

Hey good looking, how have you been cooking? The role of cooking method on cooked color
and palatability of beef steaks

by

Greta Elizabeth Huber

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College of Agriculture

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Manhattan, Kansas

Approved by:

Major Professor
Dr. Erin Beyer

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Abstract

Cooking method and degree of doneness (DOD) are crucial in determining beef palatability, affecting key sensory attributes such as juiciness, tenderness, flavor, and color. While various cooking methods are commonly used to prepare beef, their impact on appearance at different DOD remains a point of interest. Consumers often rely on both internal and external color to assess doneness which shapes their expectations and overall eating experience. Thus, the objective of this study was to determine the palatability and appearance differences between six cooking methods and two DODs. Paired beef strip loins were denuded into the *Longissimus lumborum* (LL) and sliced into 2.54-cm. thick steaks, then randomly assigned one of six cooking methods (Sous Vide, Oven, Grill, Flat-top, Clamshell, or Air Fryer) and a DOD (medium rare [MR] or well done [WD]). Steaks were thawed for 24 hours and then cooked to their designated DOD. Consumers ($N = 96$ per DOD, $N = 192$ total) evaluated six samples using a 100-point line scale for juiciness, tenderness, flavor, overall liking, and overall appearance. Acceptability (acceptable/unacceptable) was determined for each trait. Consumers were asked about the visual expectations by determining (yes/no) if the steak's appearance matched the expected DOD. The steaks assigned for lab assays were used to measure SSF, cook loss, objective color traits, and multiple myoglobin chemistry assays. Consumers determined Oven steaks were juicier and more tender ($P < 0.05$) than all other cooking methods, although overall liking did not differ ($P > 0.05$). Across methods, MR steaks were consistently rated higher ($P < 0.05$) than WD for juiciness, tenderness, flavor, and appearance, except for Flat-top flavor ratings. Consumers rated Oven and Flat-top steaks higher ($P < 0.05$) than all other cooking methods but similar ($P > 0.05$) to Grill steaks. Flat-top steaks had least amount ($P < 0.05$) of myoglobin denaturation than all other cooking methods. However, there were no differences ($P > 0.05$) observed for MRA

within cooking methods, but as DOD increased, MRA levels decreased ($P < 0.05$). The MR Oven, MR Air fryer and MR Clamshell had the higher ($P < 0.05$) a^* values than all other treatments but were similar to MR Flat-top steaks. This study highlighted a common discrepancy between objective and subjective measures with subjective measures connecting to the differences in consumer opinions of appearance ratings. Cooking method influenced appearance ratings and visual expectations of DOD. These results suggest that despite similar endpoint temperatures, differences in internal and external color influenced consumer perception and acceptability of not only the appearance, but potentially other palatability traits.

Keywords: cooking method, degree of doneness, palatability, cooked color

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Dedication

This thesis is dedicated to my parents. Mom and Dad, I am so thankful for your continuous support, encouragement, and enthusiasm in my endeavors.

Chapter 1 - Review of Literature

Introduction

Meat color is an important attribute that influences consumer perception from purchase through consumption. In raw meat, color serves as a primary indicator of freshness and wholesomeness and is a major driver of purchasing decisions. Discoloration during retail display contributes substantially to product discounting and economic loss, highlighting the importance of understanding the mechanisms governing color stability. Although raw meat color has been extensively researched, the processes that translate these mechanisms into cooked color outcomes remain less understood.

Cooked color represents the final visual cue consumers rely on to assess degree of doneness and expected eating quality. While internal temperature defines degree of doneness, consumers frequently depend on visual color cues, which can vary due to muscle characteristics, biochemical properties, and cooking conditions. Much of the existing research on cooking method has focused on tenderness and palatability rather than visual appearance. Therefore, a more comprehensive understanding of how raw meat color mechanisms, degree of doneness, and cooking method interact to influence cooked color is needed.

Raw meat color

Understanding raw meat color is essential for interpreting the color changes that occur across different degrees of doneness (DOD) in addition to using different cooking methods. Raw meat color is one of the most heavily studied areas in meat science, and for good reason, as it is a primary factor influencing consumer purchasing decisions (Mancini and Hunt, 2005). Consumers often use meat color as a visual cue for freshness and wholesomeness, despite the fact that changes in color are not primarily driven by bacterial growth (Seideman et al., 1984). At the

retail level, discoloration contributes substantially to product discounting, food waste, and economic loss, with estimated losses reaching \$3.7 annually in the U.S. (Mancini and Hunt, 2005; Ramanathan et al., 2022). Because meat color is widely used as an indicator of shelf-life and freshness, identifying strategies to maintain color stability and extend shelf-life has been a research focus for several decades. Although significant advancements have been made, gaps remain within the industry, particularly in color stability.

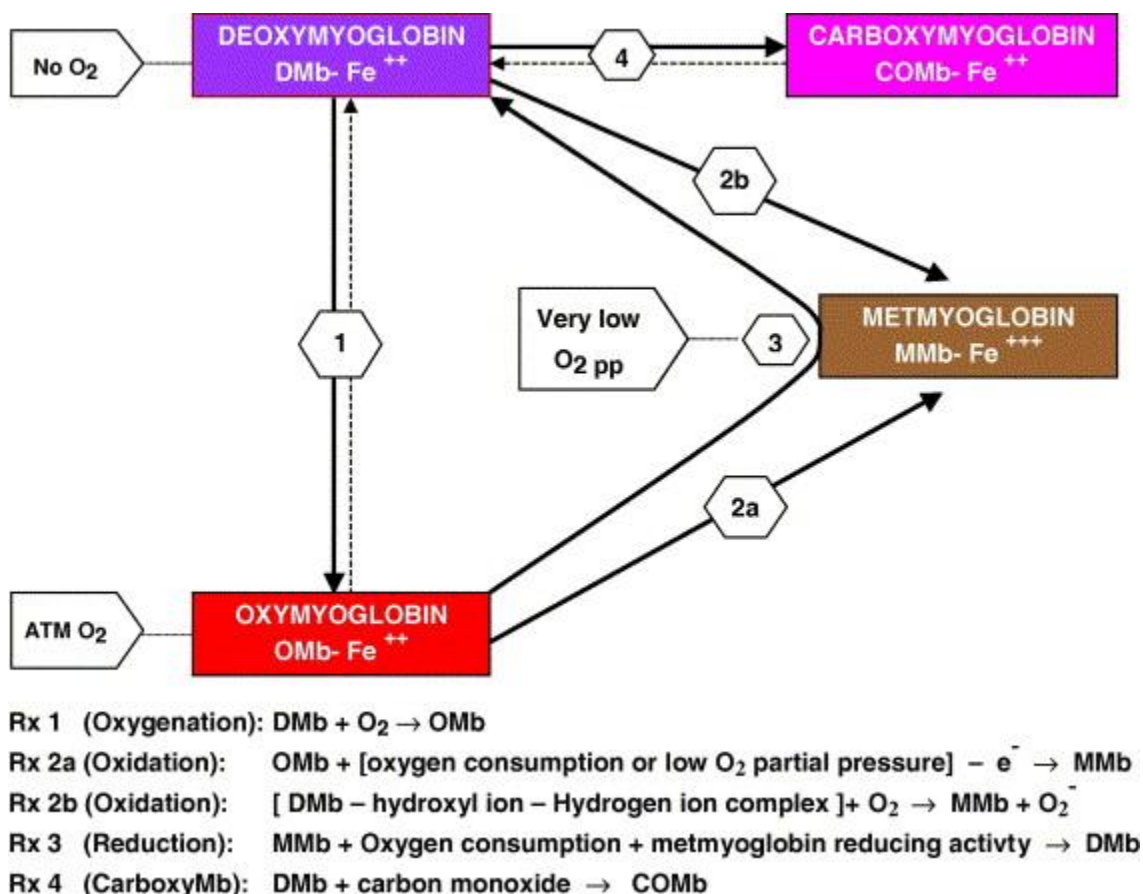
Meat color is largely driven by the behavior of a single molecule: myoglobin (Mb) (Mancini and Hunt, 2005). Myoglobin functions as an oxygen-binding protein in muscle, serving as an oxygen reserve in living tissue while also determining the color and pigment forms in meat products post-mortem (Mancini and Hunt, 2005). In the live animal, oxygen is transported from the lungs to muscle by hemoglobin in blood; because myoglobin has a greater affinity for oxygen, oxygen is transferred from hemoglobin to myoglobin and retained within the muscle (Seideman et al., 1984). Following harvest of an animal, myoglobin no longer serves a physiological role but continues to interact with oxygen in the environment, binding atmospheric oxygen in fresh meat. Although the function of myoglobin differs between living and post-mortem systems, it continues its fundamental role as an oxygen-binding molecule.

In fresh meat, myoglobin can exist in several pigment forms, which are determined by both the oxidative state of the heme iron and the ligand bound at the sixth coordination site (Suman and Joseph, 2013; Bekhit and Faustman, 2005). The most commonly observed forms include deoxymyoglobin (DMb), oxymyoglobin (OMb), carboxymyoglobin (CMb), and metmyoglobin (MetMb) (Mancini and Hunt, 2005; Suman and Joseph, 2013). These pigment states are dynamic and can shift in response to a range of intrinsic and extrinsic factors, including packaging environment, oxygen availability and affinity, metmyoglobin-reducing activity

(MRA), ligand availability, and the structural properties of the myoglobin molecule itself (Mancini and Hunt, 2005). The interaction of these factors, combined with the inherent complexity of myoglobin chemistry, contributes to the challenge of understanding and controlling raw meat color.

The role of myoglobin in meat color is closely tied to its molecular structure. Myoglobin contains a heme group with a central iron atom that is capable of binding different molecules depending on the surrounding environment (Mancini and Hunt, 2005). Most of the iron's bonding sites are fixed within the heme structure; however, one site remains available and can reversibly bind ligands such as oxygen, carbon monoxide, or water (Suman and Joseph, 2013; Mancini and Hunt, 2005). The pigment form of myoglobin, and therefore the color of raw meat, is primarily determined by two factors: the ligand bound at this available site and the oxidation state of the iron (Suman and Joseph, 2013; Bekhit and Faustman, 2005). Iron can exist in a reduced ferrous (Fe^{2+}) state or an oxidized ferric (Fe^{3+}) state, with each state contributing to distinct color outcomes. Once meat is exposed to oxygen, predictable color changes occur as myoglobin transitions among pigment forms, commonly described by the color stability triangle (Mancini and Hunt, 2005).

Figure 1.1. Visible myoglobin redox interconversions on the surface of meat (Mancini and Hunt, 2005).



The color stability triangle, adapted from Mancini and Hunt (2005), illustrates the dynamic transitions among myoglobin pigment forms in fresh meat. Prior to oxygen exposure, myoglobin primarily exists as deoxymyoglobin (DMb), which gives meat a purplish appearance. Upon exposure to atmospheric oxygen, oxygenation occurs during the bloom period as oxygen binds to the available coordination site on the heme iron, forming oxymyoglobin (OMb) and producing the characteristic bright cherry-red color associated with freshness (Mancini and Hunt, 2005). Although oxygen binding does not immediately oxidize the iron, interactions with the distal histidine alter myoglobin function and stabilize the ferrous (Fe²⁺) state through resonance within

the OMb structure, making DMb more susceptible to oxidation (Mancini and Hunt, 2005; Bekhit et al., 2019). In the presence of carbon monoxide, myoglobin can also form carboxymyoglobin (CMb), a highly stable ferrous pigment that produces a bright red color and resists oxidation more effectively than OMb due to the strong affinity of carbon monoxide for the heme iron (Mancini and Hunt, 2005). Despite the desirability of bright red pigments at retail, oxidation of the heme iron from Fe^{2+} to Fe^{3+} inevitably occurs under oxygen-limited or prolonged display conditions, resulting in the formation of metmyoglobin (MetMb) and visible browning or discoloration (Bekhit et al., 2019). Metmyoglobin can be reduced back to DMb through metmyoglobin-reducing activity (MRA); however, this process is limited by factors such as autooxidation rate, availability of reducing equivalents including NADH, and enzymatic activity within the muscle (Bekhit and Faustman, 2005; Bekhit et al., 2019). Consequently, strategies that enhance MRA, or stabilize ferrous myoglobin forms, have been identified as potential approaches to improving meat color stability and extending shelf-life.

Although myoglobin chemistry defines the pigment forms responsible for raw meat color, maintaining these desirable states over time requires an active reducing system. This dependence on metabolic processes highlights the importance of mitochondrial function in supporting metmyoglobin reduction and overall color stability.

Mitochondrial role in meat color

Mitochondria are double membrane bound organelles that are responsible for cellular respiration (Ramanathan & Mancini 2018). It is often assumed that mitochondria lose functionality soon after harvest as oxygen delivery from the circulatory system ceases. However, research has demonstrated that mitochondria continue to metabolize oxygen in postmortem

muscle (Ramanathan & Mancini 2018). This prolonged activity enables mitochondria to continue contributing to raw meat color stability during storage and retail display.

The influence of mitochondria on raw meat color is largely mediated through oxygen consumption rate (OCR) and metmyoglobin-reducing activity (MRA). Metmyoglobin-reducing activity is essential for maintaining desirable meat color, as it enables the conversion of brown metmyoglobin (MetMb) back to deoxymyoglobin (DMb), thereby extending color shelf-life. Two major pathways contribute to MRA: an electron-transport-mediated, non-enzymatic pathway and an NADH-dependent reductase pathway (Zhu et al., 2009).

Muscle composition and fiber type strongly influence MRA activity (Bekhit et al., 2019; Mancini et al., 2018). Muscles with a greater proportion of oxidative fibers that are rich in mitochondria, allows MRA to persist for longer periods postmortem (Suman et al., 2013; Van Bibber-Krueger et al., 2020). As a result, MRA is often greater in muscles with higher mitochondrial content and directly impacted by the leading fiber type. However, higher MRA does not necessarily translate to improved color stability, as other mitochondrial processes also influence meat color. For example, the Longissimus dorsi (LD) has demonstrated greater color stability and higher a^* values during display compared with the Psoas major (PM), despite the PM being a more oxidative muscle (Mancini et al., 2018). This suggests that color stability is governed by a balance of multiple factors rather than MRA alone.

Oxygen consumption rate is another critical mitochondrial mechanism influencing raw meat color. OCR reflects the amount of atmospheric oxygen utilized by mitochondria in postmortem muscle (Mancini et al., 2018). Because mitochondria remain active during storage, they directly compete with myoglobin for available oxygen. High OCR limits oxygen availability at the myoglobin surface, favoring DMb and increasing susceptibility to oxidation

and MetMb formation (Van Bibber-Krueger et al., 2020; Mancini et al., 2018). Excessively high OCR can result in rapid discoloration, with meat exhibiting either dark purplish or brown appearances that negatively influence consumer acceptance (Van Bibber-Krueger et al., 2020; Mancini et al., 2018).

