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Analysis of Beef Steaks of Varying USDA Quality Grades and Thicknesses Cooked on Low and High Grill Surface Temperatures

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ANALYSIS OF BEEF STEAKS OF VARYING USDA QUALITY GRADES AND THICKNESSES COOKED ON LOW AND HIGH GRILL SURFACE TEMPERATURES

by

ToniRae Gardner

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ABSTRACT

Analysis of Beef Steaks of Varying USDA Quality Grades and Thicknesses Cooked on Low and High Grill Surface Temperatures

by

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Utah State University, 2017

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The ability of an anisotropic (directionally dependent)-multi-component material, such as beef, to conduct heat is highly dependent on protein states, water content and other variables. It is also widely known that beef composition greatly impacts overall palatability described by juiciness, tenderness, and flavor. Analysis of these properties in beef steaks of varying USDA quality grades and thicknesses cooked on low and high grill surface temperatures will help to elucidate their importance and how they are affected by cooking.

Thermal characteristics described by changes in the denaturation temperature (between 55-60°C) and enthalpies of protein denaturation (between 70-75°C) both differed ($P = 0.0307$ and $P = 0.0012$, respectively) among thick steaks with high grill surface steaks having a lower denaturation temperature and enthalpy as compared to steaks cooked on a low grill surface. No differences ($P > 0.05$) were seen among thin steaks.

The elastic behavior of the surface and centers of the beef 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 between USDA Quality Grade, steak thickness, and grill surface temperature while the elastic behavior of the surface of steaks was influenced only by USDA Quality Grade and steak thickness. These interactions along with the differences in the thermal characteristic of proteins suggest that the microstructure of beef steaks is significantly affected by each cooking treatment group.

Textural characteristics described by hardness, resilience, and chewiness were influenced by grill surface temperature and thickness, dependent on quality grade ($P = 0.0027$; $P = 0.0138$; $P = 0.0294$, respectively). Thin steaks possessed greater cohesiveness ($P = 0.0384$) and shear force ($P = 0.0067$) values. Meanwhile, thin steaks exhibited lower springiness ($P = 0.0018$). 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 was ultimately confirmed through textural measurements.

PUBLIC ABSTRACT

Analysis of Beef Steaks of Varying USDA Quality Grades and Thicknesses Cooked on Low and High Grill Surface Temperatures

ToniRae Gardner

The objective of this project was to analyze the thermodynamics (thermal conductivity and diffusivity as well as protein denaturation) and physical properties (percent expressible moisture, cooking loss, change in steak thickness, shear force, texture profile analysis and rheological behavior) of beef steaks of different USDA quality grades (Upper 2/3 Choice and Select), thicknesses (thick and thin), and grill surface temperatures (high and low) cooked to the same internal degree of doneness to determine if a specific set of cooking parameters would create a profound difference in the eating characteristics, described by the tenderness and juiciness of cooked beef strip steaks.

The elastic behavior of the surface and centers of beef 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 between USDA Quality Grade, steak thickness, and grill surface temperature while the elastic behavior of the surface of steaks was influenced only by USDA Quality Grade and steak thickness. These interactions along with the differences in the thermal characteristic of proteins suggest that the microstructure of beef steaks is significantly affected by each cooking treatment group. The physical properties in the beef steaks further support through more

tangible applications that the composition, thickness, and cooking regiments impact the microstructure and thermal properties of beef and thus final tenderness and texture.

This project identified cooking preparation should take into consideration that quality grade, thickness and cooking temperature will affect the textural eating qualities of beef steaks. Choice steaks were shown to be ideally sliced thick and cooked on a low grill surface temperature supported by the springiness, hardness, expressible moisture, and rheological data. Select steaks were not always effected by grill surface temperature and had similar results among the different measurements but the hardness, resilience and chewiness values along with viscosity suggest a thick steak cooked at a high grill surface temperature. Therefore, cooking parameters may be utilized as a mechanism to enhance beef steak palatability.

ACKNOWLEDGMENTS

This project was funded by the Beef Checkoff.

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LIST OF ABBREVIATIONS

Abbreviation	Word
BS	Breaking Strength
DSC	Differential Scanning Calorimetry
EM	Expressible Moisture
HST	High Surface Temperature
IDD	Internal Degree of Doneness
LST	Low Surface Temperature
MRPSs	Maillard Reaction Products
NMR	Nuclear Magnetic Resonance
REA	Ribeye Area
TPA	Texture Profile Analysis
WBSF	Warner-Bratzler Shear Force

USDA	United States Dept. of Agriculture

OBJECTIVE

The objective of this project was to analyze the thermodynamics (thermal conductivity and diffusivity as well as protein denaturation) and physical properties (percent expressible moisture, cooking loss, change in steak thickness, shear force, texture profile analysis and rheological behavior) of beef steaks of different USDA quality grades (Upper 2/3 Choice and Select), thickness (thick and thin), and grill surface temperatures (high and low) cooked to the same internal degree of doneness to determine if a specific set of cooking parameters would create a profound difference in the eating characteristics, described by the tenderness and juiciness of cooked beef strip steaks.

HYPOTHESIS

It is hypothesized that the eating characteristics of the cooked beef strip steaks will be altered due to the changes induced by varying USD Quality Grade, thickness, and grill surface temperature.

INTRODUCTION

Beef palatability can be described using three major characteristics: tenderness, juiciness, and flavor. Each is necessary to achieve overall acceptability. The manner in which meat is cooked can affect each of these characteristics.

The tenderness of meat is strongly influenced by the denaturation states of the major structural proteins in beef. Proteins undergo heat-induced denaturation which causes shrinkage of muscle fibers at specific temperature ranges which can correlate to an increase in shear values or decrease in tenderness values as well as affect juice expulsion and fat migration (Brunton et al, 2006; Tornberg, 2005; Christensen et al, 2000).

Juiciness is primarily influenced by fat content, marbling, as well as somewhat by the water holding capacity (expressible moisture) of the meat which is dependent on cooking temperatures and protein states as they expel moisture during shrinkage (Bertram et al, 2006; Phelps et al, 2015).

The flavor of beef is composed of a vast array of chemicals and components which are a result of various chemical reactions such as lipid degradation, Maillard reactions (MRPSs), Strecker degradation and the interaction between MRPSs and lipid degradation (Legako et al, 2016). Maillard reaction products themselves are highly dependent on the cooking method (Trevisan et al, 2016).

Thermodynamics described by thermal conductivity and diffusivity describe how heat transfers through a material. As heat-induced changes affect all of the major palatability characteristics the need to understand how different cooking methods could alter the way in which heat penetrates a material such as beef is a necessity.

Furthermore, beef is a multi-component material that is also anisotropic (directionally-dependent) and therefore heat travels through it in a specific manner. Components such as the protein, fat, connective tissue, and moisture content of beef can be altered by how heat transfers through the meat structure depending on the cooking method which in turn alters the texture, flavor, and juiciness of the product.

If a particular set of parameters such as steak thickness or grill surface temperature can be chosen to enhance the palatability of a steak of varying quality grade, then that product could be marketed more effectively and consumed with higher acceptability thus increasing its value.

SUPPORTING RESEARCH

COOKING

The cooking of meat can broadly be described by the application of heat to a product which causes a series of chemical and physical reactions that alter the resulting structural, textural and organoleptic characteristics of the original product. Most of these heat-induced changes affect the denaturation of proteins and the physical states of water interacting with the proteins which in turn influence protein structure and water properties in the meat system (Bertram et al, 2006; Christensen et al, 2000).

Much of the study of the dynamic heat-induced process of cooking focuses on the major structural proteins (actin, myosin, collagen and sarcoplasmic proteins) in meat which can be attributed to the greatest influences in textural properties represented by Warner-Bratzler shear force (WBSF) values and Texture Profile Analysis (TPA) measurements (Bertram et al, 2006; Tornberg, 2005; Caine et al, 2003).

The three beef palatability traits (tenderness, juiciness and flavor) can be influenced by many different factors such as breed, age, feed source, quality grade, pre- and post- harvesting methods, (Phelps et al, 2015) as well as cooking method. Although a consumer cannot always choose their beef source and how it was raised they are capable of choosing a few factors that might affect the end product quality such as the intramuscular fat content identified by quality grade, the thickness of the steak and the temperature at which the steak is cooked at.

Many studies express a need and a necessity for the analysis of cooking method for food products especially meat. Ishiwatari et al (2013) state that cooking models that predict texture and weight-loss are limited being that the cooking method has to be taken into consideration for accurate modeling. Kondjoyan et al (2014) also address the importance of models considering how heat transfers during the deformation of the anisotropic muscle fibers which occurs during cooking and causes a temperature gradient between the surface and center of the product complicating modeling parameters. These considerations would help to better predict tenderness and juice expulsion and other heat-induced occurrences that are not being applied in simpler cooking models.

A significant factor in cooking method is the surface temperature at which the product is being cooked at. Berjerholm et al (2014) state that the rate at which heating occurs in a meat product is based on the conductivity of the meat and is dependent on the surface temperature of the sample. Heat is absorbed during cooking through the surface towards the center and therefore causes distinct layers of doneness within the product. These layers of doneness can have different patterning or distinction based on the kind of cooking method (conduction, convection, radiation) which differ based on surface temperature of meat, the temperature profile of the meat and the method of heat transfer.

An example of this by Berjerholm et al (2014) shows that when roasting and high (250°C) and low (150°C) temperatures. Cooking at a high temperature causes greater moisture and cooking loss as well as results in very distinct layers or doneness in the product. When cooking at a low temperature the layers of doneness are more homogenous as well as less moisture and cooking loss occurs. This example is very representative of how cooking methods, specifically temperature, can influence protein structure observed by moisture loss dependent on heat transfer.

THERMAL PROPERTIES

Heat transfer through a material can be described by thermal conductivity and diffusivity as well as heat capacity. The rate at which heat passes through a material reflects its unique thermal conductivity. The ratio of thermal conductivity to the heat capacity of a material, described by the ability to store heat during transfer, is thermal diffusivity. These parameters are usually applied in designing food processing facilities and equipment to ensure safe, thoroughly cooked foods and in obtaining efficient, cost effective cooking methods (Erdogdu, 2007; Huang & Liu, 2009; Murphy & Johnson, 2001). These same measurements can help bring an understanding to smaller scale food production focusing on obtaining ideal cooking conditions based off of different beef steak properties.

Huang and Liu (2009) found that using a transient line-source method (Hotdisk) for simultaneously determining the thermal conductivity and diffusivity of food products proved to be an accurate and efficient means to the analysis of the thermodynamic properties. Many methods for testing the thermodynamic properties of materials do not take into consideration the anisotropic properties of products such as beef which is an over-simplification of what occurs during the cooking process. The Hotdisk transient-line source method allows for these conditions to be taken into consideration.

The Hotdisk works by utilizing a Kapton-insulated sensor that is constructed using concentric heating rings composed of nickel foil that generate heat for measuring the thermal properties of a material. The probe is very thin and can be placed within or between a sample(s) of a material (Figure 1). The non-conductive material of the probe can measure how well the material conducts and diffuses the heat through specific thermal functions.

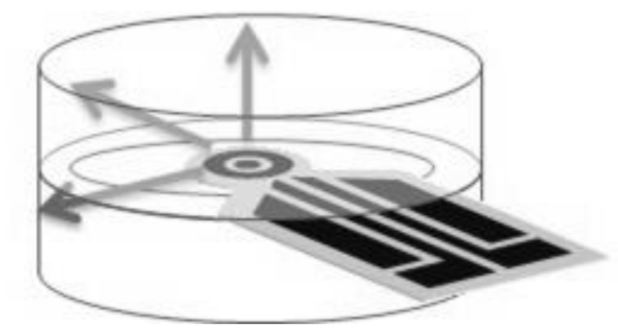

Figure 1. Hotdisk Sensor Placement. Depiction of how the Hotdisk sensor would be placed in a sample and how the heat would be conducted through the sample.

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, 1.553E-7m^2/s; thermal conductivity and diffusivity respectively) has a relatively high rate of conductivity and diffusivity as compared to fat (0.1702 W/m°C, 0.715 E-7m^2/s) and beef (0.4074 W/m°C, 1.138 E-7m^2/s) (Huang & Liu, 2009). Beef is noticeably more similar to water than it is fat which is reasonable being that about 75% of beef is water (Tornberg, 2005). However, beef also contains fat and other components integrated in to a macro meat system which reflects lower thermal property constants.

Being that water is such a large component of meat it is necessary to study how heat affects water states. The next largest component in meat is protein (20%) (Tornberg, 2005). Many of the tests that are used to analyze how cooking affects beef quality study the changes that occur in the chemical and physical states of water and protein and their interactions which are highly correlated (Phelps et al, 2015; Kondjoyan et al, 2014; Ishiwatari et al, 2013; Bertram et al, 2006).

Further, it is imperative to use tests that can analyze beef in its whole natural form especially during the dynamic process of cooking. Being that beef is a multi-component macro-meat system, studying the individual constituents outside of the system would be irrelevant. Study of the water, protein and fat must be done in concert to account for the multitude of interactions that occur between the components. (Kondjoyan et al, 2014; Ishiwatari et al, 2013; Huang & Liu, 2009, Tornberg, 2005).

PROTEIN STRUCTURE

During cooking the proteins in beef undergo heat-induced denaturation which causes structural changes in the meat and effect physical properties such as expressible moisture, texture, and color (Ishiwatari et al, 2013; Tornberg, 2005). Although the other major components of meat, water and fat, are affected during cooking a significant effect on meat quality stems from the changes that occur in the protein structure of meat.

Protein makes up around 20% of the composition of muscle fiber and within that fraction there are major groups of proteins which, when affected by the heat induced by cooking, represent the significant changes found in the physical and textural results (Tornberg, 2005).

