Meat and Muscle Biology™

Thermophysical Properties of Beef Steaks of Varying Thicknesses Cooked With Low and High Grill Surface Temperatures

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Abstract: The objective of this study was to determine the thermodynamic and physical properties of beef strip loin steaks of varying thicknesses and USDA quality grades cooked with high and low grill surface temperatures. Thermal characteristics described by changes in the denaturation temperature (between 55°C–60°C) and enthalpies of protein denaturation (70°C–75°C) both differed ($P = 0.031$ and $P = 0.001$, respectively) among thick steaks, with thick steaks cooked on a high grill surface temperature having a lower denaturation temperature and enthalpy compared with thick steaks cooked on a low grill surface temperature. No differences ($P > 0.05$) were observed among thin steaks for denaturation temperature or enthalpy. The elastic behaviors of the surface and center of the steaks were analyzed to determine how the microstructure of the beef responded to applied stress. The elastic behavior of steak centers was influenced in a three-way interaction ($P = 0.029$) between quality grade, steak thickness, and grill surface temperature. The elastic behavior of the surface of steaks was influenced by the interaction of quality grade and steak thickness ($P = 0.031$). These interactions, along with the differences in the thermal characteristic of proteins, suggest that the microstructure of steaks was affected by each cooking treatment group. Hardness, resilience, and chewiness were each influenced by a three-way interaction ($P = 0.023$; 0.014; and 0.030; respectively). Thin steaks possessed greater cohesiveness ($P = 0.038$) and shear force ($P = 0.007$) values. Meanwhile, thin steaks exhibited lower springiness ($P = 0.002$). The measured alterations in thermal and physical properties in the beef steaks suggest that the composition, thickness, and cooking regiments impact the microstructure of beef, and this was ultimately confirmed through textural measurements. The results of this research can be used in the design of cooking processes that match beef characteristics.

Key words: beef, grill temperature, quality grade, steak thickness, texture analysis, thermal properties
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Introduction

Beef palatability can be described using 3 major characteristics: tenderness, juiciness, and flavor (Morgan et al., 1991; Legako et al., 2016). Each trait makes significant contributions to consumer overall liking of beef (O'Quinn et al., 2018). Increasing quality grade and/or marbling levels increases consumer overall liking of beef (O'Quinn et al., 2012; Corbin et al., 2014). Furthermore, beef palatability traits are greatly influenced by cooking (Christensen et al., 2000; Bowers et al., 2012; Lucherk et al., 2016). Tenderness, juiciness, and flavor are all impacted by cooking method, cooking times, and final internal temperature, otherwise known as degree of doneness (Cashman et al., 2015; Vierck et al., 2019). The tenderness of meat is strongly influenced by the denaturation states of myofibrillar proteins and collagen in beef (Christensen et al., 2000). During cooking, proteins undergo heat-induced denaturation that causes shrinkage of muscle fibers within specific temperature ranges. This can correlate to an increase in shear values or reduction in tenderness values as well as affect juice expulsion and fat migration (Christensen et al., 2000; Tornberg, 2005; Brunton et al., 2006). Juiciness is primarily influenced by intramuscular fat content, as well as by the water-holding capacity (expressible moisture) of meat. Expressible moisture is dependent on cooking temperatures and protein states as meat expels moisture during shrinkage of muscle fibers (Bertram et al., 2006; Phelps et al., 2015).

Thermodynamics described by thermal conductivity and diffusivity describe how heat transfers through a material. As heat-induced changes affect all the major palatability characteristics, the need to understand how different cooking methods could alter the way in which heat penetrates beef is a necessity (Ishiwatari et al., 2013). Limited research exists regarding the thermodynamic components of beef. However, when evaluating the effects of steak thickness in a radio frequency oven, Rincon et al. (2015) observed thicker steaks to have an increased heating rate but similar expressible moisture values to thinner steaks. To the best of our knowledge, more specific thermodynamic measurements have not been employed to evaluate thermodynamic properties of beef steaks at this time.

Beef is a multicomponent material that is also anisotropic (directionally dependent), and therefore heat travels through it in a specific manner (Pathare and Roskilly, 2016). Thermal conductivity and diffusivity are unique and inherent properties of a material based on its composition. Water, fat, and protein all conduct and store heat at different rates. Water (0.5426 W/m°C and 1.553×10^{-7} m^2/s, thermal conductivity and diffusivity, respectively) has a relatively high rate of conductivity and diffusivity compared with fat (0.1702 W/m°C, 0.715×10^{-7} m^2/s) and muscle (0.4074 W/m°C, 1.138×10^{-7} m^2/s) (Huang and Liu, 2009). Beef is noticeably more similar to water than it is to fat, which is reasonable because about 75% of beef is water (Tornberg, 2005).

The combination of meat composition and cooking method may provide varied thermodynamic environments, which may in turn alter the texture, flavor, and juiciness of beef (Pathare and Roskilly, 2016). If a particular set of parameters—such as steak thickness or grill surface temperature—can be selected for beef of a specific composition (quality grade), then there exists potential for processing and cookery recommendations that improve palatability. Therefore, the objectives of this research were to determine the impact of varying steak thicknesses and USDA quality grades cooked with high and low grill surface temperatures on the thermodynamic and physical properties of beef strip loin steaks.