Similar to MRA, OCR is closely linked to muscle and fiber type. More oxidative muscles generally exhibit higher OCR due to increased mitochondrial density and activity, making them more color-labile during display (Suman et al., 2013; Mancini et al., 2018; Van Bibber-Krueger et al., 2020). Even subtle differences in fiber type distribution within a single muscle can influence OCR. Von Bibber-Krueger et al. (2020) demonstrated that differences between the anterior and posterior regions of the LD were sufficient to alter OCR and subsequent color stability. This variability within the muscle emphasizes that relatively small shifts in mitochondrial density or metabolic activity are sufficient to impact oxygen dynamics and color stability during retail display.

Muscle pH further regulates mitochondrial activity and contributes to variation in raw meat color. Higher pH enhances mitochondrial function, resulting in increases in both OCR and MRA (Kiyimba et al., 2021; Ramanathan et al., 2014). Although increased MRA may appear beneficial, elevated OCR under high-pH conditions promotes oxygen depletion at the meat surface and increases DMb vulnerability to oxidation. Additionally, higher pH increases water-holding capacity, leading to a darker meat appearance (Huff-Lonergan & Lonergan, 2005). These combined effects are most evident in dark-cutting beef. Kiyimba et al. (2021) reported higher mitochondrial activity, OCR, and MRA in dark-cutting beef compared with normal beef, highlighting the integral role of mitochondria in this condition. While the role of glycogen

depletion in dark-cutting beef is well established, mitochondrial involvement in color development remains less explored.

Collectively, OCR and MRA demonstrate the complex and sometimes opposing roles of mitochondria in raw meat color stability. Increased mitochondrial activity enhances MRA but simultaneously elevates OCR, creating a balance that ultimately determines color stability. Muscles classified as color-stable, such as the LD, typically exhibit relatively high MRA combined with moderate OCR, rather than extreme mitochondrial activity (Suman et al., 2013). In contrast, color-labile muscles tend to display high OCR and insufficient MRA. Due to this intricate relationship, improving color stability through mitochondrial pathways remains an active area of research.

Additional factors impacting raw meat color and stability

Raw meat color stability is governed by a complex interaction of biochemical, structural, and environmental factors that extend beyond mitochondrial activity alone. While muscle type, ultimate pH, and fiber composition are primary determinants of color stability, additional mechanisms contribute to the development, maintenance, and deterioration of raw meat color during storage all the way through retail display.

Myoglobin concentration is pivotal to raw meat color (Huffman, 1980). Variation in total myoglobin content among muscles, species, and individual animals influences both the intensity of redness and the susceptibility of meat to oxidative discoloration (Faustman & Cassens, 1990; Mancini & Hunt, 2005). Although higher myoglobin concentration can enhance redness, it also increases the amount of protein available for oxidation of oxymyoglobin to metmyoglobin, particularly under prolonged oxygen exposure (Suman et al., 2013; Hasan et al., 2021).

Postmortem muscle structure and water-holding capacity further influence raw meat color by altering light scattering and oxygen diffusion at the meat surface (Huff-Lonergan & Lonergan, 2005). Structural changes associated with rigor development, protein denaturation, and pH decline affect how light interacts with muscle tissue, contributing to darker or paler appearances independent of myoglobin chemistry (Huff-Lonergan & Lonergan, 2005; Mancini & Hunt, 2005).

Lipid oxidation is closely linked to pigment oxidation and plays a significant role in raw meat discoloration (Faustman et al., 2010). Oxidative products derived from lipids can accelerate myoglobin oxidation, creating a reinforcing cycle in which lipid and pigment oxidation progress simultaneously (Faustman et al., 2010). This interaction becomes increasingly important during extended storage and retail display, particularly under conditions that promote oxidative stress (Faustman et al., 2010).

Environmental conditions during storage and retail display play a critical role in raw meat color stability by influencing oxidation rates and oxygen availability at the meat surface. Temperature is one of the most influential external factors, as elevated temperatures accelerate both myoglobin and lipid oxidation, leading to more rapid discoloration during display (Mancini et al., 2024). Even short disruptions in the cold chain can increase oxidative activity and reduce subsequent color shelf-life (Mancini et al., 2024). Light exposure further contributes to discoloration through photooxidative mechanisms. Retail lighting promotes the formation of reactive oxygen species that accelerate the conversion of oxymyoglobin to metmyoglobin, particularly in oxygen-rich environments (Cooper et al., 2016; Mancini & Hunt, 2005). The extent of light-induced discoloration depends on light intensity, duration of exposure, and packaging system (Cooper et al., 2016).

Surface moisture and relative humidity also influence color stability. Increased surface moisture can initially enhance oxymyoglobin formation but may promote oxidation and discoloration during extended display (Denzer et al., 2023). Packaging environment interacts with these environmental factors by regulating oxygen availability throughout storage and display. High-oxygen systems promote bright, cherry red color initially but often accelerate oxidative discoloration under lighted retail conditions, whereas low-oxygen, like vacuum packaging, systems favor deoxymyoglobin and darker appearances (Calkins & Buford, 2005).

Overall, raw meat color stability reflects the combined influence of intrinsic muscle properties and extrinsic environmental conditions during storage and retail display. Temperature control, light exposure, surface moisture, and packaging environment, among others directly affect oxidation processes contributing to variability in color development and discoloration. Consistent management of these is essential for maintaining color stability across muscles and retail systems.

Cooked color and cooked color stability

Meat color is one of the strongest drivers of consumer purchasing decisions and strongly influences perception of meat quality at the retail level (Prill et al., 2019b; Bekhit and Faustman, 2005). This perception however extends beyond the retail case and carries all the way through to the final cooked product, where visual appearance continues to shape consumer expectations of eating quality. Research has demonstrated that sensory perception is influenced not only by different palatability traits, but also by visual cues such as color, which can significantly affect consumer palatability ratings (Imram, 1999; Prill et al., 2019b). Although cooked color may appear to be a simple outcome of cooking, it represents a highly complex system influenced by different biochemical reactions, muscle characteristics, and cooking conditions. Cooked color

primarily results from heat-induced denaturation of myoglobin and subsequent formation of denatured hemichrome pigments (Hunt et al., 1999; King & Whyte, 2006). As temperature increases, myoglobin transitions from its native red or pink forms to brown and gray pigments, producing the characteristic internal color changes associated with increasing degrees of doneness (Hunt et al., 1999; King & Whyte, 2006). This denaturation process occurs progressively with thermal exposure, and the extent of pigment transformation depends on heating rate, temperature distribution, and state of myoglobin during cooking (King & Whyte, 2006). Consequently, steaks cooked to similar endpoint temperatures may still exhibit variability in internal color expression.

In contrast to raw meat color, which has been extensively researched and characterized, cooked color remains under-researched and therefore less understood. Historically, research emphasis has been placed on cooked palatability traits such as tenderness, juiciness, and flavor due to their importance on consumer satisfaction (Drey et al., 2019; Prill et al., 2019a; Prill et al., 2019b). As consumers primarily rely on raw meat color for purchasing decisions due to the direct economic impact, cooked color has received comparatively less attention. However, cooked color is the final visual cue observed prior to consumption and may strongly influence perceived doneness, quality, and overall eating experience.

Numerous intrinsic factors contribute to variability in cooked color development. Muscle type influences cooking behavior due to differences in fiber composition. Yancey et al. (2016) observed a muscle effect, noting a decrease in a^* values as DOD increased was expressed within the *longissimus thoracis* and *semimembranosus* muscles, but was not expressed within the *infraspinatus* muscle (Yancey et al., 2016). Beyer et al., 2024 reports that the potential interaction between muscle and DOD could be explained by inherent differences in intrinsic

factors such as pH, moisture content, and oxidation levels of different muscles at the time of cooking (Beyer et al., 2024). It is also important to note the lack of understanding for cooked color with whole muscle cuts compared to ground muscle. Ryan et al. (2006) reported that approximately 80% myoglobin denaturation was required to achieve a well-done degree of doneness appearance in ground beef, whereas a study conducted by Beyer et al. (2024) indicated that only about 70% denaturation was necessary for whole muscle steaks. This discrepancy may be attributed to fundamental differences between ground meat products and intact whole muscle cuts, including variations in structure, oxygen exposure, and heat transfer characteristics. These findings suggest that relationships between myoglobin denaturation and cooked color established in ground beef cannot be directly extrapolated to whole muscle products. Although ground beef and whole muscle cuts do share common myoglobin chemistry, evaluating cooked color development separately from whole muscle to fully understand myoglobin transformations during cooking is necessary.

Extrinsic factors, particularly cooking conditions, strongly influence cooked color outcomes. Differences in heating rate, surface temperature, and thermal gradients among cooking methods can produce different internal colors, even when steaks reach similar endpoint temperatures (Yancey et al., 2011). In addition to initial cooked color development, the stability of cooked color following thermal processing is an important yet understudied aspect of meat quality. Cooked steaks often undergo continued temperature increase due to the continued rise in temperature after removal from the heat source, which can further promote myoglobin denaturation and additional color change during rest periods. Furthermore, exposure of cooked meat to oxygen, following slicing or serving, has the potential to influence pigment state and surface appearance over time. Huber et al. (2025) reported interactions for both lightness (L^*)

and redness (a^*) values, indicating that different muscles respond uniquely to increasing thermal exposure. The *semitendinosus* exhibited greater lightness compared with the *longissimus lumborum* at medium rare and medium DOD, whereas no differences among muscles were observed at the well-done level. Redness values further highlighted muscle-specific behavior, with the *longissimus lumborum* maintaining greater a^* values across increasing degrees of doneness compared with the *semitendinosus*. These findings support previous work demonstrating that muscle characteristics influence cooked color outcomes and suggest that muscle-specific properties such as myoglobin concentration and heat transfer dynamics contribute to variability in cooked color expression (Beyer et al., 2024).

Cooked color stability following slicing was also shown to vary by degree of doneness and time. Huber et al. (2025) found higher oxymyoglobin (OMb) percentages in medium-rare samples when compared with medium and well-done samples, indicating there was a greater ability to maintain redness at lower cooking levels. Additionally, lightness values increased over time following slicing, with the greatest L^* values observed at later time points, suggesting that cooked color continues to develop after cooking due to residual heat and oxygen exposure. As a whole, these results demonstrate that cooked color and its stability are dynamic processes influenced by multiple interacting factors, further emphasizing the complexity of cooked color systems and the need for continued research across more muscles as well as different cooking methods. Despite the practical relevance of all of these post-thermal changes, limited research has evaluated the mechanisms governing cooked color stability over time.

Overall, cooked color represents a complex outcome of myoglobin denaturation, muscle structure, biochemical properties, and cooking conditions; meanwhile, cooked color stability is how well meat maintains its color after being sliced (Huber et al., 2025). Although substantial

progress has been made in understanding raw meat color mechanisms, significant gaps remain in knowledge regarding cooked color development and stability. Given the strong influence of visual cues on consumer perception and eating experience, greater emphasis on cooked color and its stability is warranted. Improved understanding of these processes may enhance consistency in visual appearance, reduce discrepancies between perceived and actual doneness, and ultimately improve consumer satisfaction.

Degree of doneness

Cooked color most commonly applied through the varying DODs. Degrees of doneness for meat, particularly beef, were developed to standardize the cooking process based on the relationship between internal temperature, color, and key palatability traits (tenderness, juiciness, flavor) to maximize palatability for consumers across the board. According to the American Meat Science Association (AMSA), beef degree of doneness (DOD) is defined by the final internal temperature reached during cooking rather than by visual color or cooking time (AMSA, 2016). However, there is considerable variability in the temperatures associated with common DOD classifications, including rare, medium-rare, medium, medium-well, and well-done (Prill et al., 2019a). Across different sources, recommended temperatures for these categories can differ by more than 10°C (Beef It's What's for Dinner, Certified Angus Beef, Char-Broil, What's Cooking America, Food Network Kitchen; Prill et al., 2019a). In addition, steaks typically continue to increase in temperature by approximately 5°C or more after being removed from the heat source (AMSA, 2016). This continued rise in temperature adds further confusion, as some guidelines account for this rise while others do not clearly specify it. To address this inconsistency, the National Cattlemen's Beef Association (NCBA), in collaboration with AMSA and the USDA Agricultural Research Service, developed a Beef Steak Color Guide that pairs

visual color indicators with internal temperatures. Developed over more than 35 years of research, this guide is widely recognized as the standard reference for defining beef DOD (NCBA, 2016). Prill et al., 2019a, developed a similar guide for the representation of the DODs that was evaluated by both chefs and consumers in that study. They can be compared below.



Figure 1.2 Photographic image depicting an approximate temperature for very rare, rare, medium rare, medium, well done, and very well done beef steaks. A color guide adapted by NCBA Beef Checkoff, 2016.

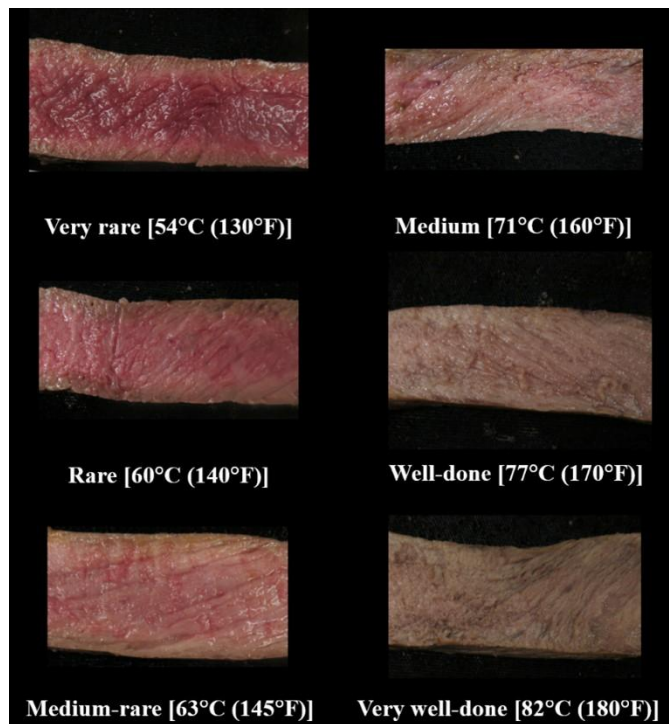


Figure 1.3 Representative degree of doneness images evaluated by consumers and chefs (Prill et al., 2019a).