These proteins are divided into groups based on their functionalities in meat. There are the myofibrillar, sarcoplasmic and connective tissue proteins. Respectively they compose 50-55%, 30-34%, and 10-15% of the total protein content of beef. The myofibrillar proteins consist of structural proteins such as myosin, actin and titin. The sarcoplasmic proteins are generally enzymatic and are involved in pathways such as the glycolytic pathways. Myoglobin is also a sarcoplasmic protein. Collagen is the significant protein within the connective tissue protein group. Although the connective and sarcoplasmic proteins have similar denaturation ranges the myofibrillar proteins actin and myosin have very different thermal stabilities (Tornberg, 2005).

Myosin is the least heat stable protein and denatures between 40-60°C whereas actin (as well as titin) are some of the most heat stable proteins denaturing close to 80°C. Sarcoplasmic proteins and collagen denature between 60-70°C (Kondjoyan et al, 2014; Bertram et al, 2006; Brunton et al, 2006). Each protein within these groups if isolated will have a unique pattern of heat-induced denaturation starting with the unfolding of their quaternary and tertiary structures. Next an association occurs with nearby proteins that subsequently leads to ultimate gelation of the material. This gel structure being responsible for the majority of the sensorial perceptions when eating beef. Although isolating individual proteins can give insight into their specific behaviors this data can be misleading as to how they will react within a macro-meat system (Biliaderis, 1983). For this reason it is necessary to use instrumentation that allows for analysis of muscle components within their natural state.

Differential scanning calorimetry (DSC) is a very widely used method for doing just that. The DSC measures the change in the heat flow into a sample over time and temperature. Protein denaturation and aggregation is endothermic and therefore requires an input of energy to denature. Once fully denatured there will be no change in energy and therefore no change in heat flow. The DSC can measure this change compared to a blank sample as it heats a product over a temperature gradient. By comparing known values for the major protein denaturation ranges an understanding of what proteins are still present in their natural states or aggregations can be deduced.

Although DSC data is very useful it usually requires supplemental measurements for conclusive results especially with a product such as cooked meat. As the proteins in meat denature and aggregate they form complicated structures with each other which makes it difficult to extrapolate results from a thermogram regarding specific protein states. An example of this is the contractile complex involving actin and myosin, actomyosin. As stated before actin and myosin have very different thermal stabilities, but when combined into a complex this interaction has new properties. The denaturation temperature for actomyosin is also very high, like actin, at 80°C (Kondjoyan et al, 2014). Even though this complex is not a heat-induced interaction it still represents how protein-protein interactions can change their thermal behavior in a system.

Another example of these reactions can be seen from a study by Tornberg (2005) between the leg and breast muscle of chicken with the breast having a type of gel with decreased aggregation and an increase in water-holding capacity and the leg having an increase in aggregation and a subsequently higher force to penetrate the muscle. In this model, temperature as well as moisture content had an effect on the type of gel produced. This is due to how different types of proteins, in this case myofibrillar proteins, behave regarding ionic strength. Myofibrillar proteins can either be in a monomeric or filamentous form. At higher ionic strengths myosin is in the monomeric state and forms a large porous network when it gels that is noticeably coarse. At lower ionic strengths though, myosin is in the filamentous state which results in a firmer yet much finer pore size. This represents just a small portion of the complexity of the protein interactions occurring during the cooking process.

Some of the supplemental measurements that can be used to confirm and support DSC results are nuclear magnetic resonance (NMR) T_2 relaxometry and the study of dielectric properties. What both of these methods have in common are the analysis of water states in a system. Bertram et al (2006) used NMR T_2 relaxometry simultaneously with DSC to compare protein denaturation with heat-induced changes in water characteristics. This study showed a correlation between myosin denaturation from 53-58°C and changes in T_2 relaxation time associated with heat-induced changes of myofibrillar water. It also found correlations between actin denaturation from 80-82°C and the expulsion of water from meat. This demonstrates the relationship between protein denaturation and heat-induced water characteristics and mobility.

Brunton et al (2006) also used the DSC to support the study of the dielectric properties of beef at different cooking temperatures described by the dielectric constant (ε') and loss (ε") factor as well as the rheological properties described by the storage and loss moduli. Based on the state of the water in the meat system being either "bound" to proteins and other constituents or in a "free" state capable of polarization and solvating ions will determine how a material such as beef reacts in an electromagnetic field. Depending on the heat-induced conformation of proteins the water can be in contact or dissociated from the protein structure which results in an increase or decrease of the dielectric constant or loss factor. Around 65°C collagen tightens and releases fluid which leads to an increase in the dielectric constant factor. When myosin denatures at a lower temperature solvated ions are freed and results in a subsequent increase in the dielectric loss factor. These changes were also shown to be associated with rheological behaviors.

PHYSICAL PROPERTIES

Moisture

The moisture content of a cooked meat product has a significant influence on the juiciness and tenderness of a product (Phelps et al, 2015). Moisture loss can be influenced by the cooking method, as well as genetics, age, diet, harvesting methods, and degree of marbling (Phelps et al, 2015). Cooking influences moisture loss by denaturing and shrinking the major structural proteins in meat which causes fibers to become swollen cause juice expulsion. Bertram et al (2006) found a correlation between the denaturation of actin and water expulsion at a cooked temperature of 60-80°C and Brunton et al (2006) attributed a higher collagen content with a higher rate of fluid loss.

Using NMR T_2 relaxometry (Bertram et al, 2006) and analysis of the dielectric properties (Brunton et al, 2006) of meat, protein denaturation can be linked to the chemical and physical state of water in muscle fibers. Bertram et al (2006) found correlations between shifts in water properties and DSC thermograms of the three denaturation phases associated with myosin, sarcoplasmic protein and collagen as well as actin degradation. Brunton et al (2002) also showed a connection of water state to protein state supported by DSC thermograms that associated the dielectric constant and loss factors with DSC enthalpy of degradation regions that correlate with collagen degradation. Many studies have used DSC as a method for determining protein states in complex protein systems effectively (Tomaszewska-Gras & Koniecszny, 2012; Bertram et al, 2006; Brunton et al, 2002; Biliaderis, 1983).

Intramuscular Fat Content

Intramuscular fat or marbling content which can be described by USDA Quality Grades is another important component when addressing heat transfer, tenderness, juiciness and the behavior of meat during cooking. Although intramuscular fat only composes about 5 to 15% of beef muscle components (Smith et al, 2011) it still plays a primary role in the juiciness of the product as well as a factor in the tenderness of the product (Phelps et al, 2015). Fat can also influence heat transfer being that it is a natural insulator and therefore has a lower conductivity as compared to water which could affect how heat transfers to and denatures the proteins during cooking. Quality grade has also been shown to greatly affect consumer overall liking of beef steaks (Legako et al, 2015).

Brunton et al (2006) also found a decrease in heat flow around 55°C which they attributed to the melting of intramuscular fat supporting the notion that a change in fat content would affect heat transfer and therefore heat-induced protein denaturation. It has also been suggested that the heat flow would change depending on the fatty acid composition dependent on diet.

Liu and Lanier (2016) mention in their study of comminuted fat-containing products, such as luncheon meat, that products with higher fat content present a challenge with rapid heating techniques due to insufficient time for meat protein gelation to occur prior to fat fluidization which would affect gel structure formation and lead to changes in the rheological and physical properties of the product. They go on to also present findings that substitution of animal fat with different liquid oils affects cooking method and gel structure required a two-step heating method and subsequent firmer gel strength.

TEXTURAL PROPERTIES

Tenderness has been considered one of the most important characteristics with regards to the acceptability of meat (Destefanis et al, 2008). The tenderness of beef, widely measured and predicted by Warner-Bratzler shear force and Texture Profile Analysis (TPA) (Caine et al, 2003) and supplemented through rheological measurements (Brunton et al, 2006), is greatly influenced by the major protein groups found in meat (Brunton et al, 2006; Christensen et al, 2000). With regards to heat-induced changes, myosin, actin and collagen represent a significant influence on the textural perception due to their large structural presence. Tenderness has shown to be highly variable and therefore requires methods for prediction and correlation (Destefanis et al, 2008).

Warner-Bratzler Shear force

A beef steak's Warner-Bratzler shear force (WBSF) value can be directly correlated to a consumer's perception of "tough" or "tender" of the product (Destefanis et al, 2008). Although the tenderness values obtained from WBSF measurements can be indicative of the consumer's perception, differences can also be due to muscle type, sample preparation, shear apparatus as well as cooking method. Therefore, all of these parameters must be taken into consideration when comparing WBSF results between studies. Still WBSF has been used as very useful tool that is cost and time efficient.

It has been found that both collagen and myosin denaturation and shrinkage result in an increase in shear force value (Brunton et al, 2006). This tightening of specific muscle fibers groups can be directly translated to the tenderness of cooked beef.

The tensile strength of single muscle fibers and WBSF values were tested by Christensen et al (2000) at varying internal degrees of doneness (IDDs) and it was found that there were two specific phases at which fiber breaking strength and WBSF values increased during cooking. These were between 40-50°C and 60-80°C and can be respectively associated with myosin and collagen denaturation. Interestingly the study also found a relaxation period that resulted in a decrease in meat toughness between 50-60°C. These findings support that protein denaturation has a significant impact on textural properties.

Texture Profile Analysis

Another effective method at determining textural properties of food systems is through TPA. This method involves a bicyclic compression of the product to determine measurements such as hardness, cohesiveness, chewiness, adhesion, and resilience. Caine et al (2003) found that hardness, cohesiveness, and chewiness were inversely correlated with initial tenderness, amount of perceptible connective tissue, overall tenderness and overall palatability.

Romero de Avila et al (2014) evaluated the compression parameters of the TPA test against tensile tests of beef which has been used to study the mechanical properties of whole meat, single muscle fibers as well as perimysial connective tissue very effectively. The breaking strength (BS) and energy to fracture are the tensile parameters of greatest importance and it was found that these parameters greatly complement the TPA parameters and that through multivariate regression analysis TPA measurements could be used to predict different texture profiles for meat. Specifically, this study found that there were two texture profiles between cooked meat products that were differentiated by fat content. There were noticeable differences between products with less than 8% fat and greater than 10% fat. Those with greater fat content had lower hardness and BS values and greater adhesiveness.

Rheological Properties

Rheology has also been used to further explain what occurs in the microstructure of beef that could cause changes in perceived textural differences. Beef has higher elastic behavior as compared to its viscous behavior which defines a more solid material. It has been found that the rheological parameters (storage and loss moduli) that describe beef's elastic and viscous behavior respectively are related to the denaturation of myofibrillar proteins (Brunton et al, 2006).

Khiari et al (2014) also found that the rheological parameters change with respect to changes in protein structure. They state that there is a very common pattern in meat which occurs during cooking which starts by a gradual increase in both moduli between 10 – 40°C followed by a rapid increase around 45°C which plateaus around 70°C. This is a similar pattern as seen in DSC thermograms previously stated which correlates respectively to myosin, sarcoplasmic protein, collage and actin degradation. Khiari goes to further explain how TPA hardness values are also correlated with the rheological parameters with a decrease in hardness similar to a decrease in both moduli especially the elastic modulus. This decrease was stated to be in response to a gel that is capable of retaining more water and therefore a less elastic gel.

MATERIALS AND METHODS

PRODUCT COLLECTION

Beef carcasses (n=40) were selected from a commercial processing facility representing USDA Select and upper two-thirds Choice grades. Strip loins were obtained from each selected carcass and stored at 4ºC for 14 days post-mortem and then frozen prior to strip loin fabrication into thin (12.7-mm) and thick (38.1-mm) thicknesses, vacuum-packaged, and frozen at the Rosenthal Meat Science and Technology Center (Texas A&M University, College Station, TX. Samples were shipped frozen to Utah State University where all thermophysical measurements were collected.

COOKERY

Steaks were cooked using a StarMaxx Electric Flat-Top Griddle (536TGF: Star Manufacturing Int'l; St. Louis, MO, USA) until an internal degree of doneness (IDD) of 71°C was reached. Prior to cooking, samples were thawed under refrigeration (4°C) for 12-18 hrs. After thawing an internal temperature was taken to confirm an initial IDD of 4-8°C. Griddle surface temperature was verified immediately before cooking started using a magnetic mount thermocouple (Magnetic K thermocouple 88402K: Omega; Stamford, CT, USA). Two surface temperatures were targeted and considered to be High (HST) and Low (LST), 232.2°C and 176.7°C (respectively).

Two wire thermocouple probes were used to measure the internal temperature of the steak as it progressed through cooking. These wires were threaded through the steak on each lateral end, serving as anchors, before being positioned each approximately 2 – 3 cm away from each other on either side of the geometric center to obtain an average reading of the IDD. Positioning was done using a size 3 embroidery needle to create an initial entrance for the wire thermocouple which was quickly followed into place after the needle was removed. Care was taken to measuring the necessary length of thermocouple wire to reach within 2 – 3 cm of the geometric center horizontal axis as well as maintain a straight wire for accurate positioning.

Prior to cooking an initial temperature reading was taken of the beef steak, then again at the turning temperature of 35°C, and of the final temperature of 71°C, as well as of the peak temperature. During cooking the steak was flipped once it had reached an IDD of 35°C. Time points were taken with each respective temperature range starting when the steak was placed on the grill. Once the steak had finished cooking it was allowed to rest for 3 minutes before being sealed in plastic wrap (Saran™ Premium Wrap) and allowed to cool until its internal temperature reached room temperature (25°C).

SAMPLE LAYOUT

Due to the numerous measurements obtained from each individual steak, care was taken to divide each steak for all measurements. Depicted in Figure 2 is the method by which each steak was segmented.