Materials and Methods

Product collection

Beef strip loins ($n = 40$; 20/grade) were selected from a commercial processing facility from 2 quality grade treatments: USDA Select (Slight^{00}–Slight^{100}) and USDA Choice (Modest^{00}–Moderate^{100}). Following carcass fabrication at 24 h post mortem, strip loins were transported to the Texas A&M Rosenthal Meat Science and Technology Center (College Station, TX) and stored at 4°C and aged for 14 d post mortem. After the aging period, strip loins were fabricated into thick (38.1 mm) and thin (12.7 mm) steaks, vacuum packaged, and frozen at −20°C. Steak thickness and cooking temperature were randomly assigned within each strip loin. Frozen steaks designated for thermophysical measurements were then shipped overnight to Utah State University (Logan, UT).

Cooking protocols

Prior to cooking, all steaks were thawed for 12 to 18 h at 4°C. Steaks were cooked using a StarMaxx Electric Flat-Top Griddle (536TGF; Star Manufacturing International, St. Louis, MO). Griddle surface temperature was verified immediately prior to cooking using a magnetic mount thermocouple (Magnetic K thermocouple 88402K; Omega Engineering, Stamford, CT). Steaks were cooked until a medium degree of doneness (71°C) was reached internally. Two grill temperatures were targeted: high surface temperature (HST) at 232.5°C and low surface temperature (LST) at 168.5°C. To monitor internal steak temperatures, 2 wire thermocouple probes were anchored on the lateral ends of the steaks and placed approximately 2 to 3 cm from the other thermocouple on either side of the geometric center of the steak to determine an average measurement of internal temperature. The true geometric center was used for thermal diffusivity and conductivity analyses. After placement of the thermocouples, steaks were cooked to 35°C internally, then flipped one time. Following cooking, steaks rested for 3 min and then were sealed in plastic wrap and allowed to cool to room temperature (25°C). Areas designated for various sample analyses are described in Figure 1.

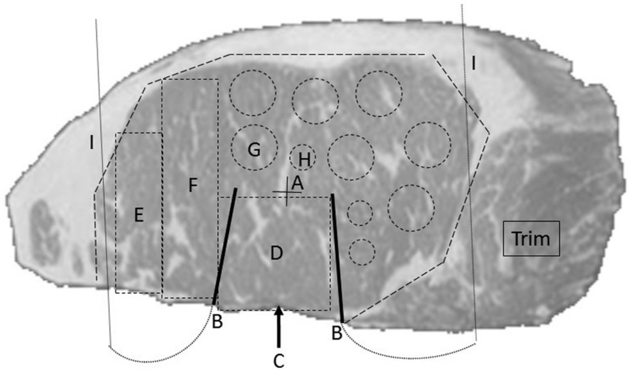

Figure 1. Sample layout diagram. (A) geometric center of steak; (B) thermocouple probe positions; (C) indication of caliper placement for thickness; (D) Hot-Disk sample; (E) expressible moisture sample; (F) compression sample; (G) Warner-Bratzler shear force samples (7 cores); (H) rheometer samples (3 cores); (I) thermocouple anchor positioning.

Rheology measurements

The dynamic rheological behavior described by the elastic and viscous modulus (pascal) of the beef steaks was analyzed using an AR-G2 Rheometer (TA Instruments, Albuquerque, NM) fitted with an 8-mm diameter parallel plate geometry. Three 8-mm-thick cores were taken from portion H (Figure 1) of each steak, and an approximately 2-mm-thick cross section was sliced from the center and surface of the cores to be measured.

A strain sweep test was used under an oscillatory mode with an angular frequency of 6.283 rad/s at 25°C. The test was performed for 3 s and occurred in a multiwave harmonic fashion for a total of 45 measurements. Analysis of the data required selecting a stable elastic modulus (G’) region by removing the onset of stress as well as degradation regions on the representative graph. Subsequently, means were calculated for the elastic and viscous (G”) moduli, where means were accepted if the average of the standard error was within 10% of the average.

Protein denaturation

A differential scanning calorimeter (DSC) (DSC Q20; TA Instruments, Newcastle, DE) was used to measure the enthalpy and temperature of protein denaturation of the myofibrillar proteins. Each steak had a 1- to 2-mm slice taken from an adjacent edge of portion D (Figure 1). Each slice was then divided into surface, mid-center (thick [38.1 mm] steaks only), and center regions. Samples (4–8 mg) were taken from each region and sealed hermetically in DSC high-volume pans. During protein denaturation and enthalpy analysis, samples were heated at a rate of 2°C every 5 min until reaching the final temperature of 100°C. Denaturation temperatures and enthalpy values were calculated using the max peaks and areas of each separate curve present in the thermograms.

Thermal diffusivity and conductivity

A TPS-500 Hot-Disk (Hot Disk AB, Gothenburg, Sweden) was used to simultaneously measure thermal diffusivity and conductivity of each steak sample. This sample was taken from section D from the cooked steaks. A 2.5 × 2.5-cm sample was sliced in half horizontally to reveal the interior surface of the steak. Following exposure of the interior of the steak, a sensor (Kapton-Insulated, 3.189-mm radius; Omega Engineering, Stamford, CT) was placed in the center between the 2 pieces of sample and run for 40 s at 200 mW for 5 repetitions.