Overall, the premise of developing DODs was to provide consumers with a consistent eating experience while also ensuring wholesomeness. A study done by Prill et al., 2019b evaluated the impact of DOD on beef palatability ratings of strip loin steaks cooked to multiple DOD using consumers with various DOD preferences under both red and white-lighting, and to assess the impact of both under- and overcooking on beef palatability ratings. They found that when consumers evaluated steaks under red lighting, where degree of doneness (DOD) was visually masked, few differences were observed in palatability ratings among individuals with different DOD preferences across multiple cooking levels. However, when samples were assessed under white lighting and visual cues were available, consumer perception of DOD significantly influenced sensory ratings. In general, steaks cooked to lower degrees of doneness received higher palatability scores, while overcooked steaks consistently resulted in reduced sensory ratings, regardless of individual DOD preference. These findings suggest that serving steaks slightly under the target DOD may enhance overall eating quality and improve consumer

satisfaction in restaurant settings (Prill et al., 2019b). The color changes depicted in the images above are the main indicators of quality for consumers and thus is important that they be met.

It is also important to note that DOD is commonly communicated to consumers through descriptive color cues, including terms such as cool red center and warm pink center, with consumers often cutting into the product to visually confirm doneness. Cooked color associated with DOD is an important indicator of doneness and the quality changes that occur across cooking levels, but it is not always completely reliable. Along with the major impact of degree of doneness on cooked color, cooking method is the next most influential factor affecting palatability that remains within the consumer's control.

Despite the use of standardized temperature guidelines and visual color references, variability in cooked color expression at a given DOD remains a persistent challenge. Factors such as muscle composition, myoglobin concentration, pH, and rate of heat transfer can influence the extent of myoglobin denaturation and subsequent color development during cooking. As a result, steaks cooked to identical internal temperatures may exhibit noticeably different internal color appearances, potentially leading to consumer misinterpretation of doneness and quality. This inconsistency has important implications for both consumer satisfaction and food safety perception. Such discrepancies highlight the limitations of relying solely on visual cues to assess doneness and emphasize the need to better understand the mechanisms governing cooked color development.

Cooking method likely plays a significant role in shaping these color outcomes by influencing heating rate, moisture loss, and surface temperature gradients. Different cooking systems may promote distinct patterns of myoglobin denaturation and internal color progression, even when steaks reach similar endpoint temperatures. While degree of doneness remains the

primary driver of cooked color change, the interaction between DOD and cooking method has not been fully characterized. Therefore, evaluating how various cooking methods influence cooked color development across degrees of doneness is essential for improving consistency in visual appearance and aligning consumer expectations with actual doneness. Greater understanding of these relationships may help reduce variability in cooked color outcomes and enhance the reliability of visual cues used by consumers to assess beef quality.

Cooking method

Consumers utilize a wide range of cooking methods to prepare meat products, with the end goal of achieving desirable eating quality and visually appealing product. Cooking method is one of the primary factors under consumer control and plays a critical role in determining the extent of thermal exposure experienced by meat, which in turn influences cooked color and appearance. Broadly, cookery methods can be categorized into dry heat and moist heat systems. Dry heat methods involve the direct application of high temperatures through conduction, convection, or radiant heat, such as grilling, pan-frying, broiling, and oven cooking (Vierck, 2020). In contrast, moist heat cookery relies on liquid as the primary heat transfer medium at comparatively lower temperatures, including methods such as braising and stewing (Vierck, 2020).

Dry heat cookery methods are more commonly used by consumers than moist heat methods, particularly for whole muscle beef cuts (Savell et al., 1999). These methods typically expose meat surfaces to higher temperatures and greater oxygen availability, conditions that promote rapid myoglobin denaturation and subsequent changes in cooked color development. As internal temperature increases, myoglobin transitions from its native state to denatured pigments, resulting in the progressive shift from red and pink hues to brown and gray coloration

characteristic of higher degrees of doneness (Hunt et al., 1999). The intensity and uniformity of this color change can vary among cooking methods due to differences in heat transfer efficiency, surface temperature, and moisture loss.

Despite the importance of cooking method in shaping cooked appearance, much of the existing literature has historically focused on tenderness rather than visual attributes (Powell et al., 2000; Lawrence et al., 2001; Boles and Swan, 2002; Herring and Rogers, 2003; Jeremiah and Gibson, 2003; Obuz et al., 2003; McKenna et al., 2004; Yancey et al., 2011; Yancey et al., 2016; Fabre et al., 2018). Comparatively fewer studies have evaluated how different cooking methods influence cooked color development and stability at similar degrees of doneness (García-Segovia et al., 2007; Yancey et al., 2011; Kim et al., 2025). Given that consumers frequently rely on cooked color as an indicator of doneness and perceived quality, understanding the effects of various cooking methods on color outcomes is essential. Differences in heating rate, surface dehydration, and thermal gradients among cooking systems may contribute to variation in myoglobin denaturation patterns and internal color expression, even when steaks are cooked to the same endpoint temperature.

Cooking, and therefore cooked color development, is strongly influenced by the rate and efficiency of heat transfer, which can vary based on product composition and muscle characteristics. Differences in quality grade are largely attributed to variation in intramuscular fat content, which can alter thermal conductivity and heating patterns within steaks, potentially influencing the extent and uniformity of myoglobin denaturation during cooking (Legako et al., 2015). Greater fat content may slow heat penetration in some regions of the steak, contributing to differences in internal cooked color expression at similar endpoint temperatures.

In addition to quality grade, muscle type has a direct impact on cooked meat characteristics, including color development and visual appearance. Variations in muscle fiber type, fiber orientation, and connective tissue content influence heat transfer and moisture retention during cooking, which can affect the rate of myoglobin denaturation and subsequent color change (Hunt et al., 2014; Legako et al., 2015). Muscles from locomotive portions of the carcass, such as the round and chuck, often contain greater connective tissue and may experience slower or less uniform heating, particularly when cooked using dry heat methods. In contrast, supportive muscles such as the *longissimus dorsi* and *psoas major* typically exhibit more rapid and uniform thermal exposure, allowing for more predictable cooked color development across degrees of doneness (Yancey et al., 2011).

Although much of the existing research examining quality grade and muscle type has focused primarily on tenderness and overall palatability, comparatively limited work has evaluated how these factors interact with cooking method to influence cooked color and appearance. Given that consumers frequently rely on visual cues such as internal color to assess doneness and product quality, further investigation into how muscle characteristics and heat transfer dynamics affect cooked color outcomes is warranted.

Conclusion:

Meat color is governed by complex biochemical, structural, and environmental interactions that influence both raw and cooked appearance. In fresh meat, myoglobin chemistry and mitochondrial activity play central roles in determining pigment transitions and color stability during storage and display. These processes are further affected by a multitude of intrinsic and extrinsic factors.

Following cooking, color development is primarily driven by heat-induced myoglobin denaturation and structural changes within meat. Although degree of doneness provides a standardization linking internal temperature to expected color outcomes, considerable variability exists in cooked color expression within each DOD. Cooking method further influences these outcomes by altering heating rate, moisture loss, and thermal gradients, contributing to differences in myoglobin denaturation and internal color.

Overall, the literature demonstrates that both intrinsic muscle properties and cooking conditions interact to shape cooked color development. A greater understanding of how cooking methods influence cooked color and cooked color stability is essential for improving consistency in visual appearance and aligning with consumer expectations.

References

- AMSA. 2016. Research guidelines for cookery, sensory evaluation, and instrumental tenderness measurements of meat. 2nd ed. American Meat Science Association, Champaign, IL.
- Bekhit, A. E. D., and C. Faustman. 2005. Metmyoglobin reducing activity. *Meat Science* 71(3):407–439.
- Bekhit, A. E. D., J. D. Morton, Z. F. Bhat, and L. Kong. 2019. Meat color: Factors affecting color stability. *Encyclopedia of Food Chemistry* 2:202–210.
- Beyer, E. S., K. J. Farmer, E. G. Kidwell, S. G. Davis, K. M. Harr, M. D. Chao, M. D. Zumbaugh, J. L. Vipham, M. C. Hunt, and T. G. O’Quinn. 2024. Change in myoglobin denaturation and physiochemical properties among three degrees of doneness and three beef whole muscles. *Meat and Muscle Biology* 8(1):16919.
- Boles, J. A., and J. E. Swan. 2002. Heating method and final temperature affect processing characteristics of beef semimembranosus muscle. *Meat Science* 62:107–112.
- Calkins, C. R., and M. L. Buford. 2005. Packaging effects on shelf-life and sensory traits of enhanced beef. *Nebraska Beef Cattle Reports* 155:1–4.
- Cooper, J. V., B. R. Wiegand, A. B. Koc, L. Schumacher, I. Grün, and C. L. Lorenzen. 2016. Impact of contemporary light sources on oxidation of fresh ground beef. *Journal of Animal Science* 94(10):4457–4462.
- Denzer, M. L., M. Pfeiffer, G. G. Mafi, and R. Ramanathan. 2023. Metabolomics and bioinformatic analyses to determine the effects of oxygen exposure within longissimus lumborum steak on beef discoloration. *Journal of Animal Science* 101:skad155.
- Drey, L. N., Prill, L. L., Olson, B. A., Rice, E. A., Gonzalez, J. M., Vipham, J. L., Houser, T. A., Boyle, E. A., & O’Quinn, T. G. (2019). Evaluation of marbling and enhancement’s

- abilities to compensate for reduced beef palatability at elevated degrees of doneness. *Journal of Animal Science*, 97(2), 669-686.
- Fabre, R., et al. 2018. Cooking method effect on Warner–Bratzler shear force of different beef muscles. *Meat Science* 138:10–14.
- Faustman, C. 2014. Myoglobin chemistry and modifications that influence color and color stability. *Proceedings of the Reciprocal Meat Conference* 67:1–6.
- Faustman, C., Q. Sun, R. Mancini, and S. P. Suman. 2010. Myoglobin and lipid oxidation interactions: mechanistic bases and control. *Meat Science* 86(1):86–94.
- García-Segovia, P., A. Andrés-Bello, and J. Martínez-Monzó. 2007. Effect of cooking method on mechanical properties, color and structure of beef muscle (M. pectoralis). *Journal of Food Engineering* 80(3):813–821.
- Hasan, M. M., V. Sood, C. Erkinbaev, J. Paliwal, S. Suman, and A. Rodas-Gonzalez. 2021. Principal component analysis of lipid and protein oxidation products and their impact on color stability in bison longissimus lumborum and psoas major muscles. *Meat Science* 178:108523.
- Herring, J. L., and R. W. Rogers. 2003. Evaluation of cooking methods on various beef steaks. *Journal of Muscle Foods* 14:163–171.
- Huber, G. E., T. M. Dieball, N. T. Acosta Castellanos, K. M. Gundersen, K. R. Maddock Carlin, M. D. Chao, J. L. Vipham, M. D. Zumbaugh, T. G. O’Quinn, and E. S. Beyer. 2025. The impact of degree of doneness, muscle source, and bloom time on cooked color and cooked color stability. *Kansas Agricultural Experiment Station Research Reports* 11:Article 8678.

- Huff-Lonergan, E., and S. M. Lonergan. 2005. Mechanisms of water-holding capacity of meat: The role of postmortem biochemical and structural changes. *Meat Science* 71(1):194–204.
- Huffman, D. L. 1980. Processing effects on fresh and frozen meat color. *Proceedings of the Reciprocal Meat Conference* 33:1–11.
- Hunt, M. C., O. Sørheim, and E. Slinde. 1999. Color and heat denaturation of myoglobin forms in ground beef. *Journal of Food Science* 64:847–851.
- Hunt, M. R., et al. 2014. Consumer assessment of beef palatability from four beef muscles from USDA Choice and Select carcasses. *Meat Science* 98:1–8.
- Imram, N. 1999. The role of visual cues in consumer perception and acceptance of food products. *Nutrition & Food Science* 99:224–230.
- Jeremiah, L. E., and L. L. Gibson. 2003. Cooking influences on the palatability of roasts from the beef hip. *Food Research International* 36:1–9.
- Kim, J., Y. Zhang, Y. Han, Y. Lee, et al. 2025. The impact of cooking methods on the texture and color characteristics of beef, pork, and chicken. *Food Science and Preservation* 32(2):246–259.
- King, N. J., and R. Whyte. 2006. Does it look cooked? A review of factors that influence cooked meat color. *Journal of Food Science* 71(4):R31–R40.
- Kiyimba, F., S. D. Hartson, J. Rogers, D. L. VanOverbeke, G. G. Mafi, and R. Ramanathan. 2021. Changes in glycolytic and mitochondrial protein profiles regulate postmortem muscle acidification and oxygen consumption in dark-cutting beef. *Journal of proteomics* 232:104016.

- Lawrence, T. E., D. A. King, E. Obuz, E. J. Yancey, and M. E. Dikeman. 2001. Evaluation of belt grill, convection oven, and electric broiler cookery methods for beef tenderness research. *Meat Science* 58:239–246.
- Legako, J. F., et al. 2015. Consumer palatability scores and volatile beef flavor compounds of USDA quality grades and muscles. *Meat Science* 100:291–300.
- Mancini, R. A., and M. C. Hunt. 2005. Current research in meat color. *Meat Science* 71(1):100–121.
- Mancini, R. A., K. Belskie, S. P. Suman, and R. Ramanathan. 2018. Muscle-specific mitochondrial functionality and its influence on fresh beef color stability. *Journal of Food Science* 83:2077–2082.
- Mancini, R. A., M. C. Hunt, K. A. Hachmeister, D. H. Kropf, R. Feuz, D. E. Johnson, and R. Ramanathan. 2024. Combined effects of storage and display conditions on ground beef color and economic losses. *Meat and Muscle Biology* 8(1):18171.
- McKenna, D. R., D. A. King, and J. W. Savell. 2004. Comparison of clamshell cookers and electric broilers on cooking traits and shear force repeatability. *Meat Science* 66:225–229.
- NCBA. 2016. Beef steak color guide. National Cattlemen’s Beef Association, Centennial, CO.
- Obuz, E., M. E. Dikeman, and T. M. Loughin. 2003. Effects of cooking method and holding conditions on beef tenderness. *Meat Science* 65:841–851.
- Powell, T. H., M. E. Dikeman, and M. C. Hunt. 2000. Tenderness and collagen composition of semitendinosus roasts cooked by convective methods. *Meat Science* 55:421–425.
- Prill, L. L., et al. 2019a. Profiling the impact of visual degree of doneness on palatability ratings of beef strip loin steaks. *Meat and Muscle Biology* 3(2):10683.