PHYSICAL MEASUREMENTS

Physical measurements of each sample were taken before and after cooking once the internal temperature of the steak had reached room temperature. These measurements included percent cooking loss (Equation 1), percent change in steak thickness (Equation 3), and percent change in ribeye area (REA) (Equation 2). Steak thickness was measured

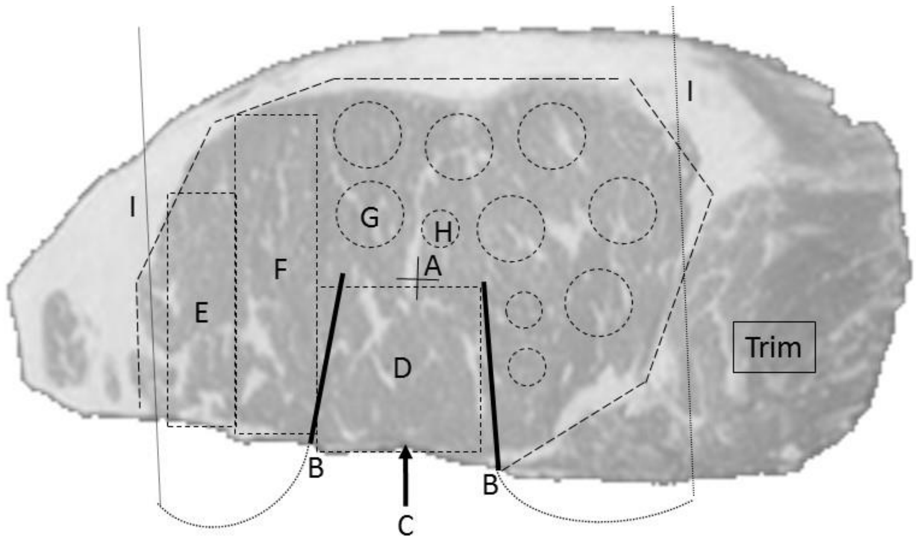

Figure 2. Sample Layout Diagram. A) geometric center of steak B) thermocouple probe positions C) indication of caliper placement for thickness D) Hot-Disk sample E) expressible moisture sample F) compression sample G) shear force samples (7 cores) H) rheometer samples (3 cores) I) thermocouple anchor positioning.

using a digital caliper (General Tools: 147 Fraction+ Digital Fractional Stainless Steel Caliper). Samples were weighed before and after cooking for cooking loss measurements (g). The caliper measurement for change in steak thickness (mm) was taken on the same location for each steak before and after cooking in position C (Figure 3) of the steak. The REA (cm^2) of the steaks was determined by creating an imprint of the steak surface before and after cooking on a piece of sketch paper, tracing the imprint, and then calculating the area of the REA imprint using the online irregular area calculator software, SketchAndCalc (www.sketchandcalc.com) (Figure 3).

$$\%\text{Cooking Loss} = \left(\frac{\text{Wt}_\text{i} - \text{Wt}_\text{f}}{\text{Wt}_\text{i}}\right) * 100 \qquad (1)$$

$$\%\text{Change in REA} = \left(\frac{\text{REA}_\text{i} - \text{REA}_\text{f}}{\text{REA}_\text{i}}\right) * 100 \qquad (2)$$

$$\%\text{Change in Thickness} = \left(\frac{\text{Th}_\text{i} - \text{Th}_\text{f}}{\text{Th}_\text{i}}\right) * 100 \qquad (3)$$

$\mathrm{Wt} =$ weight of whole strip steak

$\mathrm{REA} =$ ribeye area of whole strip steak

$\mathrm{Th} =$ thickness of whole strip steak

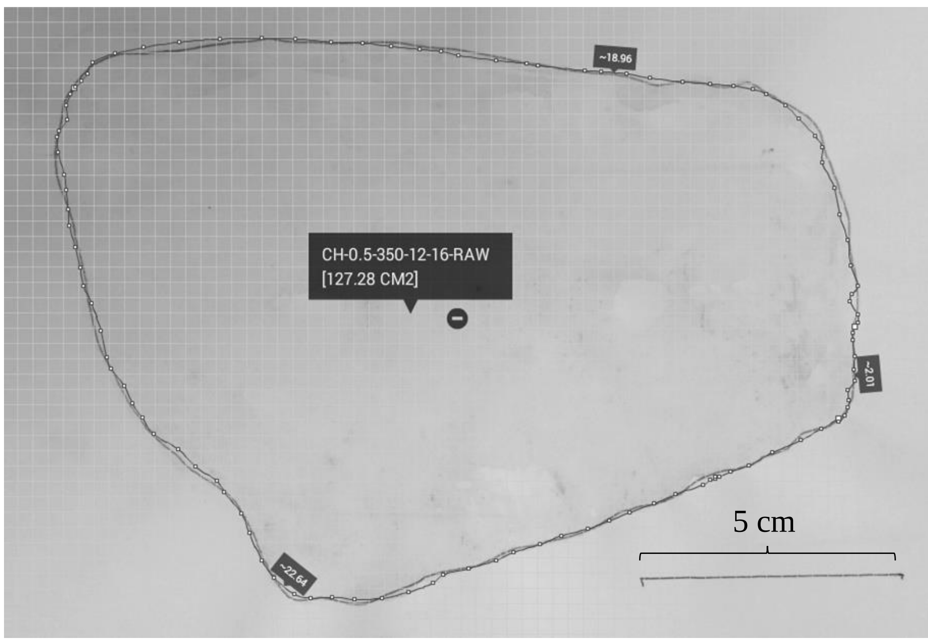

Figure 3. Ribeye Area Tracing Example. Example of the output obtained from the SketchAndCalc software used to trace and calculate the ribeye area (REA) of raw and cooked beef strip steaks. Scale set at 5 cm.

EXPRESSIBLE MOISTURE

Expressible moisture samples were taken from portion E (Figure 2) of the cooked steaks. Four separate samples were divided equally from this portion, each of similar size ranging from 1.5 - 2.5g. Sample pre-centrifuging weight (Wt_i) was recorded. Each sample was placed in a 50mL centrifuge tube that had 20 g of glass beads pre-weighed inside. Samples were centrifuged (Beckman Coulter Allegra X-22; Brea, CA, USA) for

10 minutes at 900 × g and their post-centrifuging weight was recorded (Wt_f). Expressible moisture was calculated using the following equation (4) (Earl et al, 1996):

$$\%\text{Exp. Mois.} = \left(\frac{Wt_i - Wt_f}{Wt_i}\right) * 100 \qquad (4)$$

Wt = weight of expressible moisture sample

THERMAL DIFFUSIVITY & CONDUCTIVITY

The thermal diffusivity and conductivity of the steaks was measured simultaneously by a transient line-source method using a TPS-500 Hot-disk (Hot Disk AB; Gothenburg, Sweden). This sample was taken from portion D (Figure 2) of the cooked steaks. This 2.5 × 2.5cm square sample was sliced in half horizontally to expose the interior surface of the steak. The sensor (Kapton-insulated, 3.189mm radius) was then placed in the center between the two sides of the sample and ran for 40 seconds at 200mW with 5 repetitions. See Figure 1 for a visual representation of the sensor placement.

PROTEIN DENATURATION

The enthalpy and temperature of protein denaturation were taken using a differential scanning calorimeter (DSC) (TA Instruments; DSC Q20; Albuquerque, NM, USA). A 1 – 2 mm slice was taken from an adjacent edge of portion D (Figure 2). This slice was then segmented into surface regions, mid-center regions (only in thick (38.1 mm) steaks), and center regions. Samples (4 – 8 mg) were taken from each region and sealed hermetically in DSC high-volume pans. Samples were then heated at a rate of 2°C every 5 minutes until 100°C had been reached. The denaturation temperature and enthalpy values were calculated by obtaining the max peaks and areas of each distinct curve in the thermograms (Figure 5).

In order to calculate the enthalpy on a solids basis (equation 7) the percent solid content was determined for the calculation of DSC protein degradation data on a dry-matter basis. Only the center portions of steaks which corresponded to center DSC measurements were evaluated. Prior to evaluation, steaks were sliced into 4 mm thin segments using a commercial meat slicer (Globe Food Equipment; 3600N, Dayton, OH, USA) separating the surface, center, and for thick steaks, the mid-center. Center portions were flash frozen in liquid nitrogen and stored at -80°C.

The percent moisture and solids content was determined (Equations 5 and 6) using 1.0 g of frozen homogenized sample taken from the center of post-experimentally portioned steak samples. Samples were weighed onto pre-weighed aluminum pans and dried in an oven (100°C) for 16-18 hrs. Samples were allowed to cool in desiccators for 30 minutes and then weighed.

$$\%\text{Moisture} = \left(\frac{(\text{Wt}_{\text{pan+dry sample}} - \text{Wt}_{\text{pan}}}{\text{Wt}_{\text{wet sample}}}\right) * 100 \tag{5}$$

$$\%\text{Solids} = 100 - \%\text{Moisture} \tag{6}$$

$$\frac{J}{g\ solids} = \frac{\frac{J}{g}}{\%solids} \tag{7}$$

RHEOLOGY

The dynamic rheological behavior described by the elastic and viscous modulus (Pa) of the beef steaks were analyzed using an AR-G2 Rheometer (TA Instruments; Albuquerque, NM, USA) fitted with an 8 mm diameter parallel plate geometry. Three 8 mm diameter thick cores were taken from portion H (Figure 2) 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. Sample time was 3 seconds and occurred in a multi-wave 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 and then proceeded to calculate an average of the elastic and viscous (G”) moduli accepting the average if the standard error was within 10% of the average.

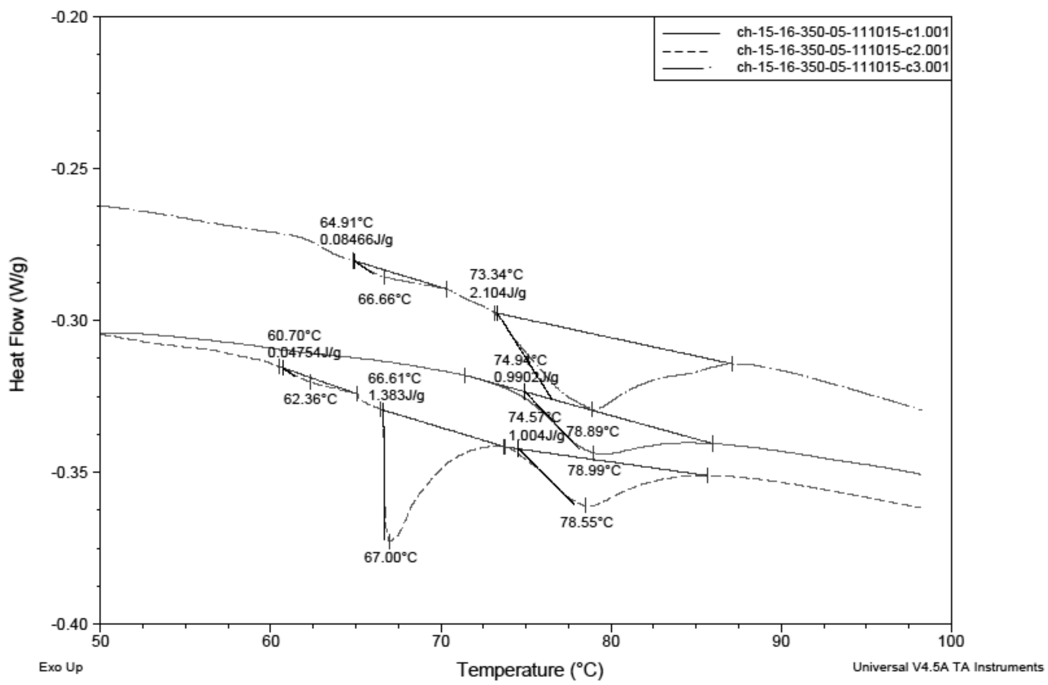

Figure 4. Differential Scanning Calorimeter Thermogram. Example of a thermogram of a sample (in triplicate) ran on a differential scanning calorimeter including curve analysis of thermal denaturation and enthalpy.

WARNER-BRATZLER SHEAR FORCE

The shear force of seven 12.7 mm diameter thick cores (Figure 2; portion G) were measured using a TSM-Pro (Food Technology Corporation; Sterling, VA, USA) fitted with a Warner-Bratzler shear force (WBSF) blade. A 500 N cell was used and the crosshead oscillated through 7 rotations shearing perpendicular to the steak muscle fiber at a rate of 200 mm/min. (AMSA, 2015).

TEXTURE PROFILE ANALYSIS

The compression, or texture profile analysis (TPA), of the beef steaks was carried out using a TSM-Pro (Food Technology Corporation; Sterling, VA, USA) fitted with a 25.4 mm diameter parallel plate geometry and 500 N cell. Three 25 × 25 mm samples were taken from portion F (Figure 2) of each steak and were subjected to a bicyclic compression to 50% the original height of the sample perpendicular to the grain of the meat at a rate of 100 mm/min. The different measurements of hardness, cohesiveness, springiness, resilience, chewiness, and adhesion were calculated using the TSM-Pro Software which uses the following equations (8 – 13) (Figure 5):

$$Hardness = Peak\ 1\ force \tag{8}$$

$$Cohesiveness = Area\ 2\ /\ Area\ 1 \tag{9}$$

$$Springiness = Length\ 2\ /\ Length\ 1 \tag{10}$$

$$Resilience = (Area\ 1 - Area\ 2)\ /\ 2 \tag{11}$$

$$Chewiness = Cohesiveness \times Hardness \times Springiness \tag{12}$$

$$Adhesion = Area\ 3 \tag{13}$$

Data was normalized to account for the increased mass of thick steaks by dividing the thick steak measurements that were dependent on mass (hardness, resilience, chewiness and adhesion) of each treatment groups by a ratio of Thick:Thin (ranging from 2.38 – 2.92) which was taken from the cooked thicknesses of the beef strip steaks. See Appendix, Table 1, for ratios of each treatment group.