Expressible moisture

The protocol of Pietrasik and Janz (2009) was used for expressible moisture analysis of the cooked steaks. In brief, approximately 1.5 to 2.5 g of cooked sample was weighed into 50-mL centrifuge tubes pre-weighed with 20 g of glass beads. Samples were then centrifuged at 900 × *g* for 10 min. A post-centrifuged weight was recorded after solid sample was removed from the tube. Expressible moisture was calculated using the equation derived from Earl et al. (1996): Expressible moisture = [(initial weight − final weight) ÷ initial weight] × 100.

Warner-Bratzler shear force analysis

The American Meat Science Association protocol for Warner-Bratzler shear force (WBSF) was followed, with modifications (AMSA, 2015). Seven 12.7-mm-diameter cores were removed parallel to the orientation of the muscle fibers by hand. A TSM-Pro texture analyzer (Food Technology Corporation, Sterling, VA) fitted with a 500 N load cell was used to measure the kg force necessary to shear perpendicular to the fiber orientation. For each sample, the analyzer used a crosshead speed of 200 mm/min to continually rotate through 7 cores per steak.

Texture profile analysis

A modification of the protocol from Caine et al. (2003) was used for texture profile analysis (TPA). A TSM-Pro (Food Technology Corporation, Sterling, VA) was outfitted with a 25.4-mm-diameter parallel plate fixture and 500 N cell. Three 25-×-25-mm samples were removed from section F of each steak

(Figure 1) and were compressed 2 times at a crosshead speed of 100 mm/min to 50% of the original height of the sample, measured perpendicular to the fiber orientation. The measurements determined included hardness, cohesiveness, springiness, resilience, chewiness, and adhesion. Each measurement was calculated according to Caine et al. (2003).

Statistical analysis

A generalized linear mixed model using the PROC GLIMMIX procedure of SAS version 9.4 (SAS Institute Inc., Cary, NC) was used for statistical analysis. Treatment effects were determined by analysis of variance by a split-plot design. Quality grade served as the main plot, with steak thickness and grill surface temperature represented as subplots. Carcass was considered a random effect. Denominator degrees of freedom were calculated by the Kenward-Rogers approximation. All treatment mean separation was conducted using a protected *t* test by the LSMEANS/PDIFF option of the GLIMMIX procedure. Pearson correlation coefficients were obtained using the PROC CORR procedure of SAS. Statistical significance was determined at $P \leq 0.05$.

Results and Discussion

Thermal properties

Results from thermal diffusivity and conductivity are presented in Table 1. Thermal diffusivity and conductivity were not impacted by any interaction or main effect ($P \geq 0.063$). These results imply that the beef steaks of this study had similar thermodynamics, meaning that heat travelled through each steak in a similar manner. This finding is in contrast to our initial hypotheses that meat of varying composition and thickness cooked with different surface temperatures would have varying thermal properties. However, in this study all steaks were cooked to a medium degree of doneness. By this parameter, the impact of steak thickness and grill surface temperature would largely be removed because cooking endpoint was standardized. Other data generated in our lab have indicated that, when degree of doneness is varied, thermal conductivity is reduced in steaks cooked to greater degree of doneness.

Quality grade or intramuscular fat content had no impact on thermal properties. This result implies that, in this study, meat composition—as it relates to fat content—does not dictate how heat travels through beef steaks. Beef has been cited to be more similar to water than it is to fat with regard to thermal properties (Tornberg, 2005). The beef steaks of this study would not be considered to have a wide range in fat content. Select strip steaks are frequently described to have a fat content of approximately 3%, while upper 2/3 Choice strip steaks have been determined to have a fat content of approximately 7% to 8% (O'Quinn et al., 2012; Emerson et al., 2013; Legako et al., 2015). It is unclear how results would compare among a more diverse beef population. It can be speculated that a more diverse set of beef samples would have provided the compositional differences that are influential toward thermal properties, such as beef of broad fat content or beef steaks from different muscles.

Table 1. Least-squares means of thermal diffusivity and conductivity of beef strip loin steaks of varying thicknesses[1] and USDA quality grades[2] cooked on high and low grill surface temperatures[3]

Treatment	Thermal diffusivity	Thermal conductivity
Steak thickness		
Thick	0.16	0.48
Thin	0.18	0.48
SEM	0.001	0.001
P value	0.101	0.929
Surface temperature		
High	0.17	0.47
Low	0.17	0.48
SEM	0.001	0.001
P value	0.640	0.083
Quality grade		
Choice	0.17	0.47
Select	0.17	0.48
SEM	0.008	0.001
P value	0.496	0.541
Thickness × surface temperature		
P value	0.525	0.398
Surface temperature × quality grade		
P value	0.199	0.063
Thickness × quality grade		
P value	0.836	0.171
Thickness × surface temperature × quality grade		
P value	0.094	0.281

[1]Thick: 38.1 mm; thin: 17.6 mm.

[2]Choice: USDA marbling score of Modest^{00}–Moderate ^{100}; Select: Slight^{00}–Slight^{100}.

[3]High grill surface temperature: 232.2°C; low grill surface temperature: 176.7°C.