- Prill, L. L., et al. 2019b. Visual degree of doneness impacts beef palatability for consumers with differing preferences. *Meat and Muscle Biology* 3(1):0024.
- Ramanathan, R., et al. 2022. Economic loss and environmental impact due to beef discoloration. *Meat and Muscle Biology* 6(1):13218.
- Ramanathan, R., and R. A. Mancini. 2018. Role of mitochondria in beef color. *Meat and Muscle Biology* 2(1).
- Ryan, S. M., M. Seyfert, M. C. Hunt, and R. A. Mancini. 2006. Influence of cooking rate and temperature on internal color of ground beef patties. *Journal of Food Science* 71:C216–C221.
- Savell, J. W., et al. 1999. Cooking method and degree of doneness effects on beef satisfaction. *Journal of Animal Science* 77:645–652.
- Seideman, S. C., S. H. Cohen, and J. V. Schollmeyer. 1984. Factors influencing ante-mortem muscle changes. *Food Structure* 3(2):Article 4.
- Suman, S. P., and P. Joseph. 2013. Myoglobin chemistry and meat color. *Annual Review of Food Science and Technology* 4:79–99.
- Van Bibber-Krueger, C. L., A. M. Collins, K. J. Phelps, T. G. O’Quinn, T. A. Houser, K. K. Turner, and J. M. Gonzalez. 2020. Effects of quality grade and intramuscular location on beef semitendinosus muscle fiber characteristics, NADH content, and color stability. *Journal of Animal Science* 98(4):skaa078.
- Vierck, K. R. 2020. Effects of dry heat cookery method on beef strip loin steaks of two quality grades following sous vide preparation. PhD Dissertation, Texas Tech University.
- Vierck, K. R., J. F. Legako, and J. C. Brooks. 2021. Evaluation of dry-heat cookery method on volatile flavor compound development. *Meat and Muscle Biology* 5(1):20.

- Yancey, J. W., J. K. Apple, and M. C. Wharton. 2016. Cookery method and endpoint temperature effects on shear force and cooked color. *Journal of Animal Science* 94:4434–4446.
- Yancey, J. W., M. C. Wharton, and J. K. Apple. 2011. Cookery method and endpoint temperature effects on longissimus steaks. *Meat Science* 88:1–7.
- Zhu, J., F. Liu, X. Li, and R. Dai. 2009. Effect of succinate sodium on the metMb reduction and color stability of beef patties. *Journal of agricultural and food chemistry* 57:5976-5981.

Chapter 2 - Hey good looking, how have you been cooking? The role of cooking method on cooked color and palatability of beef steaks

Introduction

Meat color is widely recognized as one of the most important attributes for consumers, spanning from purchase through consumption (Beyer et al., 2024b; Prill et al., 2019a). While raw meat color has been extensively studied, the cooked color of whole muscles remains relatively underexplored. Cooked color refers to the visual appearance of a steak, both internally and externally (Beyer et al., 2024b). This trait directly impacts the eating experience by shaping consumer expectations of quality (Prill et al., 2019b). Importantly, cooked color is the final pigment state at the time of consumption rather than the initial internal color that most strongly influences consumer perception (Garber et al., 2000). Because of its central role in consumer satisfaction and perceived product quality, further research on cooked color is warranted to fully understand its impact.

Cooked color also represents a continuum of degrees of doneness, each carrying specific consumer expectations (Prill et al., 2019b). The concept of DOD was developed to standardize consistency in steak preparation, whether ordered at restaurants or cooked at home (Prill et al., 2019a). Defined by a range of internal peak temperatures from rare to well-done, these categories generally correspond with predictable internal colors (Prill et al., 2019a). The DOD is particularly important because it aligns with consumer preferences for flavor, texture, juiciness, and color, all of which contribute to the overall eating experience (Prill et al., 2019b).

Cooking is the single most important factor that can influence the eating experience once a steak is selected at retail. While DOD has a major impact on palatability, the cooking method is equally influential. Cooking method is one of the primary factors that consumers have control

over in producing a highly palatable beef product for consumption (Vierck et al., 2021). Besides intrinsic carcass factors like marbling content and muscle source that are well known factors influencing eating experience, along with DOD, cooking method is the next most influential factor for palatability.

While there are some studies that have evaluated the impact of cooking method on beef flavor and other palatability attributes, internal or external color remains unmeasured. Different heat-transfer mechanisms and surface heating profiles can produce steaks that reach the same DOD yet differ in surface browning, internal color, and external appearance, differences consumers readily perceive as changes in palatability (Miller et al., 2023; Sepulveda et al., 2019; Prill et al., 2019b). While various cooking methods are commonly used to prepare beef, their impact on palatability and appearance at different DODs remains a point of interest. Therefore, the goal of this study was to determine the palatability and appearance differences between six cooking methods and two degrees of doneness on beef steaks.

Materials and Methods

The procedures for the use of human subjects in the sensory panel evaluations in this study were approved by the Kansas State University (KSU) Institutional Review Board (IRB 7440.10; July 2025).

Product collection and fabrication

Paired beef strip loins ($N = 12$) grading USDA Choice were collected at a midwestern commercial beef processing plant and transported to Kansas State University. Strip loins were denuded into the *Longissimus lumborum* (LL) and sliced into 2.54-cm. thick steaks. Twelve steaks were randomly assigned one of six cooking methods (Sous Vide, Oven, Grill, Flat-top, Clamshell, or Air Fryer) and one of two DODs (medium rare [MR] or well-done [WD]) by

numbering the steaks beginning at the anterior end. Twelve steaks from each DOD were reserved for Sliced Shear Force (SSF) or laboratory assays. Once labeled and vacuum sealed, steaks were aged for 21 days at 4°C in the absence of light, then frozen and held at -40°C until use.

Cooking procedures

Prior to cooking, all steaks were thawed under refrigeration for 24 hours at a temperature of 2–4°C to ensure even and consistent internal temperatures during thermal preparation. Following thawing, steaks were cooked using one of six methods: Air Fryer, Oven, Flat-Top, Clamshell, Grill, or Sous Vide. Each cooking method was carefully standardized to ensure repeatability and accurate comparisons between treatments. Steaks were cooked to either a medium rare (MR) or well-done (WD) degree of doneness chosen to represent both ends of the DOD range, with internal temperatures verified using calibrated thermocouples or digital thermometers as detailed below.

Steaks designated for air frying were cooked at 204°C using a preheated air fryer (Chefman ExacTemp 5-Quart Air Fryer, Mahwah, NJ). Internal temperatures were continuously monitored using a Type K ThermoWorks thermocouple probe (ThermoWorks Q Series High Temp 64mm Probe, American Fork, UT) inserted into the geometric center of each steak. Steaks were flipped once during cooking, with MR steaks flipped at an internal temperature of 32°C and WD steaks at 46°C. Cooking continued until internal target temperatures of 58°C for MR and 74°C for WD were reached, steaks were removed from the air fryer, and final endpoint temperatures were recorded.

Both oven (Blodgett Dual Oven Flow, Essex Junction, VT) and grill (Char-Broil Grill2Go x200, Columbus, GA) steaks were prepared at an ambient cooking temperature of 177°C. Steaks were flipped once during the cooking process, with MR steaks turned at 29°C and

WD steaks at 35°C. Cooking proceeded until internal temperatures reached 58°C for MR and 75°C for WD, where steaks were removed from the heat. Final endpoint temperatures were monitored using a Thermapen digital thermometer to ensure consistency across replicates.

Flat-top (Model: 351GCPG48M, Cooking Performance Group, Lancaster, PA) steaks were cooked at 177°C, with surface temperature verified using an infrared thermometer. Cast iron steak weights (8 × 4 in, 1.18 kg) were used to ensure even cooking throughout, as well as assisting in an efficient cook time. MR steaks were flipped at an internal temperature of 29°C and removed at 57°C, while WD steaks were flipped at 32°C and removed at 74°C. Internal temperatures were recorded using a Thermapen inserted into the geometric center of each steak.

Clamshell (Cuisinart Griddler Deluxe clam-shell style grill, Stamford, Connecticut, USA) steaks were cooked at 177°C between two heated plates without flipping, allowing for the simultaneous cooking of both sides. Steaks were monitored using a Thermapen thermometer and removed once internal temperatures of 57°C (MR) or 74°C (WD) were achieved.

Sous vide (Anova Sous Vide Precision Cooker, San Francisco, CA) steaks were vacuum-sealed, placed in food-grade plastic bags, and submerged in a water bath maintained at a constant temperature of 57°C for MR and 68°C for WD. All sous vide samples were cooked for one hour. Following the water bath, steaks were removed from their packaging and seared on a preheated flat-top at 177°C for approximately 30 seconds per side. After searing, internal temperatures were measured using a Thermapen, with MR steaks removed from the flat-top at 60°C and WD steaks at 75°C.

For all cooking methods, endpoint temperatures were verified by inserting a Thermapen digital thermometer into the geometric center of each steak. Final internal temperature targets

were 62.8°C for MR and 76.7°C for WD, consistent with industry standards for MR and WD DODs.

Consumer sensory panel evaluation

Consumers ($n = 96$ per DOD, $N = 192$ total) evaluated six samples, one per cooking method within each DOD. Consumer sensory panels were conducted and fed similar to previous panels held at KSU (Beyer et al., 2024a; Decker et al., 2024; Farmer et al., 2022; Prill et al., 2019a; Prill et al., 2019b). Samples were cooked as described above. Steaks were cooked to an internal peak temperature of 62.8°C for MR and 76.7°C for WD, sliced into 1×1 -cm cubes, and served to each group of consumers. The consumers were given unsalted crackers, water, and apple juice as palate cleansers.

The consumers were asked to evaluate the palatability traits of samples for tenderness, juiciness, flavor liking, overall liking, and overall appearance as well as indicate if each sensory trait was acceptable (acceptable/unacceptable). The palatability traits were measured on a 0 to 100 line-scale with 0 representing not tender, not juicy, or dislike extremely, and 100 representing very tender, very juicy, or like extremely. The consumers were also asked if the sample presented met their visual expectations for the DOD being fed (MR or WD). If consumers answered no, they were asked what DOD (very rare, rare, medium-rare, medium, medium-well, well-done, very well-done) they would choose to best represent the sample. If they answered yes, it met their expectations, they were to select N/A. The consumer sensory panel data was collected similarly to descriptive panel data, on the same electronic tablets (Lenovo TB-8505F, Morrisville, NC) using Qualtrics (Version 2417833; Qualtrics Software, Provo, UT).

Objective measurements

Before cooking, samples were removed from their packaging, blotted dry, and weighed. Steaks were cooked according to the cooking procedures above. Once peak temperatures were recorded, steaks were weighed to calculate cook loss and immediately prepared and sliced for slice shear force (SSF) using the approved method from the American Meat Science Association (AMSA, 2016). A 2.54-cm wide cut was made parallel to the muscle fibers in the lateral portion of the steak to measure the SSF and internal color using a Hunterlab Miniscan Spectrophotometer (Illuminant A, 2.54 cm aperture, 10° observer, Hunter Lab Associates Laboratory, Reston, VA). After a 3-min bloom time measured with a timer, 3 readings were taken in different locations within the internal cut surface, and an average of L^* , a^* , and b^* values were recorded. The relative percentages of metmyoglobin, oxymyoglobin, and deoxymyoglobin were determined using spectral data according to the AMSA Color Guidelines (King et al., 2023). After the color readings were recorded, the steaks were immediately chopped and frozen in liquid nitrogen, then blended (Waring Products, New Hartford, CT) into powder for future assays and held in a -80°C freezer.

Myoglobin denaturation

Myoglobin denaturation was determined using the protocol in the AMSA Color Guidelines (King et al., 2023). Approximately 0.3 g of the powdered sample was weighed and added to a centrifuge tube with ceramic beads to aid homogenization. 1.4 ml of ice-cold 40 mM potassium phosphate buffer (pH 6.8) including KH_2PO_4 and K_2HPO_4 . Samples were homogenized for 45 s using a homogenizer (Benchmark D2400 BeadBlaster Microtube Homogenizer, Sayreville, NJ) at low speed and subsequently held on ice (0–4 °C) for 1 h. Following extraction, homogenates were centrifuged at $20,000 \times g$ for 30 min at 4°C. The

resulting supernatant was extracted. If turbidity was observed ($A_{700} > 0.05$), the extract was further clarified through a syringe filter. The absorbance of the clarified supernatant was measured at 525 nm using a spectrophotometer, which corresponds to the isosbestic point common to deoxymyoglobin, oxymyoglobin, and metmyoglobin. This measurement allowed for the determination of total myoglobin concentration without bias toward redox state.

$$\text{Myoglobin denaturation} = ((\text{Raw}-\text{Cooked})/\text{Raw}) \times 100$$

Metmyoglobin-reducing activity

The metmyoglobin-reducing activity (MRA) was determined using the protocol in the AMSA Color Guidelines and modified to use 0.3 g instead of 5 g of sample (King et al., 2023). Briefly, 0.3 g of the powdered sample was weighed, and 1.2 ml of 40 mM potassium phosphate buffer (pH 5.62) was added before being homogenized for 45 s. It was subsequently centrifuged at 20,000 rpm for 30 min at 4°C. A 96-well plate was prepared by adding 50 μ l of 0.75 mM metmyoglobin, 25 μ l of 3.0 mM potassium ferrocyanide, 50 μ l of deionized water, 25 μ l of 5 mM EDTA, and 25 μ l 3 mM sodium citrate buffer. Next, 50 μ l of each sample was added in duplicate. After the sample was added to each well, 25 μ l of 1 mM NADH was quickly added, and the cells were then read at 525nm using a spectrophotometer. One raw steak was powdered from each primal and were used to compare cooked samples back to. Beer's law was used to calculate the change in absorbance as the change from metmyoglobin to oxymyoglobin.

$$\text{MRA} = \text{change in absorbance} \times 12,000 \cdot l \cdot \text{minutes}^{-1} \cdot \text{g of sample}^{-1} \cdot \text{volume of reagents}^{-1}$$

Statistical analysis

Statistical analyses were performed using the procedures of SAS (SAS Inst. Inc., Cary, NC) with α set at 0.05. Using SAS PROC GLIMMIX and a split-plot design, with cooking

method as a whole-plot factor and DOD as the subplot factor. Carcass, panel session, and replication * treatment were accounted for as a random effect. The Kenward-Roger adjustment was used in all analyses.