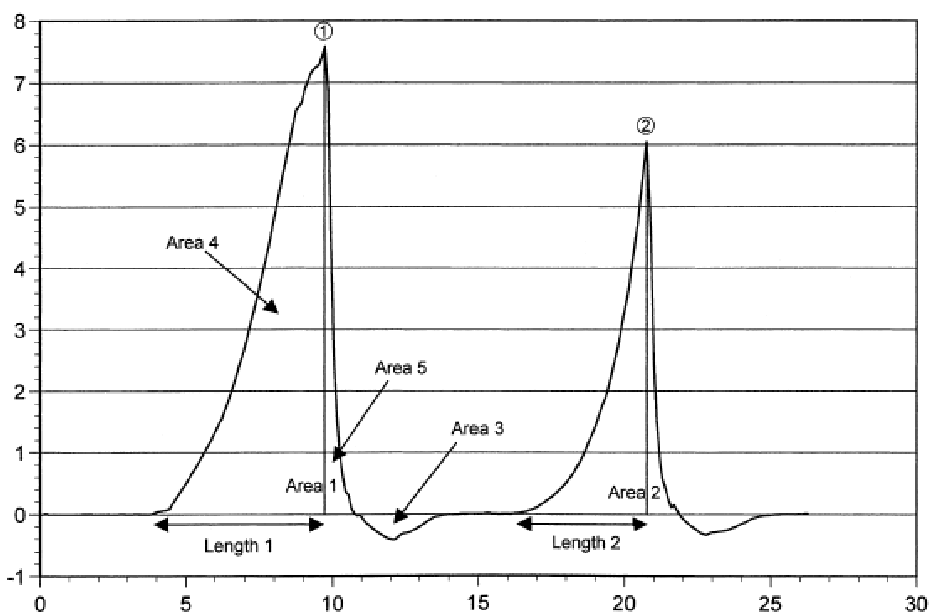

Figure 5. Texture Profile Analysis Compression Graph. Representation of texture profile analysis data segmented into specific areas, peaks and lengths for data analysis. Hardness = Peak 1 force, Cohesiveness = Area 2 / Area 1, Springiness = Length 2 / Length 1, Resilience = (Area 1 – Area 2) / 2, Chewiness = Chewiness × Hardness × Springiness, Adhesion = Area 3 (Caine et al, 2003).

STATISTICAL ANALYSIS

A generalized linear mixed model using the PROC GLIMMIX procedure of SAS (Version 9.4, Cary, NC) was used for statistical analysis. Treatment effects were determined by ANOVA by a split-plot design. USDA quality grade was the main plot with the steak thickness and grill surface temperature as sub-plots. Strip loins served as the experimental unit and was replicated five times per the eight combinations of quality grade (2), thickness (2), and surface temperature (2). 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 PROC CORR. Statistical significance was determined at $P \leq 0.05$.

RESULTS AND DISCUSSION

For tables including LS Means, Pearson correlation coefficients, P-values, standard errors of the mean (SEMs), and F-values for the data included in this section, please see the Appendix (Page 51) at the end of this document.

COOKING RESULTS

The parameters measured during cooking consisted of the following: actual grill surface temperature, the internal temperature of the steak before cooking, the temperature at the flip of the steak during cooking, the final internal temperature when the steak was removed from the grill, the max temperature reached after removing the steak from the grill, and the time it took to reach these critical points. A difference ($P < 0.0001$; Figure 6) between grill surface temperatures was achieved with an average high temperature of 228.97°C and an average low of 178.06°C.

The initial internal temperature of the steaks was affected by the thickness ($P = 0.0001$; Figure 7) of the steaks with thin steaks having a higher initial temperature than thick steaks on average by 4.9°C. This can be attributed to a rise in the temperature of thin steaks during preparation (thermocouple wire placement) just prior to the start of cooking which did not affect thick steaks as significantly due to their greater overall mass. The initial internal temperature of steaks was also affected by a two-way interaction of USDA Quality Grade × Grill Surface Temperature ($P = 0.0411$; Figure 8) with Choice steaks having no difference among surface temperatures but Select steaks cooked at a High grill surface temperature (HST) having a higher initial temperature compared to Low surface temperatures (LST). This result could be attributed to a longer wait time needed in between cooking steaks at a HST to allow for the grill to obtain optimum surface temperature. The fact that there were no differences ($P > 0.05$) seen among Choice steaks among grill surface temperatures could be due to the insulative effect of a higher fat content.

There were no differences ($P > 0.05$) seen among treatment groups regarding the flip and final internal cooking temperatures which support that the actual cooking process was executed correctly and fairly among all treatment groups. There was however, a difference seen for the max internal temperature reached, or carry-over cooking, for the main effect of grill surface temperature ($P = 0.0262$; Figure 9) with steaks cooked at a HST reaching a higher degree of doneness on average by 0.85°C than steaks cooked at a LST.

Regarding the time required to cook the steaks, on average thick steaks required 860.09 seconds (14 min 19.8 sec) until they were flipped at 35°C and a total of 1638.12 seconds (27 min 18sec) to achieve a final internal temperature of 71°C. Thin steaks however required 134.62 seconds (2 min 13.8 sec) until they were flipped and cooked on average for a total of 413.33 seconds (6 min 52.8 sec). Therefore, significant differences were seen for both steak flip times ($P < 0.0001$; Figure 10) and final cook times ($P < 0.0001$; Figure 11). Final cooking time, as well as flip time, were found to have a strong ($0.6 \leq r < 0.8$; $P \leq 0.0005$) correlation with the initial steak temperature, shear force values and the surface elastic modulus. This represents how an increase in cooking time can significantly affect the microstructure of the steak surface as well as the internal structure of the muscle fibers.

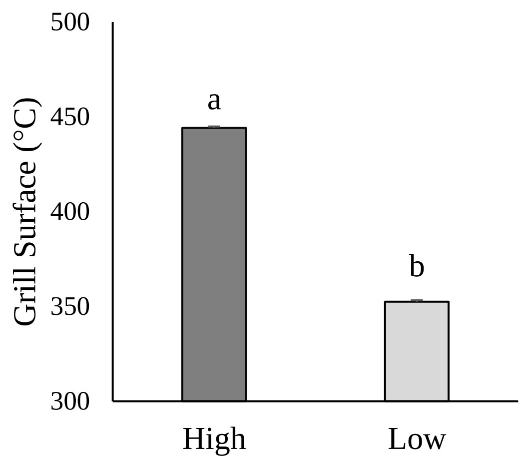

Figure 6. Actual Grill Surface Temperature. Actual grill surface temperature of thick (38.1) and thin (17.6) steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Main effect of Grill Surface Temperature was observed ($P < 0.0001$). Error bars represent pooled (largest) SEM. ^{ab}Columns lacking a common superscript differ ($P < 0.050$).

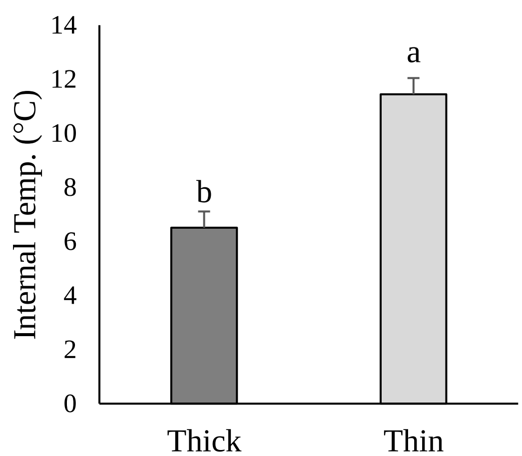

Figure 7. Initial Steak Temperature (Thickness). Initial steak temperature of thick (38.1) and thin (17.6) steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Main effect of Steak Thickness was observed ($P < 0.0001$). Error bars represent pooled (largest) SEM. ^{ab}Columns lacking a common superscript differ ($P < 0.050$).

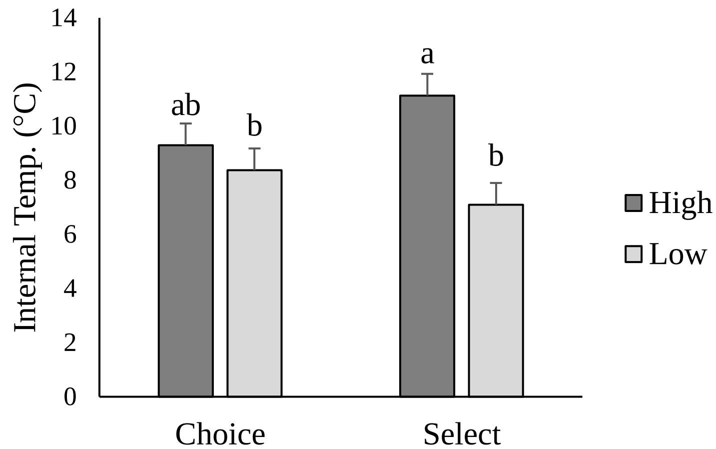

Figure 8. Initial Steak Temperature (QGrade × Surf Temp). Initial steak temperature of thick (38.1) and thin (17.6) steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Two-way interaction of USDA Quality Grade × Grill Surface Temperature was observed (P = 0.0411). Error bars represent pooled (largest) SEM. [ab]Columns lacking a common superscript differ (P < 0.050).

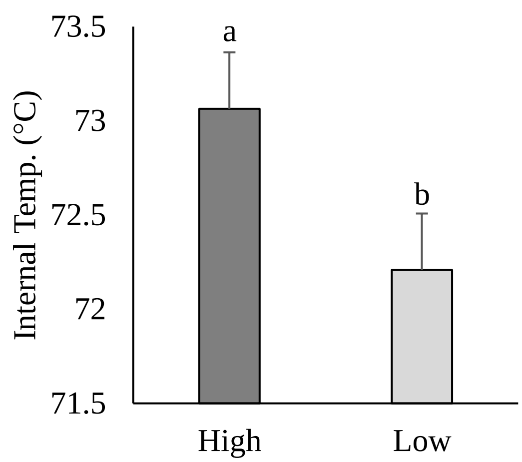

Figure 9. Max Steak Temperature. Max steak temperature of thick (38.1) and thin (17.6) steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Main effect of Grill Surface Temperature was observed (P = 0.0262). Error bars represent pooled (largest) SEM. [ab]Columns lacking a common superscript differ (P < 0.050).

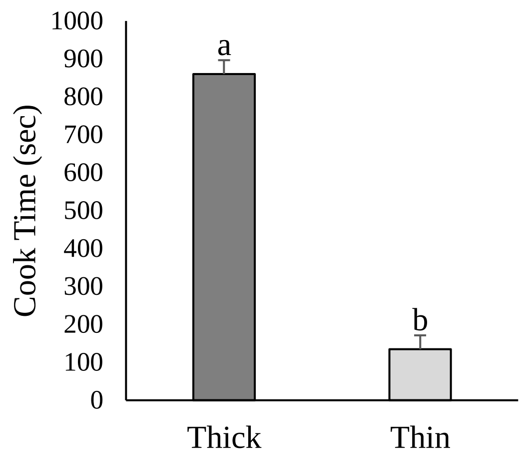

Figure 10. Time to Flip Steaks. Time to flip steaks of thick (38.1) and thin (17.6) steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Main effect of Thickness was observed ($P < 0.0001$). Error bars represent pooled (largest) SEM. ^{ab}Columns lacking a common superscript differ ($P < 0.050$).

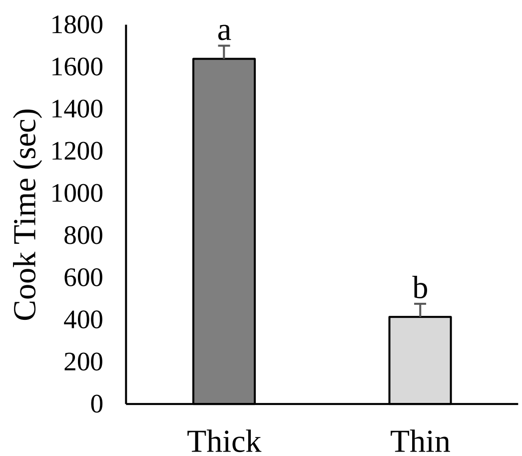

Figure 11. Final Steak Cook Time. Final cook time of steaks of thick (38.1) and thin (17.6) steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Main effect of Thickness was observed ($P < 0.0001$). Error bars represent pooled (largest) SEM. ^{ab}Columns lacking a common superscript differ ($P < 0.050$).

TEXTURAL RESULTS

Warner-Bratzler Shear Force

Warner-Bratzler shear force values were impacted by steak thickness ($P = 0.0067$; Figure 12). Thin steaks were shown to have a greater shear force (kgf) compared with thick steaks. Shear force values showed a strong negative correlation with steak flip times ($r = -0.6012$; $P \leq 0.0005$) and moderately so with final cooking times ($r = -0.5543$; $P \leq 0.005$). Therefore, although thick steaks required a longer time cooking and in 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 (Berjerholm et al, 2014; Bertram et al, 2006; Caine et al, 2003; Christensen et al, 2000; Phelps et al, 2015; Tornberg, 2005). Previous studies have shown that depending on the type of cooking method this gel structure can play a significant role in the sensorial properties of the cooked product specifically affecting aspects such as water holding capacity (expressible moisture) (Berjerholm et al, 2014; Brunton et al, 2006; Ishiwatari et al, 2013) as well as penetration force (shear force) (Tornberg, 2005) which are representative of juiciness and tenderness respectively.

Texture Profile Analysis

Three-way interactions between quality grade × steak thickness × grill surface temperature were found for the TPA measurements hardness ($P = 0.0227$; Figure 13), resilience ($P = 0.0138$; Figure 14) and chewiness ($P = 0.0300$; Figure 15).

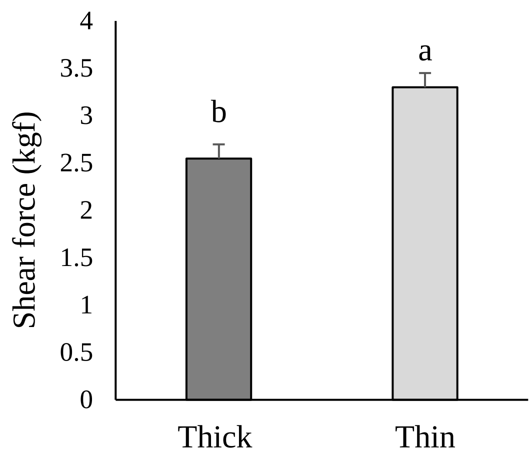

Figure 12. Warner-Bratzler Shear Force. Warner-Bratzler shear force values (kgf) of thick (38.1) and thin (17.6) steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Main effect of Steak Thickness was observed ($P = 0.0067$). Error bars represent pooled (largest) SEM. [ab]Columns lacking a common superscript differ ($P < 0.050$).