Rheological results

An interaction ($P = 0.029$) of quality grade × steak thickness × grill surface temperature was seen for the elastic behavior of the center of steak samples (Figure 2). Elastic behavior, or elasticity, describes the ability of materials to return to their rest shape after applied stress is removed (Vilgis, 2015). Choice steaks cooked on an LST grill showed no difference ($P > 0.05$) among thicknesses, but when cooked on HST, thick steaks had greater ($P < 0.05$) elastic nature than thin steaks. Select steaks did not exhibit any defining pattern among the treatments. In a two-way interaction of quality grade × steak thickness ($P = 0.031$; Figure 3), the elastic behavior among Choice steaks that were thick maintained greater ($P < 0.05$) elastic nature than thin steaks. Select steaks did not exhibit a difference ($P > 0.05$) among the thicknesses for elastic behavior. Additionally, grill surface temperature did not impact the elastic behavior of steaks ($P > 0.05$). These elasticity results were almost identical to the viscous behavior of the steaks. However, because meat is regarded as more of an elastic material than a viscous material, the elasticity modulus better reflects this notion by exhibiting much greater values than the viscosity modulus; therefore, only the elastic behavior of the steaks is shown.

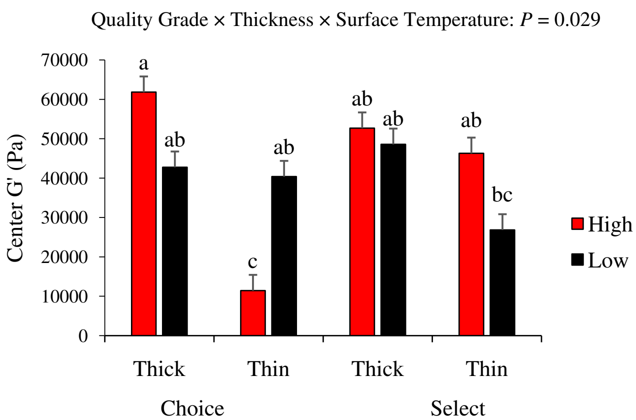

Figure 2. Interaction least-squares means of center elastic modulus from beef strip loin steaks of varying thicknesses[1] and USDA quality grades[2] cooked on high and low grill surface temperatures[3].

[1]Thick: 38.1 mm; Thin: 17.6 mm.

[2]Choice: USDA marbling score of Modest^{00}–Moderate ^{100}; Select: Slight^{00}–Slight^{100}.

[3]High grill surface temperature: 232.2°C; Low grill surface temperature: 176.7°C.

[abc]Columns lacking a common superscript differ ($P < 0.05$).

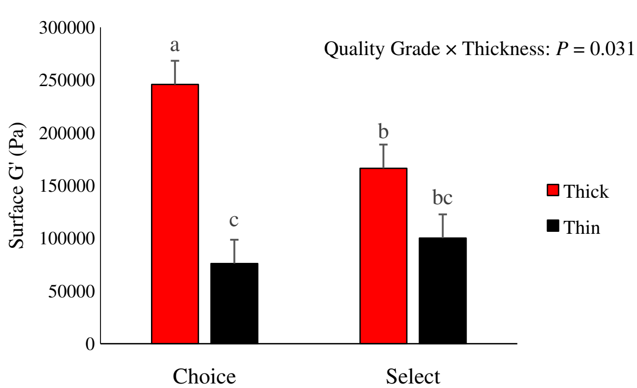

Figure 3. Interaction least-squares means of surface elastic modulus from beef strip loin steaks of varying thicknesses[1] and USDA quality grades[2] cooked on high and low grill surface temperatures[3].

[1]Thick: 38.1 mm; Thin: 17.6 mm.

[2]Choice: USDA marbling score of Modest^{00}–Moderate ^{100}; Select: Slight^{00}–Slight^{100}.

[3]High grill surface temperature: 232.2°C; Low grill surface temperature: 176.7°C.

[abc]Columns lacking a common superscript differ ($P < 0.05$).

Protein enthalpy and denaturation

The protein denaturation patterns obtained from DSC thermograms were categorized into 3 specific groups of peaks: 55°C–65°C, 70°C–75°C, and 80°C–85°C. The denaturation peak 70°C–75°C was found to have a two-way interaction between steak thickness × grill surface temperature ($P = 0.001$; Figure 4). Steaks cooked at HST showed no difference among thicknesses ($P > 0.05$), but thickness was observed to impact protein denaturation at LST. Thick steaks at LST also exhibited greater enthalpy than thin steaks.

The denaturation temperature of proteins that were found to degrade at 55°C–60°C were affected by a two-way interaction of steak thickness × grill surface temperature ($P = 0.03$; Figure 5) and in a similar pattern as the enthalpy of proteins that degraded at 70°C–75°C. However, thick steaks cooked on LST degraded

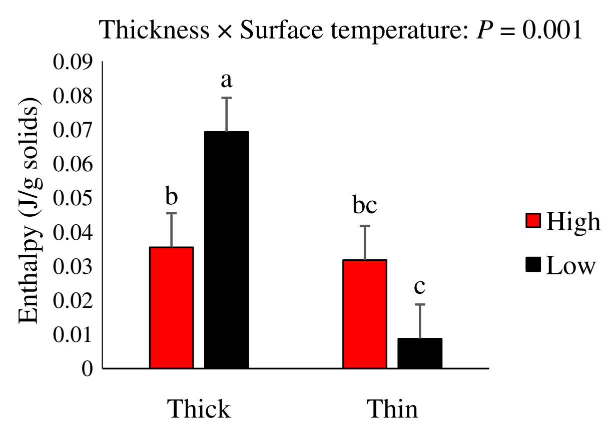

Figure 4. Interaction least-squares means of enthalpy values at 70°C–75°C from beef strip loin steaks of varying thicknesses[1] and USDA quality grades[2] cooked on high and low grill surface temperatures[3].