Results

Demographics

Demographic characteristics of the consumer panelists ($N = 192$) are summarized in Table 2.1. The panel was relatively balanced in gender distribution, consisting of 53.93% females and 46.07% males. A majority of participants (54.97%) identified as single, and most respondents lived in smaller households, with 73.30% reporting a household size of one to three individuals. The sample was predominantly Caucasian/White, with 89.53% of panelists identifying with this ethnic group. In terms of socioeconomic status, 58.69% of participants reported an annual household income that fell within the mid-high-income range of \$50,000 to \$149,999. Educational attainment was relatively high, with 91.68% of consumers reporting completion of some college, a college degree, or post-graduate education. The age distribution skewed younger, with 56.55% of panelists under the age of 40. Regarding beef consumption, 79.58% of panelists indicated they consumed beef one to six times per week. When asked about their preferred degree of doneness (DOD), over half of the respondents (56.02%) favored medium rare. Palatability perceptions were also evaluated, with flavor identified as the most important trait by 54.45% of consumers. However, tenderness was considered the most variable trait, selected by 53.16% of participants.

Consumer sensory analysis

As shown in Table 2.3, the consumers determined the Oven steaks were juicier ($P < 0.05$) than the Flat-top, Air fryer, Sous Vide, and Grill steaks, while being rated similar ($P > 0.05$) for

juiciness compared to Clamshell. Similarly, Oven samples were rated the most tender ($P < 0.05$) compared to all other cooking methods. There was an interaction ($P < 0.05$; Table 2.5) between cooking method and DOD for flavor liking. The MR Grill steaks had a higher ($P < 0.05$) flavor rating compared to all cooking methods within the WD DOD, as well as the MR Sous Vide and Clamshell steaks. Within each cooking method, besides the Flat-top and Oven, consumers rated the MR samples higher for flavor liking ($P < 0.05$) compared to the WD samples. The Flat-top samples were rated similarly ($P > 0.05$) between the MR and WD DOD. Interestingly, even though consumers found differences ($P < 0.05$) in juiciness, tenderness, and flavor liking among the cooking methods, these did not ($P > 0.05$) illicit an impact on the overall liking scores.

The acceptability data told a similar story to the palatability rating scores results. Consumers rated the highest (Table 2.4; $P < 0.05$) percentage of steaks from the Oven and Clamshell as acceptable for juiciness. Similar to the overall liking results, the percentage of consumers that rated samples as acceptable for the remaining traits were similar (Table 2.4; $P > 0.05$) among cooking methods.

As expected, DOD influenced all sensory attributes evaluated by consumers ($P < 0.05$). The MR steaks were rated higher ($P < 0.05$) than WD steaks for all traits: juiciness, tenderness, flavor, overall liking, and overall appearance. DOD historically has played a major role in determining beef palatability and has been extensively studied. Subsequently, the percentage of consumers that rated each sample as acceptable for all traits (juiciness, tenderness, flavor, overall liking, and overall appearance) found in Table 2.4, was higher ($P < 0.05$) in the MR samples than the WD. DOD has been shown to have an inverse relationship with palatability ratings. Higher DODs have lower ratings for traits like tenderness, juiciness and flavor, and lower DODs have higher palatability ratings, respectively (Beyer et al., 2019b; Drey et al., 2019; Prill et al., 2019a).

It is important to note that this study also aimed to understand the impact of cooking method on appearance rating and acceptability. Oven and Flat-top steaks had a higher ($P < 0.05$) overall appearance rating compared to the Clamshell, Sous Vide, and Air fryer steaks, while being similar ($P > 0.05$) to the Grill. However, there was an interaction ($P < 0.05$) for the visual expectation of the steaks when consumers were asked if each sample met their criteria for a MR or WD DOD. The WD Air fryer steaks resulted in a higher ($P < 0.05$) percentage of consumers who determined samples met their visual expectations compared to all treatment and DOD combinations, besides ($P > 0.05$) the Sous Vide cooked to a WD DOD. These results can be found in Table 2.6 and depicted in Figure 2.1.

Almost half (47.92%) of consumers or more were able to visually assign the DOD correctly, but most interestingly, 25% or more consumers for every cooking method believed the sample fit a different DOD rather than its true classification. For MR steaks, answers varied from Very Rare to Very Well-done. The MR Air fryer steaks had the lowest percentage (54.74%) of consumers of all MR treatments who said that the sample met the MR DOD visually. All other MR cooking methods had percentages 60% or greater for visually meeting the MR DOD, with, Flat-top steaks having the highest percentage at 67.37%. The MR Flat-top, MR Grill, and MR Sous Vide steaks had a higher percentage of consumers choose DODs with greater final internal temperatures (Medium, Medium-well, Well-done, Very Well-done) whereas MR Oven and MR Clamshell had higher percentages of consumers choose a DOD with lower endpoint temperatures (Rare and Very rare). These results can be found in Figure 2.2.

The WD cooking methods had a wider range of percentages for the correct DOD classifications ranging from as low as 47.92% up to 75% but there was a consistent trend where consumers inferred that it was undercooked to a Medium Well-done DOD. The WD Air fryer

and WD Sous Vide steaks had the highest percentage of consumers say it matched the expected DOD at 75% which is opposite to the MR Air-fryer steaks with the lowest percentage of consumers. The WD Flat-top steaks had the lowest percentage of consumers say samples visually met the WD DOD at 47.92% with 42.71% of consumers selecting that it was undercooked. The WD Clamshell steaks had 57.29% of consumers determined samples met the expectations for a WD DOD and 31.25% of consumers determined Medium-well DOD was a better fit. Following the same pattern as the Clamshell steaks, 65.63% of consumers said samples visually met the WD DOD and 25% of consumers said a Medium-well DOD was visually a better fit. The WD Grill steaks had 58.33% of consumers say samples visually met the WD DOD and was split with 19.79% of consumers saying samples better fit a Medium-well DOD and 17.71% of consumers saying samples better fit a Very Well-done DOD. Overall, Medium rare expectations had relatively even splits of being overcooked and undercooked, while Well-done was most often either classified as the correct DOD or as undercooked. These results can be found in figures 2.3.

Of all cooking methods, the Flat-top and Air fryer cooking methods have the most interesting results where the results are inverted for the two DODs. For the Flat-top more than 67% of consumers found it visually matched the expected MR DOD but less than 50% of consumers said it matched the MR DOD visually. For Air fryer steaks, 75% of consumers said it met a WD DOD visually but just over 50% of consumers said it visually met a MR DOD, giving the Air fryer the largest spread of percentages between the two DODs of all cooking methods closely followed by Flat-top. These results can be found in figure 2.4.

Objective color measurement analysis

There was an interaction ($P < 0.05$) between cooking method and DOD for a^* , b^* and Oxymyoglobin percentage. These results can be found in Table 2.8. The MR Oven, MR Air fryer and MR Clamshell steaks had the highest ($P < 0.05$) a^* values meaning they were the reddest when compared to all other treatments and DODs but were similar ($P > 0.05$) to MR Flat-top steaks. The MR Sous Vide steaks had higher ($P < 0.05$) a^* values or redness when compared to all WD cooking methods but were ($P > 0.05$) similar to MR Flat-top steaks. The Grill steaks had the lowest ($P < 0.05$) a^* values among MR cooking methods but were higher ($P < 0.05$) when compared to all WD cooking methods. The WD Flat-top and WD Clamshell steaks had a higher ($P < 0.05$) a^* value compared to WD Grill steaks but were similar ($P > 0.05$) to WD Sous Vide, WD Oven and WD Air fryer steaks. The WD Grill steaks had the lowest ($P < 0.05$) a^* value when compared to all other cooking methods and DOD steaks but were similar ($P > 0.05$) to WD Sous Vide, WD Oven and WD Air fryer steaks.

For b^* , MR Clamshell steaks had the highest ($P < 0.05$) values across all treatments but were similar ($P > 0.05$) to MR Oven steaks. MR Sous Vide, MR Flat-top and MR Air fryer steaks had higher ($P < 0.05$) b^* values compared to all WD cooking methods and MR Grill steaks but were similar ($P > 0.05$) to MR Oven steaks. The MR Grill steaks again had the lowest ($P < 0.05$) b^* values when compared to MR cooking methods but were higher ($P < 0.05$) than all WD cooking methods. All WD cooking method treatments had similar ($P > 0.05$) b^* values and there were no differences observed.

For the Oxymyoglobin (OMb) results, the higher the percentage of Oxymyoglobin means the meat surface is dominated by the oxygen-bound form of myoglobin, appearing brighter and more cherry-red. All MR cooking methods had higher ($P < 0.05$) percentages of OMb compared to all WD treatments other than the WD Grill steaks. The WD Oven and Flat-top steaks had

higher ($P < 0.05$) OMb values when compared to WD Air fryer, WD Clamshell and WD Sous Vide. Finally, the WD Air fryer, WD Clamshell, and WD Sous Vide had the lowest ($P < 0.05$) OMb values when compared to all other treatments and DODs.

There was no interaction between cooking method and degree of doneness for L^* and Metmyoglobin percentage ($P > 0.05$) therefore main effects were evaluated. These results can be found in Table 2.7. Sous Vide steaks had the highest ($P < 0.05$) L^* values (lightest) when compared to all other cooking methods but were similar to ($P > 0.05$) Air fryer steaks. WD steaks had higher ($P < 0.05$) L^* values when compared to MR steaks.

For Metmyoglobin percentage (MetMb), the higher the percentage, the greater the proportion of myoglobin at the meat surface is in the oxidized (ferric) state, appearing as a brown pigment. The Grill steaks had the highest ($P < 0.05$) percentage of MetMb compared to all other cooking methods, but were similar to ($P > 0.05$) Sous Vide steaks. The Flat-top, Air fryer and Clamshell steaks had the lowest ($P < 0.05$) MetMb values compared to Grill and Sous Vide steaks, but were similar ($P > 0.05$) to Oven steaks. As expected, WD steaks had higher ($P < 0.05$) amounts of MetMb compared to MR steaks.

Cook loss analysis

There was an interaction between cooking method and DOD for cook loss ($P < 0.05$) with results presented in Table 2.8. The MR Grill exhibited the greatest ($P < 0.05$) cook loss among all cooking methods and DOD combinations but were similar to ($P > 0.05$) WD Grill, WD Air fryer, and WD Oven steaks. The MR Oven and MR Air fryer steaks had a similar ($P > 0.05$) amount of cook loss to WD Grill, WD Air fryer, WD Oven, and WD Flat-top steaks but a greater percentage ($P < 0.05$) of cook loss compared to all other MR cooking methods apart from ($P > 0.05$) MR Grill steaks. The WD Sous Vide steak had the lowest ($P < 0.05$) cook loss

compared to all treatment combinations followed by the WD Clamshell steaks which had less ($P < 0.05$) cook loss than all remaining cooking method and DOD combinations, with the exception of MR Sous Vide and MR Clamshell steaks ($P > 0.05$).

Slice shear force analysis

Slice shear force (SSF) analysis results are depicted in Table 2.7. There was no interaction between cooking method and DOD for SSF ($P > 0.05$) so main effects were evaluated. Sous Vide steaks exhibited the lowest ($P < 0.05$) SSF values and were objectively more tender when compared to the Grill and Clamshell steaks but were similar ($P > 0.05$) to the Oven, Flat-top and Air fryer steaks. Clamshell steaks had higher ($P < 0.05$) SSF values when compared to Sous Vide steaks but were similar ($P > 0.05$) to Oven, Flat-top, and Air fryer steaks. The Grill steaks had the highest ($P < 0.05$) SSF value when compared to all other treatments indicating samples were the least tender compared to all treatments. Degree of doneness did not influence SSF, as no differences were observed between medium-rare and well-done steaks ($P > 0.05$).

Myoglobin denaturation

No interaction between cooking method and DOD was observed for myoglobin denaturation ($P > 0.05$). Cooking method independently influenced myoglobin denaturation, with Flat-top cooked steaks exhibiting lower myoglobin denaturation compared with all other cooking methods ($P < 0.05$). The DOD also affected myoglobin denaturation, as MR steaks displayed lower denaturation than WD steaks ($P < 0.05$). These results can be observed in Table 2.7. This outcome is consistent with the temperature dependent nature of myoglobin denaturation, whereby increased thermal exposure at higher degrees of doneness results in

greater protein denaturation (Beyer et al., 2024b). However, myoglobin denaturation of different cooking methods had not yet been investigated prior to this paper.

Metmyoglobin-reducing activity analysis

The MRA assay was used in the current work to determine the ability of the cooked pigment to bloom after cooking, or as a measure of cooked color stability (Bekhit and Faustman, 2005). Again, there was no interaction between cooking method and DOD observed for MRA ($P > 0.05$) which are depicted in Table 2.7. Cooking method did not illicit an impact on MRA ($P > 0.05$) meaning the ability of the muscle to bloom was not affected by cooking method. However as expected, there were differences observed between DODs ($P < 0.05$). Raw steaks resulted in the highest MRA, followed by MR steaks ($P < 0.05$). The WD steaks had minimal activity detected consistent with previous cooked MRA findings (Beyer et al., 2024b).

Discussion

Overall, cooking method and DOD influenced several key quality attributes across both consumer sensory analysis and objective measurements. Some cooking methods were rated among the highest for juiciness and tenderness by consumers but did not follow the same trends for objective measures. Flavor liking showed a cooking method $\times$ degree of doneness interaction, with certain methods having higher flavor liking ratings than others within each DOD highlighting the complex mechanism of flavor development. Although differences were detected among cooking methods for individual palatability traits, these differences did not translate into changes in overall liking. Objective color measurements demonstrated cooking method effects on redness (a^*) and oxymyoglobin percentage, indicating that cooking environment altered cooked color development. Additionally, cooking method independently influenced myoglobin denaturation, though it did not impact metmyoglobin-reducing activity indicating while protein

changes were impacted by cooking, the ability to bloom post cooking remained constant. Collectively, these findings demonstrate that cooking method alters color development, objective measurements, and consumer perception. This study highlights the complex development of cooked color providing dialogue which will be useful for academia, food service, and consumers alike.

Consumer sensory analysis

The comparison of cooking method and cooked color on consumer acceptance had yet to be evaluated prior to this research. Previous studies have largely focused on tenderness or other palatability attributes rather than visual expectations (Berry, 1993; Powell et al., 2000; Lawrence et al 2001; Boles and Swan, 2002; Herring and Rogers, 2003; McKenna et al., 2004; Yancey et al., 2011; Yancey et al., 2016; Fabre et al., 2018). However, what makes this project most unique is the investigation in cooked color consumer acceptance (García-Segovia et al., 2007; Yancey et al., 2011; Kim et al., 2025). This project asked consumers to determine if each sample matched their expected DOD and if not to determine what DOD they thought it matched. This type of data had yet to be collected and provided a new look into consumer research. Therefore, this data will serve as a benchmark for future research on how the visual appearance of a steak can influence consumer acceptance.