The most profound difference among hardness as well as chewiness was between Select steaks sliced thin, where steaks cooked on a HST had greater hardness than LST steaks. These 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 steaks sliced thin which had lower resilience, hardness, and chewiness compared with other groups.

Springiness values differed due to steak thickness ($P = 0.0018$; Figure 16 (a)) and grill surface temperature ($P = 0.0237$; Figure 16 (b)). Thick steaks were shown to have greater springiness than thin steaks while steaks cooked on a HST had greater springiness than on a LST. Steak thickness influenced cohesiveness ($P = 0.0384$; Figure 17). Thin steaks were shown to have greater cohesiveness as compared to thick steaks. Resilience was also shown to be strongly correlated with cohesiveness ($r = -0.6880$; $P \leq 0.0005$) and adhesion ($r = -0.6242$; $P \leq 0.0005$).

The results for the textural measurements are reflective of what we would expect. Thinner steaks had less of an internal degree of doneness (IDD) gradient and thus less soft tissue and greater WBSF values. Springiness of thicker samples followed this trend. However, samples cooked at a higher grill surface temperature had greater springiness than samples cooked at a lower grill surface temperature. This could be in response to an increase in tightening of muscle fibers due to the higher initial temperatures (Berjerholm et al, 2014) but does not lead to a change in WBSF tenderness of the sample based off of grill surface temperature alone.

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 and overall palatability. Another characteristic that TPA measurements have been shown to identify is texture profiles of meat based on fat content. Specifically, those lower than 8.0% fat and higher than 10.0% (M. Dolores Romero de Avila 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.

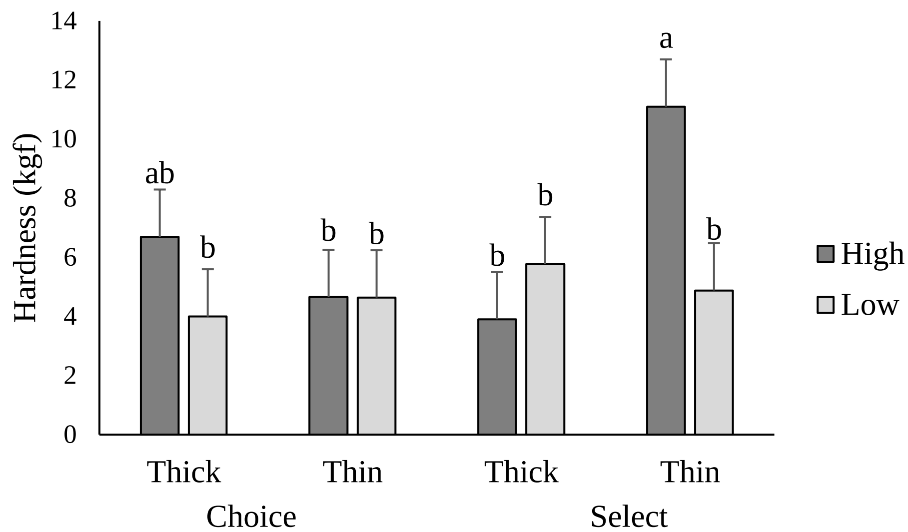

Figure 13. Hardness Values. Hardness (kgf) of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Three-way interaction of USDA Quality Grade × Steak Thickness × Grill Surface Temperature was observed ($P = 0.0227$). Error bars represent pooled (largest) SEM. [ab]Columns lacking a common super script differ ($P < 0.05$).

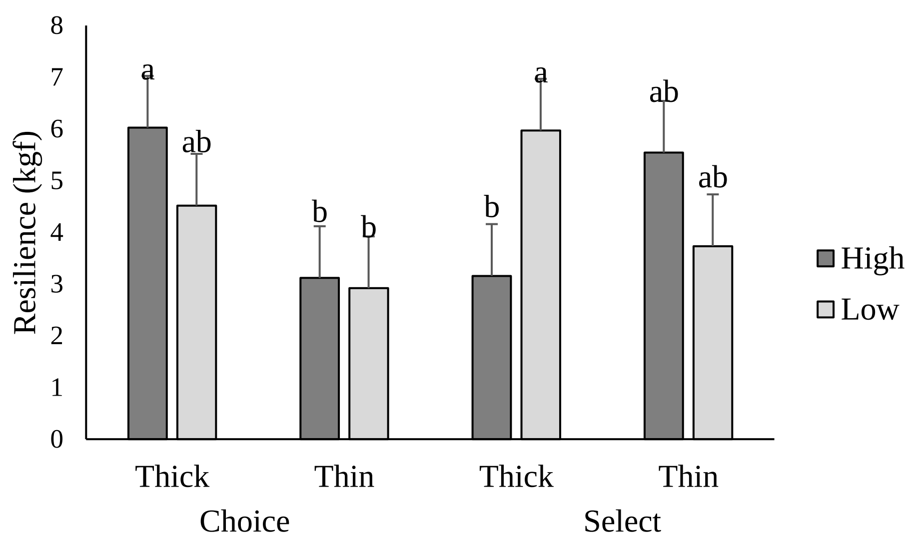

Figure 14. Resilience Values. Resilience (kgf) of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Three-way interaction of USDA Quality Grade × Steak Thickness × Grill Surface Temperature was observed ($P = 0.0138$). Error bars represent pooled (largest) SEM. [abc]Columns lacking a common super script differ ($P < 0.05$).

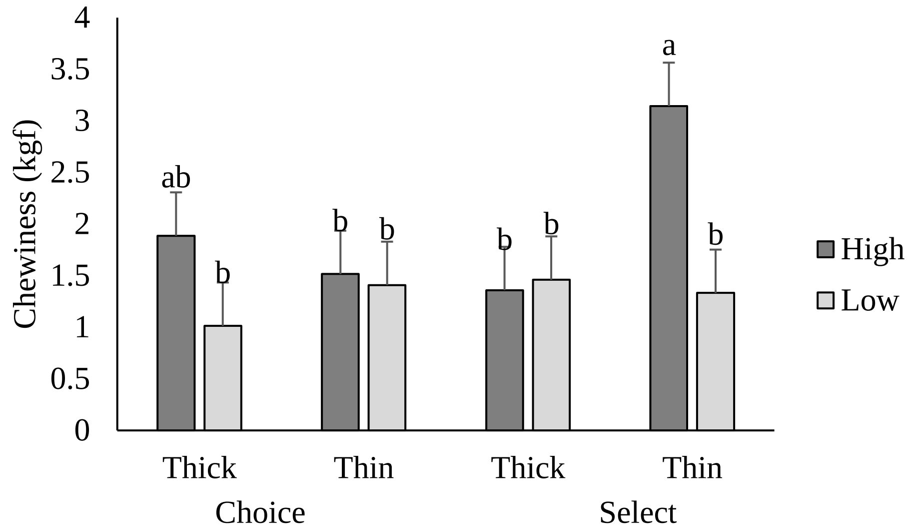

Figure 15. Chewiness Values. Chewiness (kgf) of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Main effect of Grill Surface Temperature was observed (P = 0.0294). Error bars represent pooled (largest) SEM. [abc]Columns lacking a common super script differ (P < 0.05).

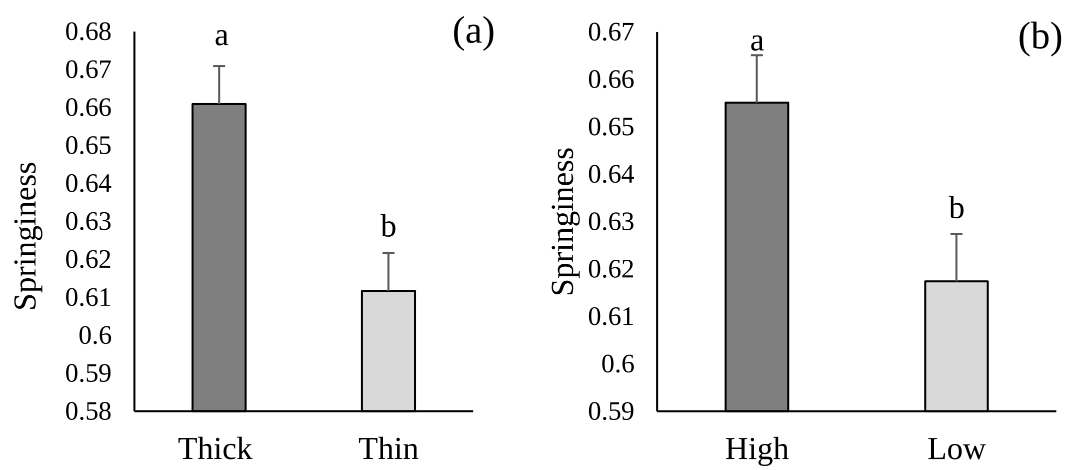

Figure 16. Springiness Values. Springiness of thick (38.1) and thin (17.6) steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. (a) Main effect of Steak Thickness was observed (P = 0.0018). (b) Main effect of Grill Surface Temperature was observed (P = 0.0137). Error bars represent pooled (largest) SEM. [ab]Columns lacking a common superscript differ (P < 0.05).

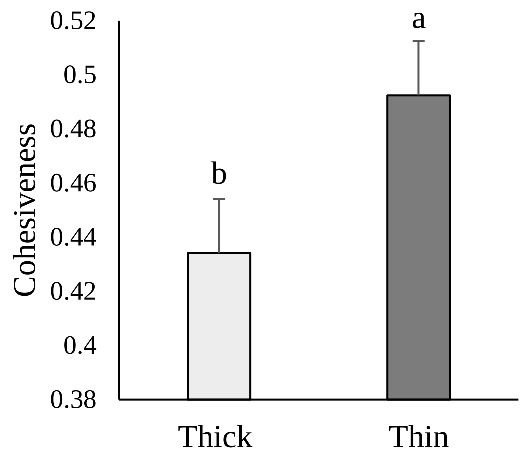

Figure 17. Cohesiveness Values. Cohesiveness values of thick (38.1) and thin (17.6) steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Main effect of Steak Thickness was observed (P = 0.0384). Error bars represent pooled (largest) SEM. [ab]Columns lacking a common superscript differ (P < 0.050).

RHEOLOGICAL RESULTS

Elastic Behavior

A three-way interaction (P = 0.0263; Figure 18) of USDA Quality Grade × steak thickness × grill surface temperature was seen for the elastic behavior of the center of steak samples. The most significant comparison of the interaction is among Choice steaks. Choice steaks cooked on a LST grill showed no difference among thicknesses but when cooked on a HST, thick steaks had much greater elastic nature than thin steaks. Select steaks did not exhibit any defining pattern among the treatments. The surface of steaks, although hardly a viscoelastic material compared to the center, still reflects the difference, in a two-way interaction of USDA Quality Grade × steak thickness (P = 0.0312; Figure 19), of elastic behavior among Choice steaks with thick steaks maintaining much greater elastic nature than thin steaks while Select steaks do not exhibit a difference (P > 0.05) among the thicknesses.

These results were almost identical to the viscous behavior of the steaks, but since meat is regarded as more of an elastic material than a viscous material and the elasticity modulus reflects this notion by being much greater than the viscosity modulus, only the elastic behavior of the steaks is shown.

Hardness values were correlated with the rheological parameters of the elasticity and viscosity moduli (Khiari et al, 214). A decrease in hardness is similar to a decrease in both moduli. Being that beef is more of a solid material the elastic behavior of the material is greater than the viscous behavior and therefore has more of an indicative relationship to TPA hardness values which was shown to be moderately correlated to the center elastic modulus ($r = 0.3810$; $P <0.05$). Rheology measurements were also shown to reflect differential scanning calorimeter (DSC) protein denaturation patterns and thus representative of myofibrillar protein states. A decrease in the elastic and viscous modulus of a meat sample is associated with a gel that is capable of retaining more water and therefore is a less elastic gel structure.

When comparing the textural and rheological data we see that the elastic modulus is very similar to the springiness of a steak but applied to the microstructure. Both the center and surface elastic moduli were greater in thicker samples at a HST. Choice thick steaks cooked on a HST had much greater values than thin steaks while Select steaks showed to difference among the treatment factors. This shows how the rheological testing of the samples helps to confirm the textural property results and helps to bridge the connection between texture, or tenderness, and what occurs in the proteins structure.

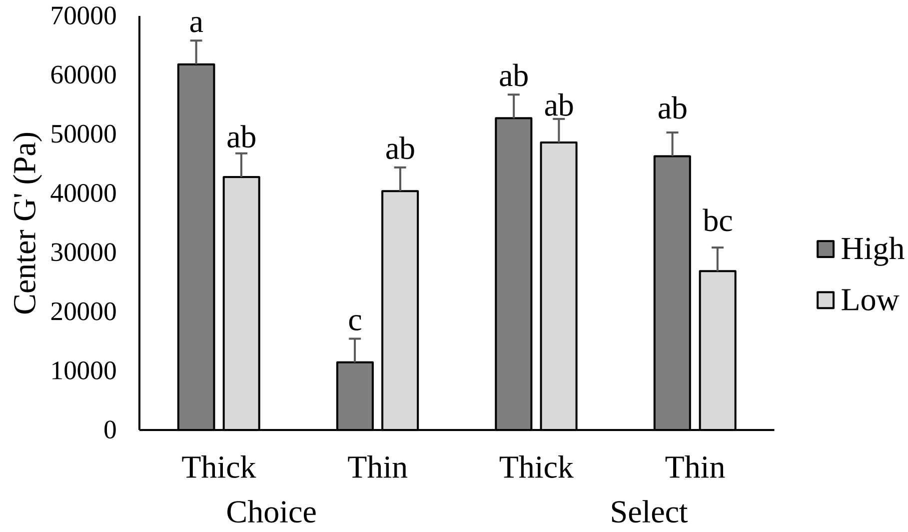

Figure 18. Center Elastic Modulus. Center elastic of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Three-way interaction of USDA Quality Grade × Steak Thickness × Grill Surface Temperature was observed ($P = 0.0263$). Error bars represent pooled (largest) SEM. [abc]Columns lacking a common super script differ ($P < 0.05$).