[1]Thick: 38.1 mm; Thin: 17.6 mm.

[2]Choice: USDA marbling score of Modest^{00}–Moderate ^{100}; Select: Slight^{00}–Slight^{100}.

[3]High grill surface temperature: 232.2°C; Low grill surface temperature: 176.7°C.

[abc]Columns lacking a common superscript differ ($P < 0.05$).

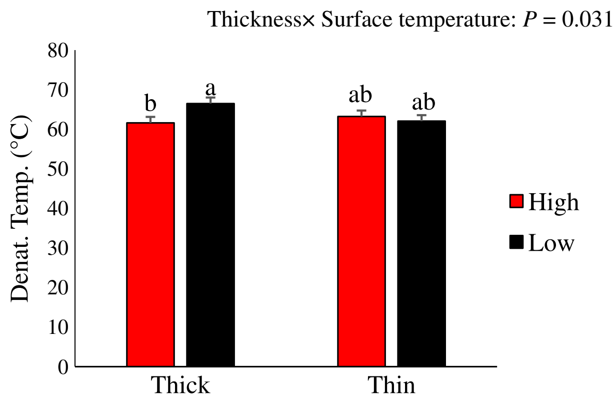

Figure 5. Interaction least-squares means of protein denaturation temperatures at 55°C–60°C from beef strip loin steaks of varying thicknesses[1] and USDA quality grades[2] cooked on high and low grill surface temperatures[3].

[1]Thick: 38.1 mm; Thin: 17.6 mm.

[2]Choice: USDA marbling score of Modest^{00}–Moderate ^{100}; Select: Slight^{00}–Slight^{100}.

[3]High grill surface temperature: 232.2°C; Low grill surface temperature: 176.7°C.

[ab]Columns lacking a common superscript differ ($P < 0.05$).

at a later temperature than to their thin counterparts. Fewer differences were observed for steaks cooked with HST, whereas thin steaks overall had more similar degradation temperatures; HST thick steaks degraded much sooner than LST thick steaks.

Considering the steaks were cooked to a degree of doneness of 71°C, the majority of myosin would be degraded, and the proteins still present in their natural state or some kind of aggregation were the sarcoplasmic proteins, collagen, and actin that degrade at 60°C–80°C (Tamilmani and Pandey, 2016). Although myosin degrades around 40°C–60°C, it could still be in some aggregation with other proteins, which were shown to be affected by steak thickness and grill surface temperature (Purslow, 1985; Tornberg, 2005). A shift of denaturation temperature for a group of proteins in a system could be related to the state the protein is in, causing it to be more or less stable in the system.

The enthalpy or amount of energy released during the degradation of these proteins is an indicator of the relative amount of intact proteins in either their native form or in a state of denaturation and aggregation with other proteins. These results imply that both thickness and grill surface temperature influence the degradation of proteins during cooking. Overall, this research confirms that even small changes in the cooking method of steaks can result in significant changes to the protein structure of steaks resulting in possible changes to the organoleptic perception of the product.

Expressible moisture

The percent expressible moisture of strip steaks was found to have 2 significant main effects, steak thickness ($P = 0.003$) and grill surface temperature ($P = 0.03$; Figure 6). Thick steaks exhibited greater expressible moisture than thin steaks. Cooking temperature contributes to moisture loss, which in turn impacts juiciness of beef products (Yancey et al., 2011). Other studies that observed the gel structure of cooked beef and described through the relative amount of protein aggregation showed that moisture loss increased as aggregation increased, suggesting that cooking at HST could lead to an increase in protein aggregation not associated with degree of doneness (Tornberg, 2005; Yancey et al., 2011). An increase in protein aggregation has also been associated with

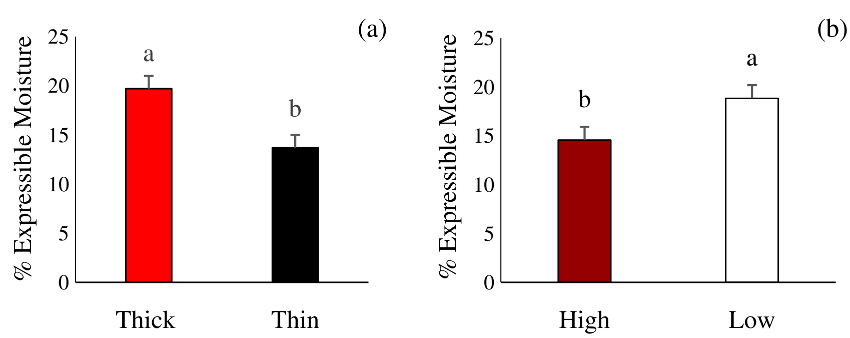

Figure 6. Least-squares means of expressible moisture values from beef strip loin steaks of varying thicknesses[1] and USDA quality grades[2] cooked on high and low grill surface temperatures[3].