The current study not only evaluated the major palatability traits, including juiciness, tenderness, flavor liking, and overall liking, but also evaluated overall appearance for two different DODs, allowing for a more comprehensive understanding of how consumers interpret both sensory and visual cues simultaneously. Consumers were able to detect differences among cooking methods for several individual sensory traits as well as between the two DODs which was consistent with previous literature. In the current study, MR steaks were rated higher for

every palatability trait as well as overall appearance. However, the cooking method data provided more intriguing results. Oven samples were rated the most tender compared to all other cooking methods. This is consistent with Vierck et al. (2021)'s study where consumers determined oven steaks were more tender than clamshell steaks which did illicit an impact on overall liking (Vierck et al., 2021). Consumers reported that of all cooking methods, clamshell steaks were rated as the most dry (Vierck et al., 2021). However, in the current study, Clamshell steaks were rated similar to the Oven samples for juiciness, being the top two cooking methods for juiciness. Another large deviation in the two studies was found in the overall liking results. Vierck et al., (2021) found that consumers were able to detect differences within each palatability trait and these differences impacted their overall liking of the samples. However, in the current study the differences in palatability traits observed did not translate into changes in overall liking. This suggests that consumers may weigh multiple attributes collectively when forming their final impression of a steak, rather than relying on a single sensory characteristic.

When consumers were asked about the acceptability of each trait, the results mirror the rating results. Interestingly, in both the current and Vierck et al. (2021) studies, consumers found differences in the juiciness acceptability for samples cooked using different cooking methods. While the presence of a significant finding is not interesting, the fact that the cooking method with the highest percentage of samples rated as acceptable for juiciness for the Viereck et al. (2021) study was the same cooking method with the lowest percentage of samples rated as acceptability for juiciness in the current study. In the current study, consumers rated the highest percentage of Clamshell samples as acceptable compared to all other cooking methods with the exception of Oven to which is was similar. These results are the exact opposite to the Vierck et al. (2021). However, Vierck et al. (2021), reported that though consumers overall liking scores

were different based on cooking method, it did not illicit an impact on the percentage of samples marked as acceptable for overall liking which is consistent with the results from the current study.

One explanation to these massive deviations lies within the methods. For the current study, samples fed to consumers were cooked according to a cooking protocol specific for that cooking method. For example, the Oven was set to an ambient cooking temperature of 177°C. Steaks were flipped once during the cooking process, with MR steaks turned at 29°C and WD steaks at 35°C. Cooking proceeded until internal temperatures reached 58°C for MR and 75°C for WD, where steaks were removed from the heat. Final endpoint temperatures were monitored using a Thermapen digital thermometer to ensure consistency across replicates and steaks were then sliced and immediately fed to consumers after peak temperature was recorded. As opposed to Vierck et al. (2021)'s study where all cooking methods were set at the same temperature (200°C) and flipped every 3 minutes no matter the cooking method. Steaks were cooked to a 71°C internal temperature, pulled off the heat and then immediately placed into a vacuum bag, then ice. Steaks were vacuum packaged and chilled for approximately 6 hours until panel sessions. One hour prior to the panel sessions, vacuum-packaged steaks were placed into a Sous Vide that was set to 63.5°C. The differences in cooking protocols likely attributes to the differences in consumer responses between the two studies. The present study confirms how important each cooking method is to the eating experience, therefore including sous vide as a reheating step makes it difficult to draw meaningful parallels between the two studies.

The impact of DOD on palatability is widely studied and understood. As expected, degree of doneness responses aligned with previous literature (Drey et al., 2019; Olson et al., 2019; Prill, 2019b;), with palatability ratings declining as DOD increased. In the present study,

steaks cooked to a MR endpoint received higher ratings than WD steaks across all sensory traits, including juiciness, tenderness, flavor liking, overall liking, and overall appearance. This pattern was also reflected in acceptability outcomes, where a higher percentage of MR samples were rated as acceptable than WD samples for every evaluated trait. While these results are not novel, they add still evidence to an under researched field in consumer research.

The most intriguing results were the investigation into appearance liking and DOD expectations. We know appearance of a steak makes an impact on eating experience; however, a study has not particularly evaluated the true connection. The strongest evidence is currently in the Prill et al. (2019a) study. Prill et al. (2019a), demonstrated that consumers rely heavily on visual cues to interpret degree of doneness and that appearance can influence expectations before consumption, highlighting that perceived doneness does not always align with the intended endpoint temperature. Similarly, in the present study, consumers were asked to evaluate overall appearance liking and visual acceptability (both external and internal) and determine whether samples matched the served DOD. While Prill et al. (2019a) focused primarily on consumer knowledge and perception of doneness categories, this study's approach further captured how cooking method and DOD interacted to influenced the perceived DOD highlighting the complexity of cooked color.

Similar to the palatability traits, consumers in this study were able to find differences for overall appearance liking between cooking methods. Oven and Flat-top steaks were rated amongst the highest and Air fryer steaks were rated the lowest by consumers for overall appearance liking. Medium rare steaks out ranked the Well-done steaks for overall appearance rankings as well as being more acceptable to consumers overall appearance. But again, these liking differences did not illicit an impact on the percentage of samples rated as acceptable for

overall appearance liking for the different cooking methods. Even though all cooking methods were cooked to the same end-point temperature for each DOD, each cooking method behaved differently at those temperatures. The evaluation of the perceived DOD by consumers provides yet even more insight to this complex relationship between cooked color, cooking method, and palatability.

The variability in how consumers visually classified degree of doneness highlights the strong influence of cooking method on perceived cooked color and doneness expectations. Even when steaks were prepared to the same targeted endpoint temperature, consumers frequently reassigned samples to alternative DOD categories, suggesting that visual cues such as surface browning, internal color, and overall appearance are influenced by more than internal temperature and have the potential to influence the eating experience. Differences observed among cooking methods indicate that certain methods may exaggerate or mute visual indicators typically associated with specific doneness levels, leading to shifts toward higher or lower perceived DOD classifications. This is directly displayed in the contrasting trends between Flat-top and Air fryer steaks which further emphasize that visual doneness perception is not consistent across cooking environments, and that the same method can alter expectations differently depending on the targeted endpoint. Panels were organized by intended degree of doneness preference; however, consumer self-reported preferences suggest the WD panel did not strongly represent consumers who typically prefer well-done beef. Within the MR panels, 57.89% of participants confirmed MR as their preferred DOD, whereas only 3.19% of participants in the WD panels identified WD as their preferred level, with the majority (73.41%) indicating a preference for MR or Medium. This imbalance in preference distribution may partially explain the greater variability observed in WD doneness perception compared with MR,

as consumers may have relied more heavily on personal expectations and familiar visual cues when evaluating samples outside of their usual preference range. Collectively, these findings support the concept that consumers rely heavily on appearance when interpreting doneness, and cooking method plays a large role in the internal and external appearance of steaks. This data reinforced the importance of considering cooking methods when evaluating consumer responses to cooked color and palatability.

Objective cooked color

Cooked color is widely recognized to change as DOD increases; however, the exact relationship between instrumental color measurements and consumer perception remains complex. In the current study, objective color values appeared to align closely with consumer responses, suggesting that acceptability may be partially driven by measurable differences in redness. Cooking method influenced all instrumental readings, but the most notable effects were observed for a^* , which represents redness and is strongly associated with consumer expectations of doneness. The interaction between DOD and cooking method indicates that redness did not shift uniformly across treatments, reinforcing that visual appearance is shaped not only by internal temperature but also by the cooking environment.

As expected, all MR treatments exhibited greater a^* values compared with WD samples; however, variation among cooking methods could provide insight into consumer interpretation of doneness. Interestingly, the MR Grill steaks displayed the lowest a^* values among MR treatments, which may explain why a portion (17.89%) of consumers perceived these samples as closer to a Medium DOD, but still a majority (63.16%) of consumers said it did meet the MR DOD. In contrast, MR Oven and MR Clamshell (MR or undercooked) steaks produced some of the highest redness values, although these were comparable to MR Air-fryer and MR Flat-top

steaks (MR or overcooked), suggesting that elevated a^* alone did not guarantee accurate visual classification. The MR Sous Vide steaks exhibited intermediate redness values, which paralleled the mid-range proportion of consumers who identified these samples as meeting the expected MR DOD. These discrepancies indicate that additional visual factors beyond internal redness, such as surface browning or color uniformity, may influence perception of DOD to consumers.

The WD samples behaved differently, however, the redness scores were still not enough to help explain consumer responses. Counterintuitively, Grill steaks showed the lowest a^* values across treatments but were not consistently perceived as the most WD, further emphasizing that consumer interpretation of doneness is multifactorial. For WD Flat-top steaks, fewer than half of consumers believed the samples matched the expected DOD despite a^* values comparable to other WD treatments, suggesting that differences in surface browning relative to internal color may have contributed to classification as Medium-well.

Myoglobin chemistry may also help explain some of the observed differences. Oxymyoglobin percentages were generally higher in MR treatments compared with WD samples, as anticipated, although WD Grill steaks showed oxymyoglobin levels similar to all MR treatments despite the low redness values. This helps explain the discrepancy of consumer responses and redness scores for the WD Grill samples and highlights a potential additional mechanism of cooked color development besides myoglobin chemistry alone. This divergence, coupled with elevated metmyoglobin percentages in Grill steaks, suggests that pigment state alone may not fully account for visual redness. Together, these findings reinforce that while a^* is strongly associated with perceived doneness (Prill et al., 2019a), consumer interpretation of cooked color results form a complex interaction among myoglobin chemistry, cooking method, and visual cues beyond a^* values.

Consumer expectations for degrees of doneness are strongly tied to visual color cues, and deviations from these expectations can influence the eating experience (Prill et al. 2019b). Although general color guidelines for DOD are well established, the biochemical mechanisms driving cooked color development, particularly across different cooking methods remain less understood. The present study aimed to further explore these mechanisms by examining myoglobin denaturation alongside instrumental color values and metmyoglobin reducing activity. Myoglobin denaturation has been studied in ground beef but has only recently been evaluated in whole muscle beef (Beyer et al., 2024b).

Myoglobin is known to begin denaturing near 55°C and becomes progressively more denatured as cooking temperature approaches 80°C (King and Whyte, 2006; Hunt et al., 1999), with the extent of denaturation influenced by the oxidation state of myoglobin at the time of cooking. While ground beef is typically cooked to temperatures that result in nearly complete pigment denaturation for safety reasons, whole muscle products span a range of DODs, creating more variability in internal color and highlighting the need for further investigation in these whole muscle cuts. In the current study, myoglobin denaturation was hypothesized to increase as a^* values decreased, and although a cooking method $\times$ DOD interaction was observed for a^* , only main effects were detected for myoglobin denaturation. As expected, MR steaks exhibited lower levels of denaturation than WD steaks, consistent with previous literature (Beyer et al., 2024b; Mancini and Hunt, 2005; Hunt et al., 1999).

Cooking method seems to have influenced denaturation patterns in ways that helped explain consumer perception. Flat-top steaks exhibited the lowest percentage of myoglobin denaturation alongside relatively high a^* values, which may have contributed to consumers frequently perceiving these samples as closer to a Medium-well rather than a WD appearance.

Thresholds reported in previous studies provide additional context for interpreting these findings. Ryan et al. (2006) suggested that approximately 80% denaturation is required to achieve a WD appearance in ground beef, whereas Beyer et al. (2024) reported that roughly 70% denaturation may be sufficient for whole muscle cuts. In the present study, consumer responses suggest that approximately 65% denaturation was adequate for a WD visual classification, potentially reflecting differences in cooking method or heat transfer characteristics compared with prior work. Similarly, Beyer et al. (2024) reported approximately 29% denaturation for MR steaks, whereas the current study observed greater denaturation at this endpoint temperature. This shift may help explain why some consumers reassigned MR samples to adjacent doneness categories, particularly for clamshell steaks that shared cooking conditions with the Beyer study but showed slightly higher denaturation values. Differences among cooking methods, such as Flat-top, Grill, and Air Fryer, further suggest that myoglobin may denature at varying rates even when steaks are cooked to the same internal temperature, reinforcing the importance of Beyer et al. (2024) in establishing a baseline for whole muscle pigment changes.

Overall, myoglobin denaturation appears to account for many of the color differences observed between degrees of doneness; however, pigment denaturation alone does not fully explain cooked color perception. Changes in color stability following cooking and slicing likely contribute to additional visual variation, indicating that many traits play a role in shaping consumer interpretation of doneness.

While metmyoglobin reducing activity (MRA) is most commonly discussed in relation to raw meat color stability, it may also influence the extent to which cooked samples are capable of blooming after slicing, thereby contributing to cooked color stability and consumer perception. In the present study, the MRA assay was used as an indicator of the capacity of cooked pigments

to regain redness following cooking, which may impact the final visual appearance observed prior to consumption (Bekhit and Faustman, 2005). As expected, MRA decreased as DOD increased, consistent with findings reported by Beyer et al (2024b) suggesting that progressive protein denaturation limits the ability of myoglobin to undergo reduction following thermal processing. However, no differences were detected among cooking methods, indicating that endpoint temperature and the associated extent of protein denaturation may play a larger role in determining post-cooking reducing capacity than the specific heat source used.

Previous work by Beyer et al. (2024b) demonstrated variation in MRA among different muscles when investigating the relationship between raw color stability and cooked color outcomes, emphasizing that myoglobin remains active even after cooking. Understanding cooked color stability is particularly important because it represents the final visual state of the steak prior to consumption and may differ from the initial appearance immediately after slicing. This dynamic was illustrated by Prill et al. (2019a), who observed changes in internal color over time following slicing and reported greater recovery of a^* values in steaks cooked to lower degrees of doneness. Similar patterns were observed in the present study, where Raw samples exhibited greater reducing capacity compared with MR steaks, and MR exhibited greater reducing capacity than WD. Previous work from Huber et al (2025) also further supports the importance of a^* values as an indicator of cooked color stability. Changes in a^* values continued during the bloom period following slicing, with lower DODs maintaining greater a^* values over time, demonstrating that the final visual appearance develops minutes after cooking rather than immediately following slicing. These findings again align with the present study, suggesting that myoglobin reducing activity contributes to post-cooking changes in redness, reinforcing the role of a^* as a key link between pigment state and consumer perception of doneness.

Although MRA declined with increasing DOD, a measurable level of activity remained even at the WD DOD, suggesting that some reduction abilities may still occur after cooking. Collectively, these findings highlight an important connection between MRA and DOD, where lower levels of thermal denaturation preserve greater potential for blooming abilities, ultimately influencing the internal appearance of steaks during the short period between slicing and consumption.

Objective measurements

One of the most surprising findings of the study was the deviation of objective and subjective measures. Objective tenderness and juiciness measurements did not follow the same trend as consumer results as shown by the Oven samples being rated the juiciest and most tender by consumers but was objectively one of the most tough with one of the highest cook loss percentage. However, Oven steaks had some of the highest overall appearance liking scores which in turn could have influenced the perceived palatability. This discrepancy in data contributes to the theory that cooked color is a complex topic that is affected by both temperature and cooking method which in turn can influence consumer perceived palatability.

