011	0.464	0.633	0.120
Internal Temperature					
4°C	2.97^{d}	2.82^{a}	2.54^{d}	3.85^{c}	0.18^{a}
25°C	2.25^{d}	2.46^{b}	1.41^{d}	2.72^{d}	0.15^{ab}
55°C	6.62^{c}	2.13^{c}	5.10^{c}	8.52^{c}	0.05^{c}
60°C	8.10^{b}	2.09^{c}	6.51^{b}	10.33^{b}	0.07^{c}
71°C	9.87^{a}	2.09^{c}	8.72^{a}	12.62^{a}	0.10^{bc}
77°C	7.75^{bc}	2.00^{c}	6.20^{bc}	9.48^{bc}	0.11^{bc}
SEM	0.485	0.063	0.466	0.600	0.210
P value	<0.001	<0.001	<0.001	<0.001	<0.001
Quality Grade × Internal Temperature					
P value	0.259	0.653	0.096	0.120	0.447

[1]Texture profile analysis attributes calculated according to Caine et al. (2003).

[2]USDA Prime, Low Choice, and Standard.

[3]4°C, 25°C, 55°C, 60°C, 71°C, and 77°C.

[4]Largest standard error of the mean (SEM) within a main effect.

[5]Observed significance level.

[a–d]Means in the same column and main effect without a common superscript differ ($P < 0.05$).

71°C were the most resilient compared with all other treatments ($P < 0.05$). Steaks cooked to 60°C were more resilient than steaks cooked to 55°C ($P < 0.05$). Moreover, cooked steaks were more resilient than raw steaks ($P < 0.05$). Steaks cooked to 71°C were the chewiest compared with all other treatments ($P < 0.05$). Steaks cooked to 60°C were chewier than steaks cooked to 55°C and tempered steaks ($P < 0.05$). Refrigerated steaks were the least chewy compared with all other treatments ($P < 0.05$). Refrigerated steaks were more adhesive compared with cooked steaks ($P < 0.05$). Tempered steaks and steaks cooked to 71°C and 77°C were similar in adhesion values ($P > 0.05$). Moreover, cooked steaks had similar adhesion values ($P > 0.05$).

These results indicate that quality grade, i.e., fat content, has minimal influence on beef texture beyond tenderness. Fat content of these quality grades are reported in Gardner (2017). Refrigerated, raw steak fat content was 2.09%, 6.26%, and 10.53% for ST, LC, and PR steaks, respectively (Gardner, 2017). Furthermore, it is clear that internal temperature readily influences beef texture. Similar to the present study, Palka and Daun (1999) reported linear increases in hardness and chewiness in beef *semitendinosus* steaks cooked from 50°C to 80°C. Moreover, sarcomere length decreased as internal temperature increased from 50°C to 80°C (Palka and Daun, 1999). Sarcomere length has been implicated in influencing final product tenderness (Rhee et al., 2004). It is plausible that sarcomere length could result in other textural changes. As previously stated, protein denaturation results in hardening of the myofibrillar proteins, explaining the increase in hardness. Caine et al. (2003) reported moderate, positive correlations between hardness, cohesiveness, chewiness, and WBSF values. de Huidobro et al. (2005) reported that TPA was more useful for measuring beef texture compared with WBSF. Both Caine et al. (2003) and de Huidobro et al. (2005) reported that TPA explained more variation and could better predict sensory texture attributes compared with WBSF.