(a) Main effect of Steak Thickness was observed ($P = 0.003$).

(b) Main effect of Grill Surface Temperature was observed ($P = 0.03$).

[1]Thick: 38.1 mm; Thin: 17.6 mm.

[2]Choice: USDA marbling score of Modest^{00}–Moderate ^{100}; Select: Slight^{00}–Slight^{100}.

[3]High grill surface temperature: 232.2°C; Low grill surface temperature: 176.7°C.

[ab]Columns within a figure lacking a common superscript differ ($P < 0.05$).

greater force to penetrate the product or a decrease in tenderness (Tornberg, 2005).

WBSF

WBSF values were impacted by steak thickness ($P = 0.007$; Figure 7). Thin steaks were shown to have a greater WBSF value kg force compared with thick steaks. Therefore, although thick steaks required a longer cooking time and therefore a greater contact with the grill surface, this did not negatively impact the shear force values.

Both tenderness and juiciness are affected by the major structural proteins in beef, which create a unique gel structure upon cooking (Christensen et al., 2000; Caine et al., 2003; Tornberg, 2005; Bertram et al., 2006; Phelps et al., 2015). Previous studies have shown that this gel structure is cooking method dependent and can play a significant role in the sensorial properties of the cooked product. This gel structure can affect other objective sensory aspects—such as water-holding capacity (expressible moisture) or penetration force (WBSF)—that are representative of juiciness and tenderness (Tornberg, 2005; Brunton et al., 2006; Yancey et al., 2011; Ishiwatari et al., 2013).

TPA

Three-way interactions between quality grade × steak thickness × grill surface temperature were found for the TPA measurements of hardness ($P = 0.02$; Figure 8), resilience ($P = 0.01$; Figure 9), and chewiness ($P = 0.03$; Figure 10). The most profound difference among hardness, as well as chewiness, was between Select thin steaks, in which steaks cooked on HST had greater hardness than LST steaks. Select, thin HST steaks also had an overall greater hardness value than any other group of steaks. The resilience of steaks was more variable; however, a pattern can be seen for Choice thin steaks, which demonstrated lower

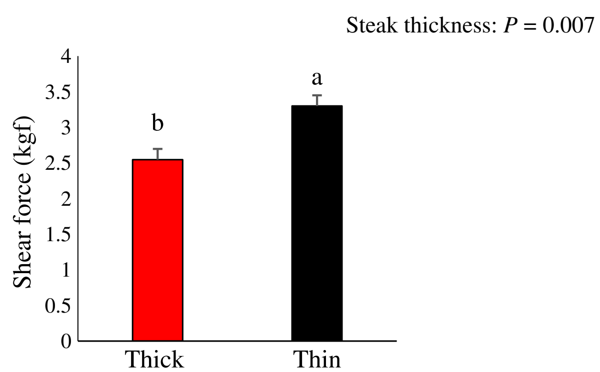

Figure 7. Least-squares means of Warner-Bratzler shear force values from beef strip loin steaks of varying thicknesses[1] and USDA quality grades[2] cooked on high and low grill surface temperatures[3].

[1]Thick: 38.1 mm; Thin: 17.6 mm.

[2]Choice: USDA marbling score of Modest^{00}–Moderate ^{100}; Select: Slight^{00}–Slight^{100}.

[3]High grill surface temperature: 232.2°C; Low grill surface temperature: 176.7°C.

[ab]Columns within a figure lacking a common superscript differ ($P < 0.05$).

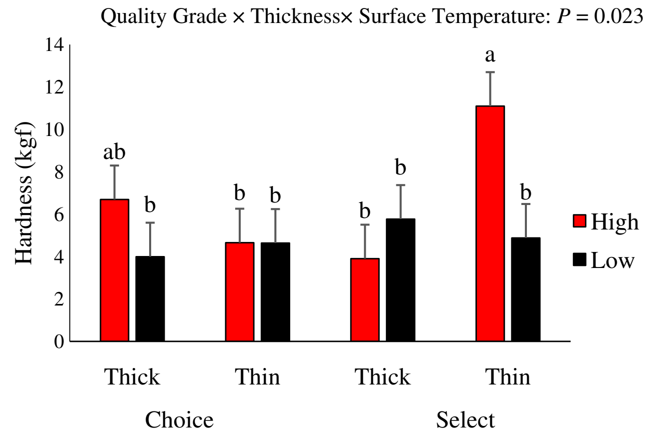

Figure 8. Interaction least-squares means of hardness values from beef strip loin steaks of varying thicknesses[1] and USDA quality grades[2] cooked on high and low grill surface temperatures[3].

[1]Thick: 38.1 mm; Thin: 17.6 mm.

[2]Choice: USDA marbling score of Modest^{00}–Moderate ^{100}; Select: Slight^{00}–Slight^{100}.

[3]High grill surface temperature: 232.2°C; Low grill surface temperature: 176.7°C.