As expected, objective tenderness measurements indicated that cooking method influenced SSF values, with Grill steaks exhibiting the highest SSF values, indicating reduced tenderness compared with other treatments. The elevated SSF values observed for Grill steaks may be related to open-flame exposure and increased surface charring, which could also promote moisture loss. In contrast, Sous Vide steaks demonstrated the lowest SSF values, although these were not rated differently from Oven, Flat-top, or Air Fryer treatments by consumers, indicating relatively similar mechanical tenderness across several cooking methods. Consumers perceived Oven steaks as the most tender despite minimal instrumental differences among multiple

treatments. The discrepancy between objective and subjective measures for tenderness still remain unknown and a point of interest. However, explaining treatment to treatment differences can be accomplished by looking at heat transfer and rate of cooking.

Findings from Fabre et al. (2018) and Yancey et al. (2011), showed oven-based cooking methods produced lower objective tenderness values compared with alternative dry or dry-moist heat methods, suggesting that slower, more uniform heat transfer may contribute to favorable palatability outcomes. Previous research has suggested that differences in tenderness among cooking methods may be partially attributed to variation in cooking rate; however, the relationship is inconsistent across studies. Yancey et al. 2011, reported that slower cooking methods sometimes produced lower shear force values, while faster methods resulted in higher values, yet other work has shown minimal or no differences in tenderness despite large differences in cooking time (Berry, 1993; Kerth et al., 2003; Lawrence et al., 2001). These conflicting findings indicate that cooking rate alone may not fully explain tenderness outcomes, and that factors such as heat transfer, surface dehydration, and protein denaturation likely interact to influence SSF values. The present results support this concept, as Sous Vide treatments tended to align with lower shear force values, whereas Grill treatments exhibited higher values despite similar endpoint temperatures.

No differences in SSF were observed between MR and WD samples, which contrasts with consumer evaluations that indicated reduced tenderness at higher degrees of doneness. Previous literature has frequently reported increased toughness with higher DOD (Beyer et al., 2024b; Yancey et al., 2011); therefore, the lack of instrumental differences in the present study suggests that perceived tenderness may have been influenced by visual cues rather than solely by structural changes in the muscle. Reduced redness in WD samples may have led consumers to

expect a firmer texture, highlighting the potential role of cooked color in shaping consumer perception even when objective measurements remain similar.

Lastly, cook loss is an objective measurement closely linked to consumer perception of juiciness. A cooking method $\times$ DOD interaction was observed for cook loss, indicating that moisture retention was influenced by both endpoint temperature and cooking environment. Grill steaks, regardless of DOD, exhibited the greatest cook loss percentages compared with most other treatments, which may help explain the lower consumer ratings for juiciness, tenderness, and juiciness acceptability. Increased moisture loss associated with open-flame cooking could also contribute to higher shear force values observed for Grill steaks. In contrast, MR Sous Vide steaks demonstrated the lowest cook loss percentages, likely due to the moist cooking environment and reduced evaporative losses. However, despite lower cook loss, Sous Vide steaks received relatively low juiciness ratings, similar to Air Fryer, Grill, and Flat-top treatments, suggesting that factors beyond moisture retention, such as surface texture or visual cues, may influence consumer perception of juiciness. Previous literature provides mixed support for the role of cooking method in cook loss outcomes. Fabre et al. 2018, reported that dry heat cooking methods resulted in the greatest cook loss, while moist methods such as water bath cooking produced the lowest, which aligns with the trends observed in the present study. In contrast, Yancey et al. (2011) observed no differences in cook loss among cooking methods; however, their study did not include a moist cooking treatment comparable to sous vide, which may explain the discrepancy. Together, these findings suggest that cook loss contributes to consumer perception of juiciness but does not solely determine sensory outcomes, highlighting the complex relationship among cooking methods and different palatability traits.

Conclusion

Although consumers perceived juiciness, tenderness, flavor, and overall appearance differently for some cooking methods, cooking method had no impact on overall liking. However, the objective measurements did not follow the same trend as consumer responses. The cooking method (Oven) that was rated as the most juicy, the most tender, and was also rated the highest for overall appearance liking, did not produce the most favorable objective measurements. This discrepancy hints at a link between appearance and palatability with visual cues influencing consumer responses more positively than previously thought. Based on consumer responses, each cooking method resulted in a different ratio of inferred DOD, indicating that while each cooking method resulted in similar end point temperatures, the cooking method impacted internal and external color thus influencing the consumer's preference and perception of DOD. This was supported by the interaction between DOD and cooking method for visual expectations, a^* , oxymyoglobin %, myoglobin denaturation. However, consumer perception of doneness was not explained by a single objective measurement. Discrepancies between instrumental values and consumer responses highlighted the importance of surface characteristics, color stability, and post-cooking dynamics in shaping eating expectations for consumers. Collectively, these findings demonstrate that cooked color is a multifactorial trait. Understanding the relationship between cooking method and DOD in this study provides insight for understanding cooked color chemistry. These results can help guide future research while potentially influencing food service and consumer cooking recommendations in the long run.

Table 2.1 Demographic characteristics of consumer panelists from taste evaluation ($N = 192$).

Characteristics	Response	Percentage of Consumers (%)
Gender	Male	46.07
	Female	53.93
Household size	1 person	6.80
	2 people	45.50
	3 people	21.00
	4 people	17.80
	5 people	6.30
	6 people	2.62
	> 6 people	
Marital status	Married	45.03
	Single	54.97
Age	< 20	5.24
	20-29	39.27
	30-39	12.04
	40-49	10.47
	50-59	11.52
	> 60	21.47
Ethnic origin	African American	1.57
	Asian	4.71
	Caucasian/white	89.53
	Latino	1.57
	Mixed race	1.57
	Native American	0.52
	Other	0.52
Household income level	< \$25,000	3.14
	\$25,000-\$34,999	9.42
	\$35,000-\$49,999	16.23
	\$50,000-\$74,999	24.08
	\$75,000-\$99,999	12.57
	\$100,000-\$149,999	22.04
	\$150,000-\$199,999	4.19
	>\$199,999	5.24
Education level	Non-high school graduate	1.05
	High school graduate	7.33
	Some college/technical school	40.84
	College graduate	29.84
	Post-college graduate	21.00
Weekly beef consumption	0 times	1.57
	1-3 times	40.84
	4-6 times	38.74
	7-9 times	8.38
	10 or more times	9.95
Most important palatability trait	Flavor	54.45
	Tenderness	29.84
	Juiciness	15.71
Most variable palatability trait	Flavor	25.26
	Tenderness	53.16
	Juiciness	21.58
Preferred degree of doneness	Very Rare	1.05
	Rare	6.81
	Medium-Rare	56.02
	Medium	21.47
	Medium-Well	12.04
	Well-Done	2.09
	Very Well-Done	0.52

Table 2.2 Fresh beef steak purchasing motivators¹ of consumers ($N = 192$) who participated in sensory panels.

Characteristic	Importance of each trait
Price	77.80 ^a
Size, weight, and thickness	73.80 ^a
Marbling	73.24 ^a
Color	74.58 ^a
Nutrient Content	61.48 ^b
USDA Grade	65.98 ^b
Familiarity with cut	65.58 ^b
Eating satisfaction claims	61.64 ^b
Growth hormone use	49.49 ^{cd}
Fresh Never Frozen	50.62 ^{cd}
Antibiotic use in the animal	53.92 ^c
Animal fed a forage-based diet	49.37 ^{cd}
Natural or Organic	41.56 ^{ef}
Animal fed a corn-based diet	48.92 ^{cd}
Packaging type	45.88 ^{de}
Brand of product	40.02 ^f
Animal welfare claims	64.13 ^b
SEM ²	2.05
P - Value	< 0.01

^{abcd} Means within the same column without a common superscript differ ($P < 0.05$).

¹Purchasing motivators: 0 = extremely unimportant, 100 = extremely important.

²SE (largest) of the least squares means

Table 2.3 Least squares means ($n = 12$) of consumer ($n = 96$) sensory panelist palatability ratings¹ for six cooking methods and two degrees of doneness.

Degree of doneness	Juiciness	Tenderness	Overall Liking	Overall Appearance
Medium rare, 62.8°C	68.22 ^a	67.83 ^a	67.04 ^a	67.15 ^a
Well-done, 76.7°C	47.18 ^b	56.40 ^b	54.62 ^b	58.43 ^b
SEM ²	1.92	1.94	2.48	2.73
<i>P</i> - Value	< 0.01	< 0.01	< 0.01	< 0.01
Cooking Method				
Sous Vide	53.02 ^c	62.41 ^b	60.25	60.51 ^{bc}
Oven	66.22 ^a	69.16 ^a	65.11	66.42 ^a
Flat-top	58.43 ^{bc}	61.22 ^b	62.30	66.42 ^a
Air fryer	53.51 ^c	58.57 ^b	56.70	58.98 ^c
Grill	52.94 ^c	58.57 ^b	60.47	63.86 ^{ab}
Clamshell	62.09 ^{ab}	62.75 ^b	60.17	60.56 ^{bc}
SEM ²	3.14	2.40	2.55	2.24
<i>P</i> - Value	< 0.01	< 0.01	0.05	< 0.01

^{abc} Means within the same column without a common superscript differ ($P < 0.05$).

¹Sensory scores: 0 = extremely dry/tough/dislike; 50 = neither dry nor juicy, neither tough nor tender, neither like nor dislike; 100 = extremely juicy/tender/like extremely.

²SE (largest) of the least squares means

Table 2.4 Least squares means ($n = 12$) of the percentage of consumers ($n = 96$) who rated each palatability trait as acceptable.

Degree of doneness	Juiciness Acceptability	Tenderness Acceptability	Flavor Acceptability	Overall Liking Acceptability	Overall Appearance Acceptability
Medium rare, 62.8°C	88.17 ^a	90.17 ^a	87.59 ^a	88.20 ^a	88.25 ^a
Well-done, 76.7°C	58.84 ^b	76.89 ^b	76.34 ^b	72.12 ^b	79.23 ^b
SEM ¹	0.16	0.18	0.16	0.16	0.17
<i>P</i> - Value	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Cooking Method ³					
Sous Vide	64.29 ^d	84.34	81.73	80.21	80.00
Oven	84.68 ^{ab}	89.95	82.00	83.86	85.19
Flat-top	77.23 ^{bc}	83.47	88.05	86.27	86.53
Air fryer	70.75 ^{cd}	81.59	81.93	76.86	80.89
Grill	68.06 ^{cd}	80.21	80.39	76.43	86.55
Clamshell	87.44 ^a	86.67	80.89	83.53	85.38
SEM ¹	0.34	0.34	0.30	0.30	0.31
<i>P</i> - Value	< 0.01	0.16	0.42	0.12	0.34

^{abcd} Means within the same column without a common superscript differ ($P < 0.05$).

¹SE (largest) of the least squares means

Table 2.5 Least square means ($n = 12$) of consumer sensory panelist ($N = 192$) flavor liking scores¹ for beef steaks cooked to two degrees of doneness using six cooking methods.

Cooking Method	Degree of doneness	Flavor
Sous Vide	Medium rare	63.88 ^{bcd}
	Well-done	56.45 ^{ef}
Oven	Medium rare	67.90 ^{ab}
	Well-done	59.73 ^{cde}
Flat-top	Medium rare	65.92 ^{abc}
	Well-done	62.86 ^{bcd}
Air fryer	Medium rare	65.75 ^{abc}
	Well-done	48.01 ^g
Grill	Medium rare	71.06 ^a
	Well-done	56.48 ^{def}
Clamshell	Medium rare	62.86 ^{bcd}
	Well-done	53.19 ^{fg}
SEM ²		0.48
<i>P</i> - Value		< 0.01

^{abcd} Means within the same column without a common superscript differ ($P < 0.05$).

¹Flavor liking scores: 0 = extremely dislike; 50 = neither like nor dislike; 100 = like extremely.

²SE (largest) of the least squares means

Table 2.6 Least square means ($n = 12$) of the percentage of consumers ($N = 192$) who rated samples acceptable of the degree of doneness for each cooking method based on visual evaluation.

Cooking Method	Degree of doneness ¹	Visual expectations, % ²
Sous Vide	Medium rare	64.21 ^{cd}
	Well-done	78.12 ^{ab}
Oven	Medium rare	65.26 ^{bc}
	Well-done	67.71 ^{bc}
Flat-top	Medium rare	67.37 ^{bc}
	Well-done	51.04 ^d
Air fryer	Medium rare	57.89 ^{cd}
	Well-done	81.25 ^a
Grill	Medium rare	67.37 ^{bc}
	Well-done	61.46 ^{cd}
Clamshell	Medium rare	67.37 ^{bc}
	Well-done	60.42 ^{cd}
SEM ³		0.48
<i>P</i> - Value		< 0.01

^{abcd} Means within the same column without a common superscript differ ($P < 0.05$).

¹MR: Medium rare, WD: Well-done

²Visual expectations, % = percentage of consumers who rated samples acceptable of the degree of doneness for each cooking method based on visual evaluation / total consumers

³SE (largest) of the least squares means

Table 2.7 Least square means of myoglobin denaturation, L^* , color stability, and relative percentage of metmyoglobin (MetMb) of six cooking methods and two degrees of doneness

Cooking Method	Myoglobin denaturation, % ²	MRA ³	SSF, N ⁴	L^* ¹	MetMb, %
Sous Vide	53.39 ^a	2.56	16.67 ^c	58.52 ^a	39.83 ^{ab}
Oven	57.68 ^a	2.67	17.15 ^{bc}	57.16 ^b	37.04 ^{bc}
Flat-top	42.52 ^b	3.00	18.31 ^{bc}	56.32 ^b	35.62 ^c
Air fryer	55.04 ^a	2.38	17.30 ^{bc}	57.26 ^{ab}	34.51 ^c
Grill	59.38 ^a	2.06	20.99 ^a	56.09 ^b	42.69 ^a
Clamshell	52.86 ^a	2.75	18.79 ^b	56.42 ^b	33.98 ^c
SEM ⁶	4.09	0.36	0.88	0.72	1.21
<i>P</i> - Value	< 0.01	0.53	< 0.01	< 0.01	< 0.01
Degree of Doneness ⁵					
Raw	-	14.63 ^a	-	-	-
MR	41.23 ^b	4.02 ^b	18.67	56.03 ^b	24.50 ^b
WD	65.75 ^a	1.13 ^c	17.73	57.89 ^a	50.06 ^a
SEM ⁷	2.78	0.79	2.08	0.61	0.64
<i>P</i> - Value	< 0.01	< 0.01	0.82	< 0.01	< 0.01

^{abc} Means within the same column without a common superscript differ ($P < 0.05$).