Warner-Bratzler shear force

An interaction between quality grade and internal temperature was observed for WBSF values ($P = 0.008$; Figure 6). Raw steaks, regardless of quality grade, had lower WBSF values compared with cooked steaks ($P < 0.05$). ST steaks cooked to 77°C had the greatest WBSF value compared with ST steaks cooked to 55°C, 60°C, or 71°C ($P < 0.05$). LC steaks cooked to

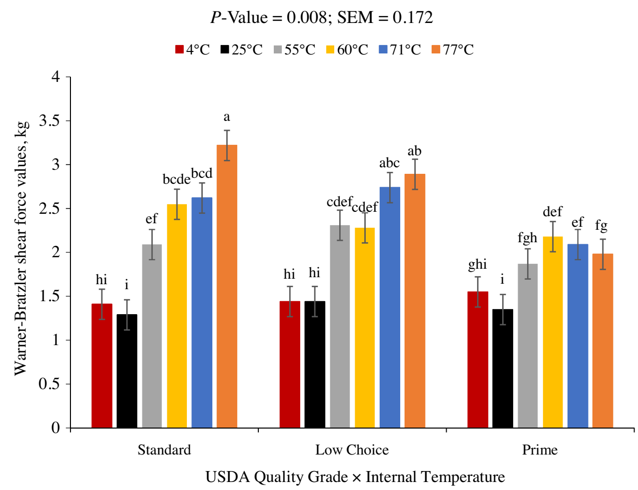

Figure 6. Interaction of Warner-Bratzler shear force values (kilograms) of beef steaks from 3 USDA quality grades and 6 final temperatures.

55°C and 60°C were more tender than LC steaks cooked to 77°C ($P < 0.05$). PR steaks, regardless of degree of doneness, were of similar tenderness ($P > 0.05$).

Previous studies have reported an increase in shear force values in steaks with less marbling and cooked to a higher degree of doneness (Savell et al., 1987; Yancey et al., 2011; Lucherk et al., 2016; Drey et al., 2018). WBSF values followed trends similar to the TPA data, specifically hardness and viscoelastic data. In the present study, the impact of final internal temperature on WBSF values was dependent on quality grade. Our results are congruent with Lucherk et al. (2016) wherein an interaction between quality grade and degree of doneness was reported. When steaks were cooked to 60°C, Prime, Top Choice, Select, and Standard had similar shear force values (Lucherk et al., 2016). PR steaks had similar WBSF values regardless of final internal temperature, thereby reinforcing the "insurance" marbling theory. This is in contrast with Drey et al. (2018), who reported no quality grade × degree of doneness interaction for WBSF or slice shear force values. Ultimately, the authors suggested that the "insurance" theory primarily influenced juiciness rather than tenderness (Drey et al., 2018). Although the insurance theory remains relatively accepted, the mechanism behind it has yet to be elucidated. Other marbling theories have been reported (Smith and Carpenter, 1974). One of these theories includes the "strain" theory. As intramuscular fat is deposited, the walls of both perimysium and endomysium are weakened, resulting in minimized connective tissue influence on tenderness (Nishimura et al., 1999). Nishimura et al. (1999) reported that deposited fat cells altered the organization of intramuscular connective tissue structure, which the authors suggested had a tenderizing effect. Moreover, theses structural changes were consistent with a decrease in mechanical connective tissue strength (Nishimura et al., 1999). The aforementioned study was conducted with Japanese black cattle (pure-bred and crossbred) varying in slaughter age (9 to 32 mo). However, in samples from cattle harvested at younger than 24 mo, crude fat was below 8% and the deposited fat cells did not alter the intramuscular connective tissue structure (Nishimura et al., 1999). Fat content of PR steaks, regardless of internal temperature, was greater than 10.53% fat, whereas LC and ST steaks were less than 6.39% and 3.95%, respectively (Gardner, 2017). This may explain how PR steaks in the present study maintain tenderness when cooked to higher internal temperatures. However, further investigation is required to fully support this hypothesis.

Conclusion

These data indicate that USDA quality grade and final internal temperature can influence the physical properties of beef. Cooking lower quality grade steaks to higher degrees of doneness can be detrimental to palatability, namely tenderness and juiciness. Quality grade had minimal influence on heat travel during cooking, suggesting that intramuscular fat does not influence protein denaturation. Final internal temperature seemed to be responsible for the extent of protein denaturation. Moreover, these data show that the extent of protein denaturation influences final beef texture.

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