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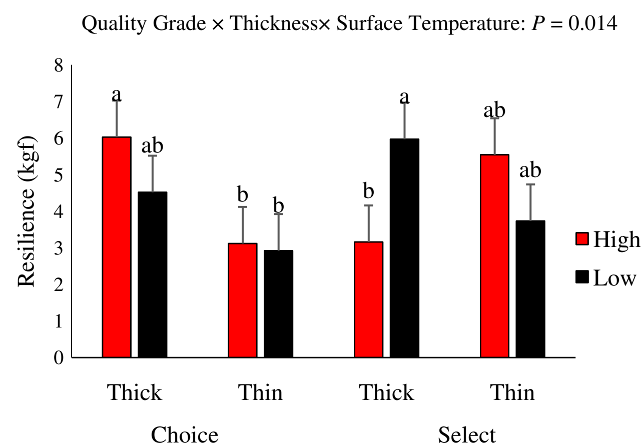

Figure 9. Interaction least-squares means of resilience values from beef strip loin steaks of varying thicknesses[1] and USDA quality grades[2] cooked on high and low grill surface temperatures[3].

[1]Thick: 38.1 mm; Thin: 17.6 mm.

[2]Choice: USDA marbling score of Modest^{00}–Moderate ^{100}; Select: Slight^{00}–Slight^{100}.

[3]High grill surface temperature: 232.2°C; Low grill surface temperature: 176.7°C.

[ab]Columns within a figure lacking a common superscript differ ($P < 0.05$).

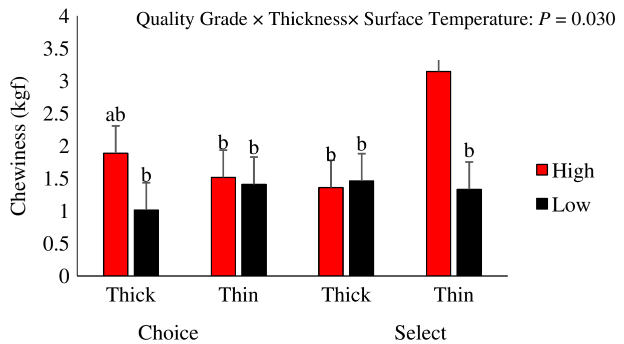

Figure 10. Interaction least-squares means of chewiness values from beef strip loin steaks of varying thicknesses[1] and USDA quality grades[2] cooked on high and low grill surface temperatures[3].

[1]Thick: 38.1 mm; Thin: 17.6 mm.

[2]Choice: USDA marbling score of Modest^{00}–Moderate ^{100}; Select: Slight^{00}–Slight^{100}.

[3]High grill surface temperature: 232.2°C; Low grill surface temperature: 176.7°C.

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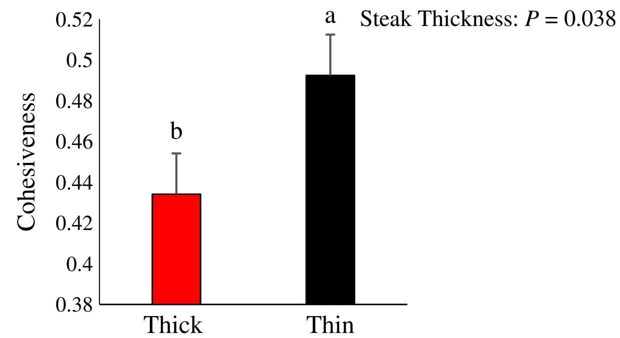

Figure 12. Least-squares means of cohesiveness values from beef strip loin steaks of varying thicknesses[1] and USDA quality grades[2] cooked on high and low grill surface temperatures[3].

[1]Thick: 38.1 mm; Thin: 17.6 mm.

[2]Choice: USDA marbling score of Modest^{00}–Moderate ^{100}; Select: Slight^{00}–Slight^{100}.

[3]High grill surface temperature: 232.2°C; Low grill surface temperature: 176.7°C.

[ab]Columns within a figure lacking a common superscript differ ($P < 0.05$).

resilience, hardness, and chewiness compared with other groups.

Springiness values differed due to steak thickness ($P = 0.002$) and grill surface temperature ($P = 0.014$; Figure 11). Thick steaks were shown to have greater springiness than thin steaks, while steaks cooked on HST had greater springiness than on LST. Steak thickness influenced cohesiveness ($P = 0.04$; Figure 12). Thin steaks were shown to have greater cohesiveness compared with thick steaks. Resilience was also shown to be strongly correlated with cohesiveness ($r = -0.69$; $P \leq 0.0005$) and adhesion ($r = -0.62$; $P \leq 0.001$; Table 2).

The results for the textural measurements are reflective of what we would expect. Thin steaks displayed a reduced degree of doneness gradient and thus less soft tissue and greater WBSF values. Additionally, springiness of thicker samples followed this trend. However, samples cooked at HST had greater springiness than samples cooked at LST. This could be a response to an increase in tightening of muscle fibers due to the higher initial grill surface temperatures, but does not result in changes in WBSF values of the sample based off of grill surface temperature alone (Yancey et al., 2011).