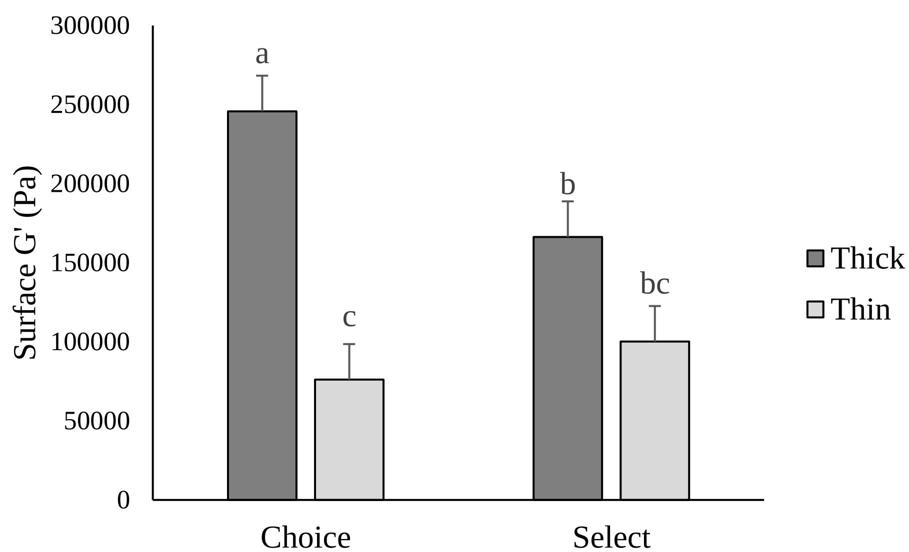

Figure 19. Surface Elastic Modulus. Surface elastic modulus of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Two-way interaction of USDA Quality Grade × Steak Thickness was observed ($P = 0.0312$). Error bars represent pooled (largest) SEM. [ab] Columns lacking a common super script differ ($P < 0.05$).

THERMAL RESULTS

Thermal Diffusivity and Conductivity

The thermal diffusivity and conductivity were found to have no significant difference among treatment factors ($P > 0.05$) for beef strip steaks of varying USDA Quality Grade, steaks thickness, and grill surface temperature.

Protein Denaturation

The protein denaturation patterns obtained from DSC thermograms were categorized into three specific groups of peaks. Peaks from 55 - 65°C, 70 - 75°C, and from 80 - 85°C. The denaturation peak from 70 - 75°C was found to have a 2-way interaction between steak thickness × grill surface temperature ($P = 0.0012$; Figure 20). Strip steaks at a HST showed no difference among thicknesses ($P > 0.05$) but did at a LST. Thick steaks at a LST had greater enthalpy than thin steaks.

The denaturation temperature of proteins that were found to degrade between 55-60°C were affected by a two-way interaction of steak thickness × grill surface temperature ($P = 0.0012$; Figure 21) and in a similar pattern as the enthalpy of proteins that degraded between 70-75°C but not as significantly where thick steaks cooked on a LST degraded at a later temperature as opposed to their thin counterparts. Fewer differences were determined for steaks cooked with HST, but thin steaks overall had more similar degradation temperatures, whereas HST thick steaks degraded much sooner than LST thick steaks. The enthalpy of proteins between 70-75°C ($r = 0.7166$; $P \leq 0.005$) as well as the denaturation temperature of proteins between 55-60°C ($r = 0.8328$; $P \leq 0.05$) were strongly correlated with the enthalpy of proteins between 80-85°C.

Being that the steaks were cooked to an internal degree of doneness of 71°C the majority of myosin has been degraded and the proteins that were still present in their natural state or some kind of aggregation were the sarcoplasmic proteins, collagen and actin which degrade between 60-80°C. Although myosin degrades around 40-60°C (Purslow et al, 1985; Tornberg, 2005) it could still be in some aggregation with other proteins which were shown to be affected by steak thickness and grill surface temperature. 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 beef strip steaks resulting in changes to the organoleptic perception of the product.

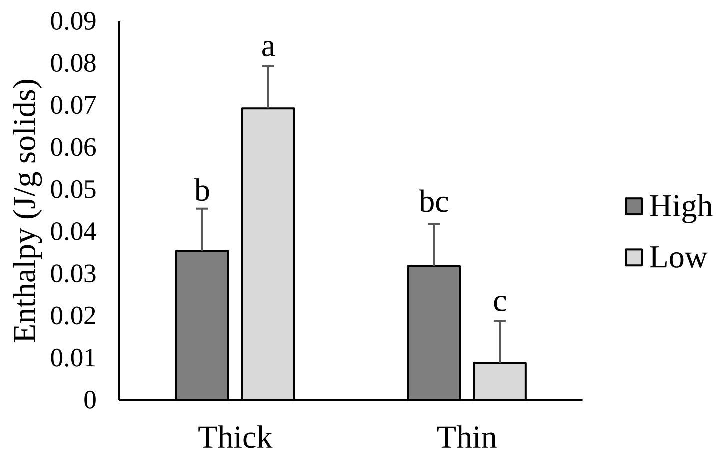

Figure 20. Enthalpy Values. Enthalpy (J/g solids) of protein denaturation at 70 – 75°C of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Two-way interaction of Steak Thickness × Grill Surface Temperature was observed ($P = 0.0012$). Error bars represent pooled (largest) SEM. [abc]Columns lacking a common super script differ ($P < 0.050$).

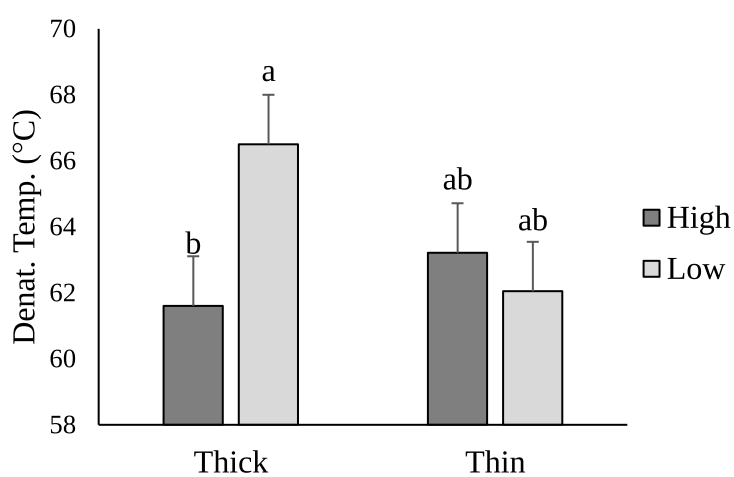

Figure 21. Denaturation Temperature Values. Temperature of protein denaturation at 55 – 60°C of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Two-way interaction of Thickness × Grill Surface Temperature was observed ($P = 0.0307$). Error bars represent pooled (largest) SEM. [abc]Columns lacking a common super script differ ($P < 0.050$).

PHYSICAL RESULTS

Expressible Moisture

The percent expressible moisture of strip steaks was found to have two significant main effects of steak thickness ($P = 0.0031$; Figure 22 (a)) and the grill surface temperature ($P = 0.0294$; Figure 22 (b)). Thick steaks had greater expressible moisture than thin steaks and steaks cooked at a LST had greater expressible moisture than at a HST.

Moisture loss during cooking impacts juiciness and it has been shown that the cooking temperature influences this loss (Berjerholm et al, 2014). It was found during this study that steaks cooked at a HST had lower expressible moisture as compared to being cooked at a low surface LST. Other studies (Tornberg, 2005; Berjerholm et al, 2014) that observed the gel structure of cooked beef and described it through the relative amount of protein aggregation showed that moisture loss increased as aggregation increased suggesting that cooking at a HST could lead to an increase in protein aggregation not associated with internal degree of doneness. An increase in protein aggregation has also been associated with greater force to penetrate the product or a decrease in tenderness (Tornberg, 2005).

Water Activity

Water activity was not found to have any significant difference among treatment factors ($P > 0.050$) for beef strip steaks of varying USDA Quality Grade, steaks thickness and grill surface temperature.

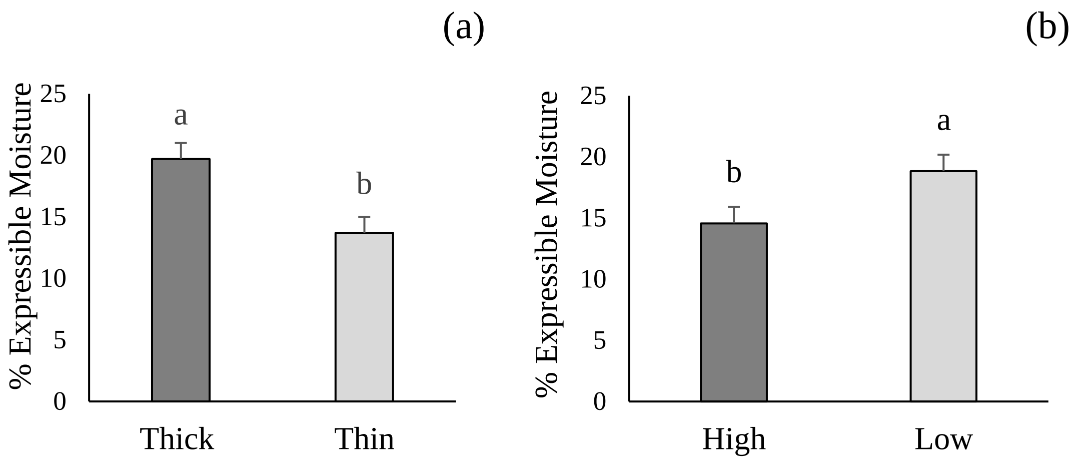

Figure 22. Expressible Moisture Values. Percent expressible moisture of thick (38.1mm) and thin (17.6mm) steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. (a) Main effect of Steak Thickness was observed ($P = 0.0031$). (b) Main effect of Grill Surface Temperature was observed ($P = 0.0294$). Error bars represent pooled (largest) SEM. [ab]Columns lacking a common superscript differ ($P < 0.050$).

Percent Change in Cooking Loss, Steak Thickness, and Ribeye Area

There were no differences found among the treatment factors ($P > 0.05$) for the percent change in cooking loss, steak thickness and ribeye area for beef strip steaks of varying USDA Quality Grade, steaks thickness and grill surface temperature.

CONCLUSION

The goal of this research was to identify how product type and cooking parameters, described by quality grade, steak thickness, and grill surface temperature, could affect the organoleptic properties of cooked beef and identify an ideal set of cooking parameters for optimum consumer experience. This experience can be defined by the three beef palatability characteristics which all must be fulfilled for overall consumer acceptance. This experiment specifically addressed two of these characteristics, tenderness and juiciness.

Although there was some conflicting data regarding some of the different treatment group combinations, there were two specific set of parameters that were undisputedly (with no negative attributes) the most favorable, and one that was the least favorable if analyzing the textural characteristics. When choosing Choice steaks, the data suggests to slice thick and cook with LST, but when choosing Select steaks, it is best to slice thick and cook with HST. Steaks with the least desirable textural characteristics were Select steaks sliced thin and cooked with HST.

The expressible moisture results, which help to support the juiciness characteristic, also suggest cooking thick steaks at a LST which combined with Choice steaks that have higher fat content, which is associated with increased juiciness, would lead to an overall suggestion for an ideal set of cooking parameters. With that in mind it should be taken into consideration that these cooking parameters are being analyzed at just one level of IDD, 71°C or medium-done, and further analysis of other IDDs such as well-done or rare could likely result in an entirely different set of ideal cooking parameters.

An interesting interaction that the cooking measurements bring up has a major influence on the microstructure and textural properties of beef steaks. The initial temperature before steaks were even cooked was shown to be affected by all treatments and was strong correlated to the final cook times which was strongly correlated to shear force values and the elastic nature of the surface of cooked steaks. Thick steaks were shown to have a lower shear force value than thin steaks while thick steaks had higher surface elastic moduli suggesting that although thick steaks required longer cooking times thus increasing their contact with the grill and increasing the crust formation on the surface this did not negatively impact the internal textural properties.

Although we cannot accurately deduce from the thermal (DSC) and rheological results exactly what is occurring in the protein states and microstructure of the cooked steaks it is apparent that there are some significant affects due to each of the cooking treatments. The protein states and stability described by the denaturation temperature and enthalpy of proteins at specific temperature ranges is shown to be affected by thickness and grill surface temperature enough that the microstructure described by the center and surface elastic modulus also depicts significant differences among all of the treatment groups. All of which are supported by the textural data actually presenting significant results that can be translated into an organoleptic eating experience as depicted above.

Previous research (Bertram et al, 2006; Brunton et al, 2006; Christensen et al, 2000; Ishiwatari et al, 2013; Tornberg, 2005) on the cooking of meat has focused on different cooking methods such as grilling, roasting or braising or on the protein states of meats cooked to varying in IDDs as well as the selection of different muscles. All have been shown to result in significant differences in the end product properties. This study removed all of those variables and identified how a single type of meat product, beef strip steaks, could be affected through simple changes that the consumer can make at home.

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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APPENDICES

APPENDIX: LIST OF TABLES

Table 1. Thick:Thin Ratio. Average Thick:Thin ratio of beef strip steaks of thick (38.1mm) and thin (17.6mm) steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures.

Quality Grade	**Surface Temp**	**Ratio**
Choice	High	2.38
	Low	2.92
Select	High	2.84
	Low	2.70

Table 2. Percent Moisture Content. Percent moisture content of centers of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures.