The tenderness of beef can be measured very effectively using the WBSF and TPA methods (Caine et al., 2003). TPA parameters—specifically hardness—have also been shown to be highly indicative of tenderness

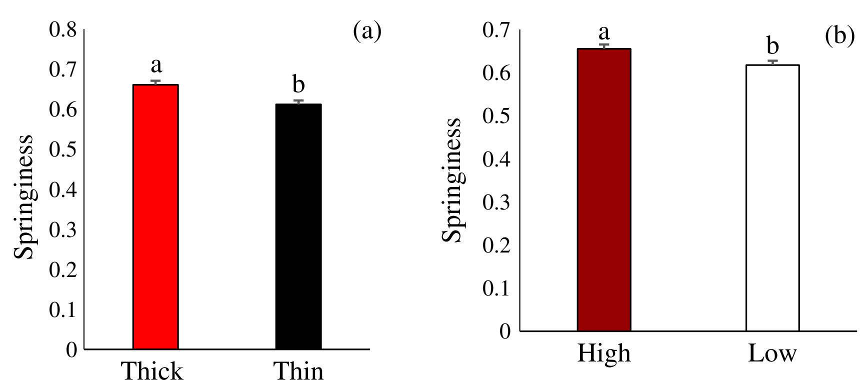

Figure 11. Least-squares means of springiness values from beef strip loin steaks of varying thicknesses[1] and USDA quality grades[2] cooked on high and low grill surface temperatures[3].

(a) Main effect of Steak Thickness was observed ($P = 0.0018$).

(b) Main effect of Grill Surface Temperature was observed ($P = 0.0137$).

[1]Thick: 38.1 mm; Thin: 17.6 mm.

[2]Choice: USDA marbling score of Modest^{00}–Moderate ^{100}; Select: Slight^{00}–Slight^{100}.

[3]High grill surface temperature: 232.2°C; Low grill surface temperature: 176.7°C.

[ab]Columns within a figure lacking a common superscript differ ($P < 0.05$).

Table 2. Pearson correlation coefficients for texture profile analysis, rheological, and Warner-Bratzler shear force values of beef strip loin steaks varying in thickness[1] and quality[2] treatments cooked on grills of high and low temperatures[3]

Measurement	WBSF	Hardness	Cohesiveness	Resilience	Springiness	Chewiness	Adhesion	Center G’	Center G”	Surface G’
Hardness	0.14									
Cohesiveness	0.21	−0.21								
Resilience	0.01	0.56**	−0.69***							
Springiness	−0.18	0.07	−0.27	0.12						
Chewiness	0.20	0.96***	0.04	0.40*	0.11					
Adhesion	−0.12	−0.21	0.33*	−0.62***	0.31	−0.08				
Center G’	−0.05	0.38*	−0.22	0.41*	0.45**	0.36*	−0.10			
Center G”	−0.05	0.40*	−0.21	0.40*	0.44**	0.39*	−0.10	0.99***		
Surface G’	−0.41*	0.02	0.19	0.26	0.35*	0.01	0.09	0.54**	0.52**	
Surface G”	−0.41*	0.04	−0.19	0.23	0.35*	0.03	0.08	0.56**	0.54**	0.99***

[1]Thick: 38.1 mm; thin: 17.6 mm.

[2]Choice: USDA marbling score of Modest[00]–Moderate[100]; Select: Slight[00]–Slight[100].

[3]High grill surface temperature: 232.2°C; low grill surface temperature: 176.7°C.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.0001$.

WBSF, Warner-Bratzler shear force.

and overall palatability. However, in this study no correlations were determined between WBSF tenderness and hardness. Another characteristic that TPA measurements have been shown to identify is texture profiles of meat based on fat content, specifically those meat products lower than 8.0% fat and higher than 10.0% (de Ávila et al., 2014). Greater fat content was reflected by lower hardness and greater adhesiveness, which can be seen in the majority of the Choice steak samples.

Correlation results

Pearson correlations between TPA, WBSF, and rheology measurements are denoted in Table 2. Hardness values from TPA analysis were correlated with the rheological parameters of the elasticity and viscosity moduli. However, beef is more of a solid foodstuff material, thus the elastic behavior of the material is greater than the viscous behavior. Therefore, the elasticity measurement results in a more indicative relationship to TPA hardness values, which was shown to be moderately correlated to the center elastic modulus ($r = 0.38$; $P < 0.05$). A reduction in the elastic and viscous modulus of a meat sample is associated with a gel that can retain more water, resulting in a less elastic gel structure. Rheology measurements were also shown to reflect DSC protein denaturation patterns and thus shown to be representative of myofibrillar protein states. The enthalpy of proteins at 70°C–75°C ($r = 0.72$; $P \leq 0.005$) as well as the denaturation temperature of proteins at 55°C–60°C ($r = 0.83$; $P \leq 0.05$) were strongly correlated with the enthalpy of proteins at 80°C–85°C.

When comparing the textural and rheological data, we observed that the elastic modulus is very similar to the springiness of a steak; however, it is more applicable to the microstructure. Both the center and surface elastic moduli were greater in thicker samples at HST. Choice thick steaks cooked on HST had greater ($P < 0.05$) values than thin steaks, whereas Select steaks revealed no difference among the treatment factors. This shows that the rheological testing of the samples are used to confirm the TPA results and helps to bridge the connection between texture, tenderness, and what occurs in the proteins structure.

Conclusions

Results from this study indicate that steak thickness and grill surface temperature readily affect thermophysical properties of elasticity, protein denaturation, and enthalpy. Additionally, steak thickness was determined to influence WBSF tenderness. However, few correlations were determined between thermophysical measurements and WBSF. Although further research is needed to compare the thermophysical results obtained in this study to consumer sensory evaluation and chemical analysis of the flavor of the beef steaks, insight can still be given based on the textural and physical results that can be connected to perceived tenderness and juiciness of the steaks.

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