Quality Grade	**Steak Thickness**	**Surface Temp**	**%Moisture**	**SD**
Choice	Thick	High	62.19	2.70
		Low	63.74	1.17
	Thin	High	61.32	1.85
		Low	61.78	3.00
Select	Thick	High	66.14	3.46
		Low	66.23	0.53
	Thin	High	62.33	2.90
		Low	63.36	1.25

Table 3. Actual Grill Surface Temperature. LS Means of actual grill surface temperature (°F) of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Main effect of Grill Surface Temperature was observed ($P < 0.0001$; F-value = 7709.44). ^{abc}Means lacking a common super script differ ($P < 0.05$).

Surface Temp	**Temperature**	**SEM**
High	444.14^{a}	0.76
Low	352.50^{b}	0.72

Table 4. Initial Steak Temperature. LS Means of the initial steak temperature (°C) of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Two-way interaction of USDA Quality Grade × Grill Surface Temperature was observed (P = 0.0411; F-value = 5.07) and main effect of Steak Thickness (P = 0.0411; F-value = 5.07). [abc]Means lacking a common super script differ (P < 0.05).

Quality Grade	Surface Temp	Temperature	SEM
Choice	High	9.30[ab]	0.84
	Low	8.38[b]	0.79
Select	High	11.13[a]	0.84
	Low	7.10[b]	0.79
Thickness			
Thick		6.51[b]	0.58
Thin		11.44[a]	0.58

Table 5. Max Steak Temperature. LS Means of the max steak temperature (°C) of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Main effect of Steak Thickness was observed (P = 0.0262; F-value = 5.72). [abc]Means lacking a common super script differ (P < 0.05).

Surface Temp	Temperature	SEM
High	73.06[a]	0.30
Low	72.21[b]	0.29

Table 6. Time to Flip Steaks. LS Means of the time to flip steaks during cooking (seconds) of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Main effect of Steak Thickness was observed (P < 0.0001; F-value = 197.37). [abc]Means lacking a common super script differ (P < 0.05).

Thickness	Time	SEM
Thick	860.09[a]	36.51
Thin	134.62[b]	36.51

Table 7. Final Steak Cook Times. LS Means of the final steak cook time (seconds) of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Main effect of Steak Thickness was observed ($P < 0.0001$; F-value = 193.14). ^{abc}Means lacking a common super script differ ($P < 0.05$).

Thickness	**Time**	**SEM**
Thick	1638.12^{a}	62.32
Thin	413.33^{b}	62.32

Table 8. Warner-Bratzler Shear Force. LS Means of Warner-Bratzler shear force values (kgf) of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Main effect of Steak Thickness was observed ($P = 0.0067$; F-value = 13.85). ^{abc}Means lacking a common super script differ ($P < 0.05$).

Steak Thickness	**Shear force**	**SEM**
Thick	2.55^{b}	0.15
Thin	3.30^{a}	0.15

Table 9. Hardness. LS Means of hardness of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Three-way interaction of USDA Quality Grade × Steak Thickness × Grill Surface Temperature was observed ($P = 0.0227$; F-value = 6.33). ^{abc}Means lacking a common super script differ ($P < 0.05$).

Quality Grade	**Steak Thickness**	**Gill Surf. Temp.**	**Hardness**	**SEM**
Choice	Thick	High	6.70^{ab}	1.67
		Low	4.00^{b}	1.47
	Thin	High	4.66^{b}	1.47
		Low	4.64^{b}	1.47
Select	Thick	High	3.90^{b}	1.47
		Low	5.77^{b}	1.47
	Thin	High	11.10^{a}	1.67
		Low	4.88^{b}	1.47

Table 10. Resilience. LS Means of resilience of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Three-way interaction of USDA Quality Grade × Steak Thickness × Grill Surface Temperature was observed (P = 0.0138; F-value = 7.72). [abc]Means lacking a common super script differ (P < 0.05).

Quality Grade	Steak Thickness	Gill Surf. Temp.	Resilience	SEM
Choice	Thick	High	6.03[a]	0.99
		Low	4.52[ab]	0.88
	Thin	High	3.12[ab]	0.88
		Low	2.92[b]	0.88
Select	Thick	High	3.16[b]	0.88
		Low	5.97[a]	0.88
	Thin	High	5.54[ab]	0.99
		Low	3.73[ab]	0.88

Table 11. Chewiness. LS Means of chewiness (kg) of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Three-way interaction of USDA Quality Grade × Thickness × Grill Surface Temperature was observed (P = 0.0300; F-value = 5.67). [abc]Means lacking a common super script differ (P < 0.05).

Quality Grade	Steak Thickness	Grill Surf. Temp.	Chewiness	SEM
Choice	Thick	High	1.89[ab]	0.39
		Low	1.01[b]	0.45
	Thin	High	1.52[b]	0.45
		Low	1.41[b]	0.45
Select	Thick	High	1.36[b]	0.39
		Low	1.46[b]	0.45
	Thin	High	3.14[a]	0.45
		Low	1.33[b]	0.45

Table 12. Springiness. LS Means of springiness values of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. (a) Main effect of Steak Thickness was observed (P = 0.0018; F-value = 11.69). (b) Main effect of Grill Surface Temperature was observed (P = 0.0137; F-value = 6.87). [ab]Means lacking a common super script differ (P < 0.05).

Steak Thickness	Springiness	SEM
Thick	0.66[a]	0.01
Thin	0.62[b]	0.01
Grill Surface Temp.		
High	0.66[a]	0.01
Low	0.62[b]	0.01

Table 13. Cohesiveness. LS Means of cohesivenesss values of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Main effect of Steak Thickness was observed (P = 0.0384; F-value = 6.12). [ab]Means lacking a common super script differ (P < 0.05).

Steak Thickness	Cohesiveness	SEM
Thick	0.43[b]	0.02
Thin	0.49[a]	0.02

Table 14. Center Elastic Modulus. LS Means of center elastic modulus (Pa) of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Three-way interaction of USDA Quality Grade × Thickness × Grill Surface Temperature was observed (P = 0.0300; F-value = 5.67). [abc]Means lacking a common super script differ (P < 0.05).

Quality Grade	Steak Thickness	Grill Surf. Temp.	Chewiness	SEM
Choice	Thick	High	61831[a]	9453
		Low	42771[ab]	9453
	Thin	High	11434[c]	9453
		Low	40389[ab]	9453
Select	Thick	High	52699[ab]	9453
		Low	48588[ab]	9453
	Thin	High	46297[ab]	9453
		Low	26846[bc]	10579

Table 15. Surface Elastic Modulus. LS Means of surface elastic modulus (Pa) of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Two-way interaction of USDA Quality Grade × Steak Thickness was observed (P = 0.0312; F-value = 5.10). [abc]Means lacking a common super script differ (P < 0.05).

Quality Grade	Steak Thickness	Elasticity	SEM
Choice	Thick	245754[a]	22572
	Thin	76055[c]	22572
Select	Thick	166302[b]	22572
	Thin	100097[bc]	23941

Table 16. Enthalpy. LS Means of enthalpy (J/g solids) of protein denaturation at 70 – 75°C of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Two-way interaction of Steak Thickness × Grill Surface Temperature was observed (P = 0.0012; F-value = 13.47). [abc]Means lacking a common super script differ (P < 0.05).

Thickness	Surface Temp	Enthalpy	SEM
Thick	High	0.0355[a]	0.01
	Low	0.0693[b]	0.01
Thin	High	0.0318[c]	0.01
	Low	0.0088[b]	0.01

Table 17. Denaturation Temperature. LS Means of the protein denaturation temperature (°C) at 55 – 60°C of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. Two-way interaction of Steak Thickness × Grill Surface Temperature was observed (P = 0.0307; F-value = 6.17). [abc]Means lacking a common super script differ (P < 0.05).

Thickness	Surface Temp	Temperature	SEM
Thick	High	61.61[b]	1.37
	Low	66.50[a]	1.99
Thin	High	63.21[ab]	1.57
	Low	62.04[ab]	1.13

Table 18. Percent Expressible Moisture. LS Means of percent expressible moisture of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures. (a) Main effect of Steak Thickness was observed (P = 0.0031; F-value = 10.36). (b) Main effect of Grill Surface Temperature was observed (P = 0.0294; F-value = 5.23). [abc]Means lacking a common super script differ (P < 0.05).

Steak Thickness	**Exp. Moist. (%)**	**SEM**
Thick	19.70[a]	1.31
Thin	13.70[b]	1.31
Grill Surface Temp		
High	14.57[b]	1.36
Low	18.84[a]	1.28

Table 19. Cooking Measurements. Correlation values for cooking measurements of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures.

* means $P \leq 0.05$; ** means $P \leq 0.005$; *** means $P \leq 0.0005$

Legend: Tp(s) = grill surface temp; Tp(i) = steak initial temp; Tp(p) = steak flip temp; Tp(f) = steak final temp; Tp(m) = steak max temp; Ti(p) = flip cook time; Ti(f) = final cook time; %Th = %loss thickness; %Ck = %cook loss; %REA = %Loss REA; SH = shearforce; HA = hardness; CO = cohesiveness; RE = resilience; SP = springiness; CH = chewiness; AD = adhesion; %EM = %expressible moisture; WHC = water holding capacity; Aw = water activity; Td 55 = denat temp at 55-60°C; En 55 = enthalpy at 55-60°C; Td 70 = denat temp at 70-75°C; En 70 = enthalpy at 70-75°C; Td 80 = denat temp at 80-85°C; En 80 = enthalpy at 80-85°C; DI = diffusivity; CD = conductivity; Ce G' = center G'; Ce G" = center G"; Su G' = surface G'; Su G" = surface G".

	Tp(s)	Tp(i)	Tp(p)	Tp(f)	Tp(m)	Ti(p)	Ti(f)
Tp(s)							
Tp(i)	0.3158						
Tp(p)	-0.2389	0.2404					
Tp(f)	-0.2569	-0.1788	0.0385				
Tp(m)	0.3876*	0.1099	0.0995	0.1313			
Ti(p)	-0.0513	-0.6338***	-0.1622	0.2387	0.3206		
Ti(f)	-0.0255	-0.6212***	-0.1969	0.2270	0.0661	0.9078	
%Th	-0.0024	0.0362	0.3453*	-0.0450	-0.0275	-0.0147	-0.0681
%Ck	0.2807	0.1257	-0.0451	-0.0007	0.0475	0.0656	0.2048
%REA	0.0422	0.1658	0.0146	0.1208	0.3156	0.1151	-0.0054
SH	0.1217	0.5837***	-0.1291	-0.1195	-0.0415	-0.6012***	-0.5543**
HA	0.2128	0.2762	-0.0955	-0.0880	-0.1881	-0.1888	-0.0592
CO	0.2284	0.2907	0.1803	-0.2502	-0.0371	-0.3492*	-0.4174*
RE	0.0185	-0.1793	-0.2275	0.2258	-0.1235	0.1745	0.3838*
SP	0.3912*	-0.0210	-0.1012	0.1194	0.3148	0.4220*	0.4469***
CH	0.3182	0.3596*	-0.0614	-0.1235	-0.1911	-0.2411	-0.1278
AD	0.2874	0.1841	0.0396	-0.0670	0.1346	0.0179	-0.1300
%EM	-0.3100	-0.5454***	-0.2945	0.1198	-0.0189	0.4694**	0.3520*
Aw	0.3716*	-0.1239	-0.0365	-0.0126	0.3049	0.1937	0.2142
Td 55	-0.2235	0.0752	-0.2174	0.2524	-0.2752	0.0565	0.0610
En 55	-0.1086	-0.3223	-0.2460	-0.0066	-0.0223	0.3184	0.2200
Td 70	-0.0557	-0.1333	-0.2698	-0.2814	-0.0487	0.0407	0.0814
En 70	-0.0775	-0.4057	-0.2167	-0.0201	-0.2261	0.3930*	0.4938**
Td 80	0.5468*	0.3990	0.1597	-0.2331	0.4949	0.1206	-0.0951
En 80	-0.2806	-0.3162	-0.2122	0.3210	0.0146	0.0692	0.0635
DI	-0.0732	0.3259	-0.0356	-0.0465	0.1211	-0.2737	-0.3763*
CD	-0.2807	-0.1204	0.0543	-0.1386	-0.2005	-0.0429	-0.0715
Ce G'	0.0691	-0.0972	-0.1694	0.1822	0.0811	0.3939*	0.4535**
Ce G"	0.0801	-0.0758	-0.1562	0.1676	0.0807	0.3719*	0.4305
Su G'	0.1039	-0.5200	-0.2099	0.1999	-0.0014	0.6415***	0.6700***
Su G"	0.1199	-0.5082	-0.2044	0.1882	0.0008	0.6428***	0.6747***

Table 20. Physical Measurements. Correlation values for physical measurements of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures.

* means $P \leq 0.05$; ** means $P \leq 0.005$; *** means $P \leq 0.0005$

Legend: Tp(s) = grill surface temp; Tp(i) = steak initial temp; Tp(p) = steak flip temp; Tp(f) = steak final temp; Tp(m) = steak max temp; Ti(p) = flip cook time; Ti(f) = final cook time; %Th = %loss thickness; %Ck = %cook loss; %REA = %Loss REA; SH = shearforce; HA = hardness; CO = cohesiveness; RE = resilience; SP = springiness; CH = chewiness; AD = adhesion; %EM = %expressible moisture; WHC = water holding capacity; Aw = water activity; Td 55 = denat temp at 55-60°C; En 55 = enthalpy at 55-60°C; Td 70 = denat temp at 70-75°C; En 70 = enthalpy at 70-75°C; Td 80 = denat temp at 80-85°C; En 80 = enthalpy at 80-85°C; DI = diffusivity; CD = conductivity; Ce G' = center G'; Ce G" = center G"; Su G' = surface G'; Su G" = surface G".

	%Th	%Ck	%REA	%EM	Aw
Tp(s)	-0.0024	0.2807	0.0422	-0.31	0.3716*
Tp(i)	0.0362	0.1257	0.1658	-0.5454***	-0.1239
Tp(p)	0.3453	-0.0451	0.0146	-0.2945	-0.0365
Tp(f)	-0.045	-0.0007	0.1208	0.1198	-0.0126
Tp(m)	-0.0275	0.0475	0.3156	-0.0189	0.3049
Ti(p)	-0.0147	0.0656	0.1151	0.4694**	0.1937
Ti(f)	-0.0681	0.2048	-0.0054	0.3520*	0.2142
%Th					
%Ck	0.0242				
%REA	0.2807	-0.2684			
SH	-0.2327	0.0879	0.1907	-0.3446*	-0.1622
HA	0.1270	0.3546	0.0269	-0.5022**	-0.1545
CO	-0.2390	-0.1716	-0.0151	-0.0897	0.0755
RE	0.0584	0.3762*	-0.0441	-0.2981	-0.0952
SP	0.2280	0.1831	0.3038	-0.0468	0.1834
CH	0.0689	0.3006	0.0670	-0.5398***	-0.1161
AD	0.1696	-0.3756*	0.3562	0.1635	0.0513
%EM	-0.1798	-0.2608	-0.0322		
Aw	-0.1543	-0.1875	-0.1050	0.0894	
Td 55	-0.2940	0.1644	-0.2894	0.2072	-0.2695
En 55	-0.0900	0.0572	-0.0809	0.2412	0.1063
Td 70	-0.1780	-0.0617	-0.1848	-0.1000	0.0756
En 70	0.0207	-0.0950	-0.1444	0.0204	-0.0084
Td 80	0.0688	0.2118	0.3337	-0.3908	0.2101
En 80	-0.1069	-0.4584	-0.0929	-0.0244	-0.2297
DI	-0.0781	-0.2480	-0.1623	-0.0571	-0.2996
CD	-0.1203	-0.3006	-0.0417	0.2596	-0.0579
Ce G'	0.1164	0.0848	0.2135	-0.0295	-0.0092
Ce G"	0.1293	0.0941	0.2174	-0.0511	-0.0181
Su G'	0.0676	0.0455	0.0099	0.3415*	0.2940
Su G"	0.0742	0.0593	0.0110	0.3180	0.2914

Table 21. Textural Measurements. Correlation values for textural measurements of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures.
* means P ≤ 0.05; ** means P ≤ 0.005; *** means P ≤ 0.0005

Legend: Tp(s) = grill surface temp; Tp(i) = steak initial temp; Tp(p) = steak flip temp; Tp(f) = steak final temp; Tp(m) = steak max temp; Ti(p) = flip cook time; Ti(f) = final cook time; %Th = %loss thickness; %Ck = %cook loss; %REA = %Loss REA; SH = shearforce; HA = hardness; CO = cohesiveness; RE = resilience; SP = springiness; CH = chewiness; AD = adhesion; %EM = %expressible moisture; WHC = water holding capacity; Aw = water activity; Td 55 = denat temp at 55-60°C; En 55 = enthalpy at 55-60°C; Td 70 = denat temp at 70-75°C; En 70 = enthalpy at 70-75°C; Td 80 = denat temp at 80-85°C; En 80 = enthalpy at 80-85°C; DI = diffusivity; CD = conductivity; Ce G' = center G'; Ce G" = center G"; Su G' = surface G'; Su G" = surface G".

	SH	HA	CO	RE	SP	CH	AD
Tp(s)	0.1217	0.2128	0.2284	0.0185	0.3912*	0.3182	0.2874
Tp(i)	0.5837***	0.2762	0.2907	-0.1793	-0.0210	0.3596*	0.1841
Tp(p)	-0.1291	-0.0955	0.1803	-0.2275	-0.1012	-0.0614	0.0396
Tp(f)	-0.1195	-0.0880	-0.2502	0.2258	0.1194	-0.1235	-0.0670
Tp(m)	-0.0415	-0.1881	-0.0371	-0.1235	0.3148	-0.1911	0.1346
Ti(p)	-0.6012***	-0.1888	-0.3492*	0.1745	0.4220*	-0.2411	0.0179
Ti(f)	-0.5543***	-0.0592	-0.4174*	0.3838*	0.4469*	-0.1278	-0.1300
%Th	-0.2327	0.1270	-0.2390	0.0584	0.2280	0.0689	0.1696
%Ck	0.0879	0.3546	-0.1716	0.3762*	0.1831	0.3006	-0.3756*
%REA	0.1907	0.0269	-0.0151	-0.0441	0.3038	0.0670	0.3562
SH							
HA	0.1406						
CO	0.2119	-0.2097					
RE	0.0129	0.5584**	-0.6880***				
SP	-0.1786	0.0685	-0.2691	0.1193			
CH	0.2016	0.9591***	0.0381	0.3976*	0.0995		
AD	-0.1203	-0.2135	0.3250*	-0.6242***	0.3130	-0.0799	
%EM	-0.3446*	-0.5022**	-0.0897	-0.2981	-0.0468	-0.5398**	0.1635
Aw	-0.1622	-0.1545	0.0755	-0.0952	0.1834	-0.1161	0.0513
Td 55	0.1059	0.0269	-0.3803	0.1456	-0.0069	-0.1364	-0.0812
En 55	-0.1620	0.2229	-0.1373	0.3664	-0.2371	0.0651	-0.4997*
Td 70	0.0211	0.0047	-0.1882	0.2259	-0.1234	-0.1293	-0.1151
En 70	-0.3024	0.0931	-0.3725*	0.3621*	0.1091	-0.0593	0.0153
Td 80	0.1180	0.1021	0.2699	-0.1996	0.0409	0.2585	0.3137
En 80	-0.2053	-0.0282	-0.2369	0.1849	0.2095	-0.1095	-0.0965
DI	0.1472	-0.0313	0.3167	-0.2625	-0.3820*	0.0220	0.1077
CD	-0.1038	-0.2837	0.0596	-0.3379*	0.0958	-0.2543	0.1581
Ce G'	-0.0481	0.3810*	-0.2242	0.4128*	0.4522**	0.3643*	-0.1003
Ce G"	-0.0461	0.4046*	-0.2067	0.4032*	0.4379**	0.3889*	-0.1029
Su G'	-0.4122*	0.0183	-0.1906	0.2257	0.3474*	0.0047	0.0871
Su G"	-0.4134*	0.0404	-0.1864	0.2349	0.3519*	0.0276	0.0790

Table 22. Differential Scanning Calorimetry. Correlation values for differential scanning calorimetry measurements of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures.
* means $P \leq 0.05$; ** means $P \leq 0.005$; *** means $P \leq 0.0005$

Legend: Tp(s) = grill surface temp; Tp(i) = steak initial temp; Tp(p) = steak flip temp; Tp(f) = steak final temp; Tp(m) = steak max temp; Ti(p) = flip cook time; Ti(f) = final cook time; %Th = %loss thickness; %Ck = %cook loss; %REA = %Loss REA; SH = shearforce; HA = hardness; CO = cohesiveness; RE = resilience; SP = springiness; CH = chewiness; AD = adhesion; %EM = %expressible moisture; WHC = water holding capacity; Aw = water activity; Td 55 = denat temp at 55-60°C; En 55 = enthalpy at 55-60°C; Td 70 = denat temp at 70-75°C; En 70 = enthalpy at 70-75°C; Td 80 = denat temp at 80-85°C; En 80 = enthalpy at 80-85°C; DI = diffusivity; CD = conductivity; Ce G' = center G'; Ce G" = center G"; Su G' = surface G'; Su G" = surface G".

	Td 55	En 55	Td 70	En 70	Td 80	En 80
Tp(s)	-0.2235	-0.1086	-0.0557	-0.0775	0.5468*	-0.2806
Tp(i)	0.0752	-0.3223	-0.1333	-0.4057*	0.3990	-0.3162
Tp(p)	-0.2174	-0.2460	-0.2698	-0.2167	0.1597	-0.2122
Tp(f)	0.2524	-0.0066	-0.2814	-0.0201	-0.2331	0.3210
Tp(m)	-0.2752	-0.0223	-0.0487	-0.2261	0.4949	0.0146
Ti(p)	0.0565	0.3184	0.0407	0.3930*	0.1206	0.0692
Ti(f)	0.0610	0.2200	0.0814	0.4938**	-0.0951	0.0635
%Th	-0.2940	-0.0900	-0.1780	0.0207	0.0688	-0.1069
%Ck	0.1644	0.0572	-0.0617	-0.0950	0.2118	-0.4584
%REA	-0.2894	-0.0809	-0.1848	-0.1444	0.3337	-0.0929
SH	0.1059	-0.1620	0.0211	-0.3024	0.1180	-0.2053
HA	0.0269	0.2229	0.0047	0.0931	0.1021	-0.0282
CO	-0.3803	-0.1373	-0.1882	-0.3725*	0.2699	-0.2369
RE	0.1456	0.3664	0.2259	0.3621*	-0.1996	0.1849
SP	-0.0069	-0.2371	-0.1234	0.1091	0.0409	0.2095
CH	-0.1364	0.0651	-0.1293	-0.0593	0.2585	-0.1095
AD	-0.0812	-0.4997*	-0.1151	0.0153	0.3137	-0.0965
%EM	0.2072	0.2412	-0.1000	0.0204	-0.3908	-0.0244
Aw	-0.2695	0.1063	0.0756	-0.0084	0.2101	-0.2297
Td 55						
En 55	0.2659					
Td 70	0.4731*	0.2104				
En 70	0.4869*	0.1341	0.5799**			
Td 80	-0.7325	0.0886	-0.0727	-0.5154		
En 80	0.8328*	0.3654	0.1750	0.7166**	-0.5982*	
DI	0.2329	0.1487	0.0658	-0.1629	0.5188*	-0.1499
CD	-0.1156	-0.2179	-0.0907	0.1568	-0.3886	0.2517
Ce G'	-0.0209	0.0814	0.0138	0.1222	-0.0638	-0.0139
Ce G"	-0.0313	0.0937	-0.0012	0.1088	-0.0384	-0.0235
Su G'	-0.2058	-0.0544	-0.0175	0.0898	0.0360	-0.2376
Su G"	-0.2099	-0.0460	-0.0281	0.0817	0.0671	-0.2479

Table 23. Thermal and Rheometry Measurements. Correlation values for thermal and rheometry measurements of thick (38.1mm) and thin (17.6mm) beef strip steaks from two quality grades (USDA Choice and Select) cooked with high (232.2°C) and low (176.7°C) grill surface temperatures.
* means $P \leq 0.05$; ** means $P \leq 0.005$; *** means $P \leq 0.0005$

Legend: Tp(s) = grill surface temp; Tp(i) = steak initial temp; Tp(p) = steak flip temp; Tp(f) = steak final temp; Tp(m) = steak max temp; Ti(p) = flip cook time; Ti(f) = final cook time; %Th = %loss thickness; %Ck = %cook loss; %REA = %Loss REA; SH = shearforce; HA = hardness; CO = cohesiveness; RE = resilience; SP = springiness; CH = chewiness; AD = adhesion; %EM = %expressible moisture; WHC = water holding capacity; Aw = water activity; Td 55 = denat temp at 55-60°C; En 55 = enthalpy at 55-60°C; Td 70 = denat temp at 70-75°C; En 70 = enthalpy at 70-75°C; Td 80 = denat temp at 80-85°C; En 80 = enthalpy at 80-85°C; DI = diffusivity; CD = conductivity; Ce G' = center G'; Ce G" = center G"; Su G' = surface G'; Su G" = surface G".

	DI	CD	Ce G'	Ce G"	Su G'	Su G"
Tp(s)	-0.0732	-0.2807	0.0691	0.0801	0.1039	0.1199
Tp(i)	0.3259	-0.1204	-0.0972	-0.0758	-0.5200***	-0.5082***
Tp(p)	-0.0356	0.0543	-0.1694	-0.1562	-0.2099	-0.2044
Tp(f)	-0.0465	-0.1386	0.1822	0.1676	0.1999	0.1882
Tp(m)	0.1211	-0.2005	0.0811	0.0807	-0.0014	0.0008
Ti(p)	-0.2737	-0.0429	0.3939*	0.3719*	0.6415***	0.6428***
Ti(f)	-0.3763*	-0.0715	0.4535**	0.4305	0.6700***	0.6747***
%Th	-0.0781	-0.1203	0.1164	0.1293	0.0676	0.0742
%Ck	-0.2480	-0.3006	0.0848	0.0941	0.0455	0.0593
%REA	-0.1623	-0.0417	0.2135	0.2174	0.0099	0.0110
SH	0.1472	-0.1038	-0.0481	-0.0461	-0.4122*	-0.4134*
HA	-0.0313	-0.2837	0.3810*	0.4046*	0.0183	0.0404
CO	0.3167	0.0596	-0.2242	-0.2067	-0.1906	-0.1864
RE	-0.2625	-0.3379*	0.4128*	0.4032*	0.2257	0.2349
SP	-0.3820*	0.0958	0.4522**	0.4379**	0.3474*	0.3519*
CH	0.0220	-0.2543	0.3643*	0.3889*	0.0047	0.0276
AD	0.1077	0.1581	-0.1003	-0.1029	0.0871	0.0790
%EM	-0.0571	0.2596	-0.0295	-0.0511	0.3415*	0.3180
Aw	-0.2996	-0.0579	-0.0092	-0.0181	0.2940	0.2914
Td 55	0.2329	-0.1156	-0.0209	-0.0313	-0.2058	-0.2099
En 55	0.1487	-0.2179	0.0814	0.0937	-0.0544	-0.0460
Td 70	0.0658	-0.0907	0.0138	-0.0012	-0.0175	-0.0281
En 70	-0.1629	0.1568	0.1222	0.1088	0.0898	0.0817
Td 80	0.5188*	-0.3886	-0.0638	-0.0384	0.0360	0.0671
En 80	-0.1499	0.2517	-0.0139	-0.0235	-0.2376	-0.2479
DI						
CD	-0.1051					
Ce G'	-0.0416	-0.2842				
Ce G"	-0.0375	-0.3065	0.9977			
Su G'	-0.2957	-0.3658*	0.5428**	0.5189**		
Su G"	-0.2961	-0.3878*	0.5597**	0.5384**	0.9983***	