¹ L^* : 0 = black, 100 = white

²Myoglobin Denaturation, %=(1-[Raw-Cooked]/Raw) x 100

³Metmyoglobin reducing activity; nmol/min/g of muscle

⁴Slice Shear Force, N

⁵Raw, MR: Medium rare, WD: Well-done

⁶Metmyoglobin, %

⁷SE (largest) of the least squares means

Table 2.8 Least square means of cook loss, cooked color (a^* and b^*), and relative percentage of oxymyoglobin (OMb) for beef steaks cooked to two degrees of doneness using six cooking methods.

Cooking Method	Degree of doneness	Cook loss, % ¹	a^* ²	b^* ³	Oxymyoglobin, % ⁴
Sous Vide	Medium rare	14.82 ^{de}	23.88 ^b	20.84 ^b	69.04 ^a
	Well-done	6.28 ^f	11.06 ^{de}	16.27 ^d	48.84 ^c
Oven	Medium rare	24.89 ^{bc}	26.88 ^a	21.76 ^{ab}	70.21 ^a
	Well-done	30.13 ^{ab}	11.06 ^{de}	16.22 ^d	58.87 ^b
Flat-top	Medium rare	19.86 ^{de}	25.69 ^{ab}	20.79 ^b	68.62 ^a
	Well-done	20.10 ^{cd}	12.98 ^d	16.47 ^d	57.50 ^b
Air fryer	Medium rare	26.09 ^{bc}	26.43 ^a	20.97 ^b	70.83 ^a
	Well-done	30.12 ^{ab}	12.52 ^{de}	15.73 ^d	52.01 ^c
Grill	Medium rare	30.81 ^a	20.30 ^c	19.25 ^c	67.51 ^a
	Well-done	29.09 ^{ab}	10.29 ^e	16.65 ^d	71.82 ^a
Clamshell	Medium rare	15.91 ^{de}	27.28 ^a	22.95 ^a	70.44 ^a
	Well-done	13.63 ^e	13.30 ^d	15.91 ^d	51.63 ^c
SEM ⁵		2.10	0.83	0.47	2.04
<i>P</i> - Value		< 0.01	< 0.01	< 0.01	< 0.01

^{abcdef} Means within the same column without a common superscript differ ($P < 0.05$).

¹Cooking loss = $1 - (\text{cooked weight} / \text{raw weight}) \times 100$

² a^* : -60 = green, 60 = red

³ b^* : -60 = blue, 60 = yellow

⁴Oxymyoglobin, %

⁵SE (largest) of the least squares means

Figure 2.1 Representation for the visual expectation of the steaks when consumers were asked if it met their criteria for a MR or WD DOD. Significance was set at $P < 0.05$. ^{a-d} Means without a common superscript differ

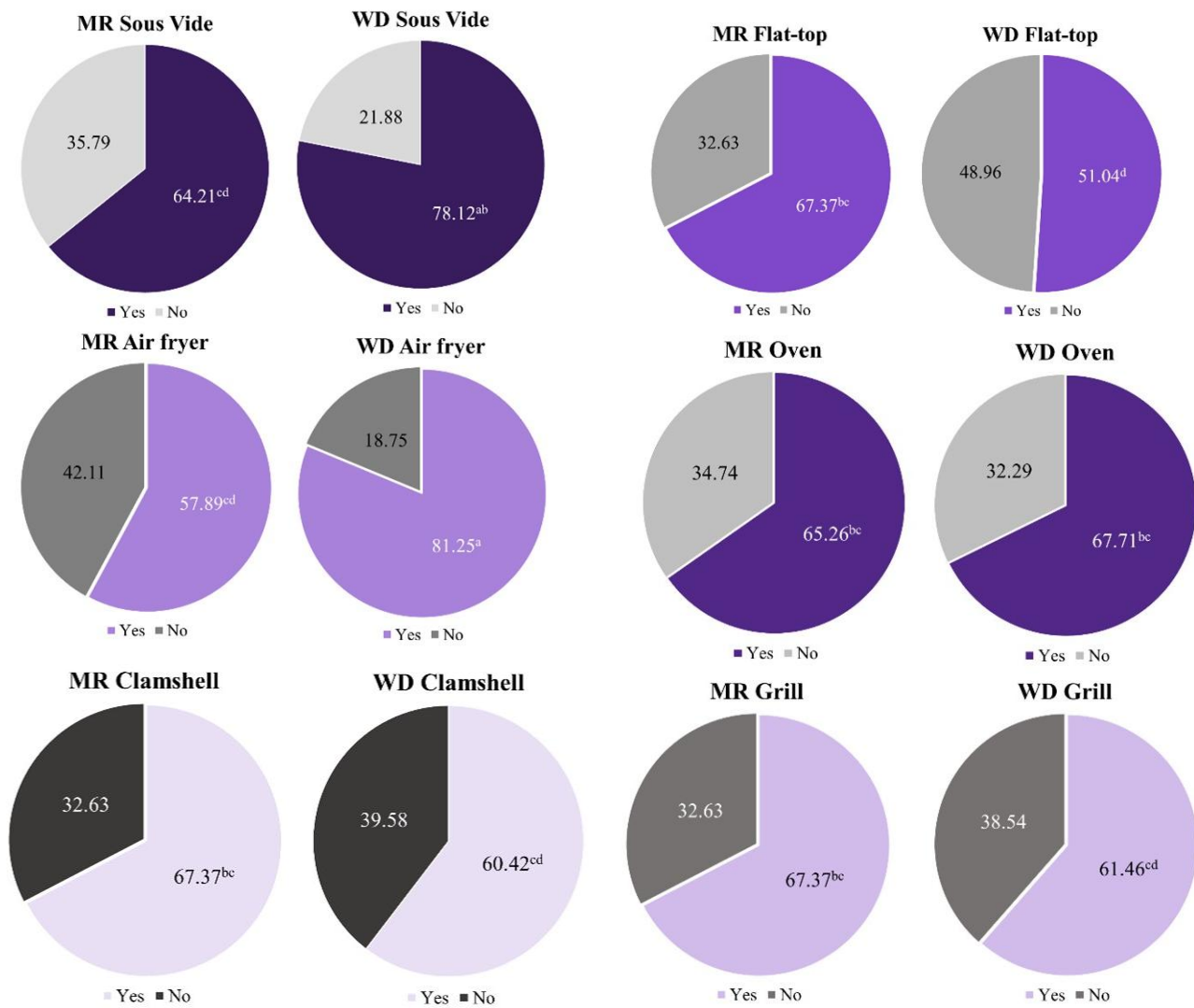


Figure 2.2 Percentage of consumers ($n = 96$) that identified beef strip loin steaks cooked to a MR degree of doneness using various cooking methods as a DOD after external and internal visual evaluation. Significance was set at $P < 0.05$.

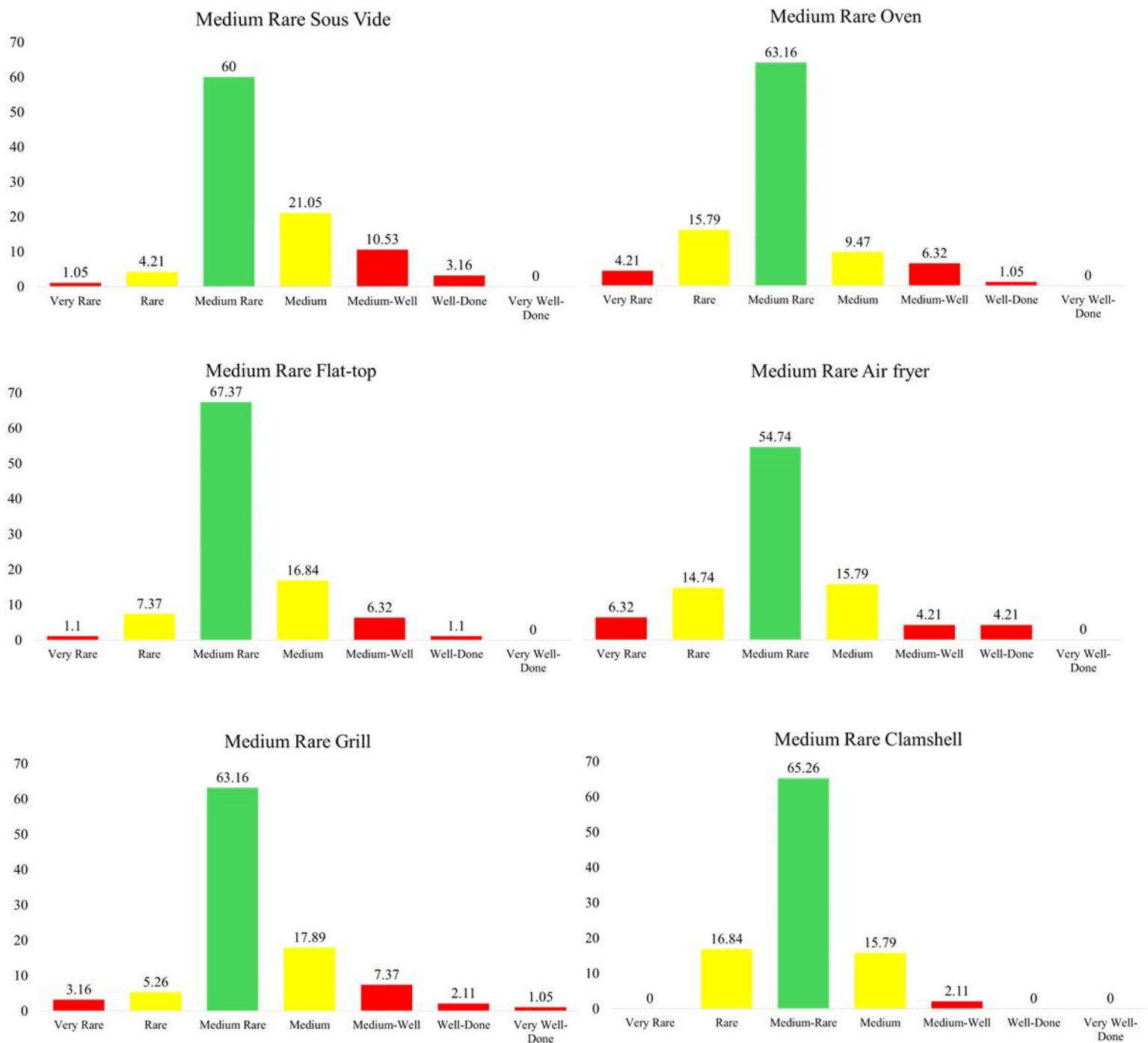


Figure 2.3 Percentage of consumers ($N = 96$) that identified beef strip loin steaks cooked to a WD degree of doneness using various cooking methods as a DOD after external and internal visual evaluation. Significance was set at $P < 0.05$.

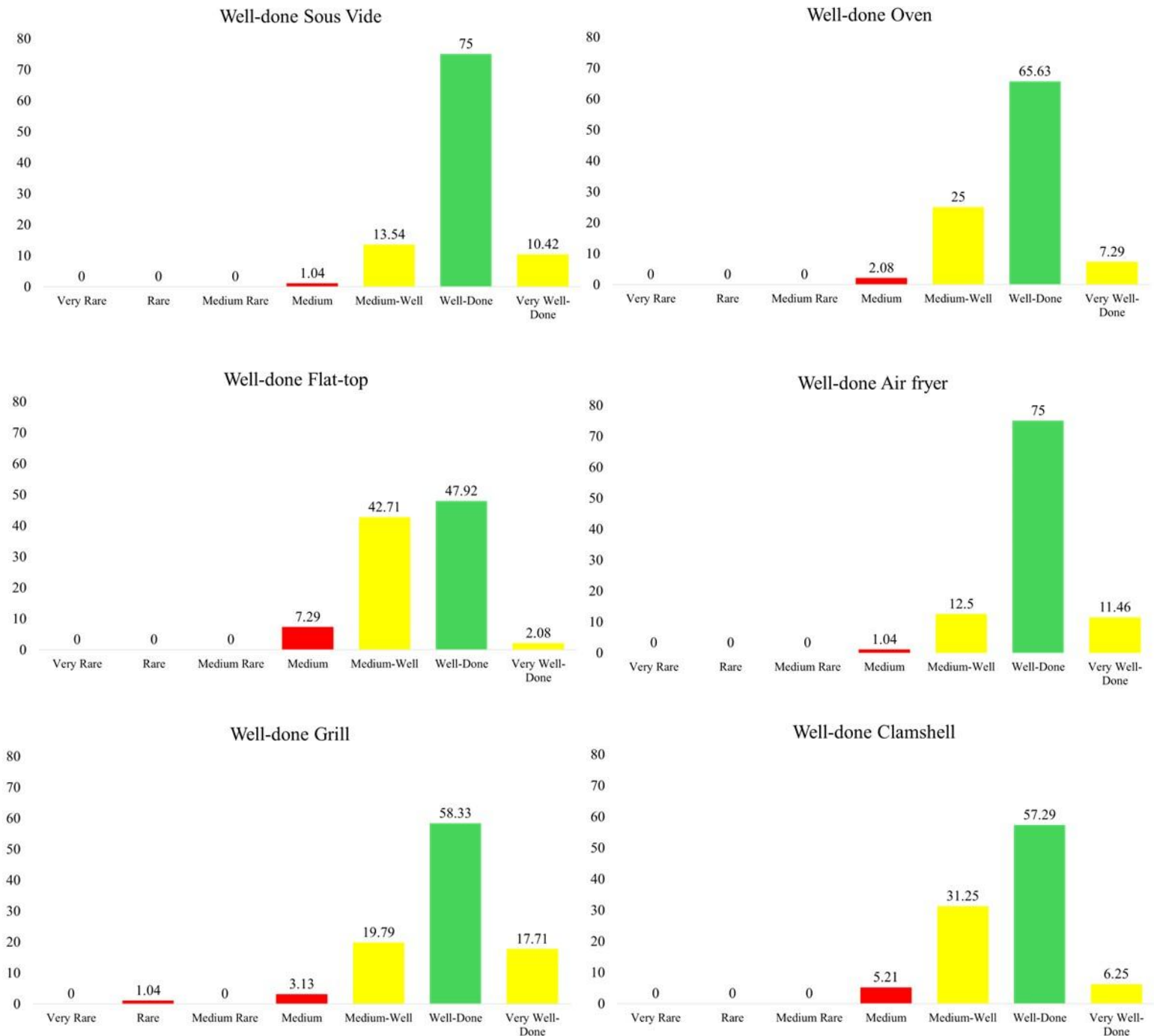
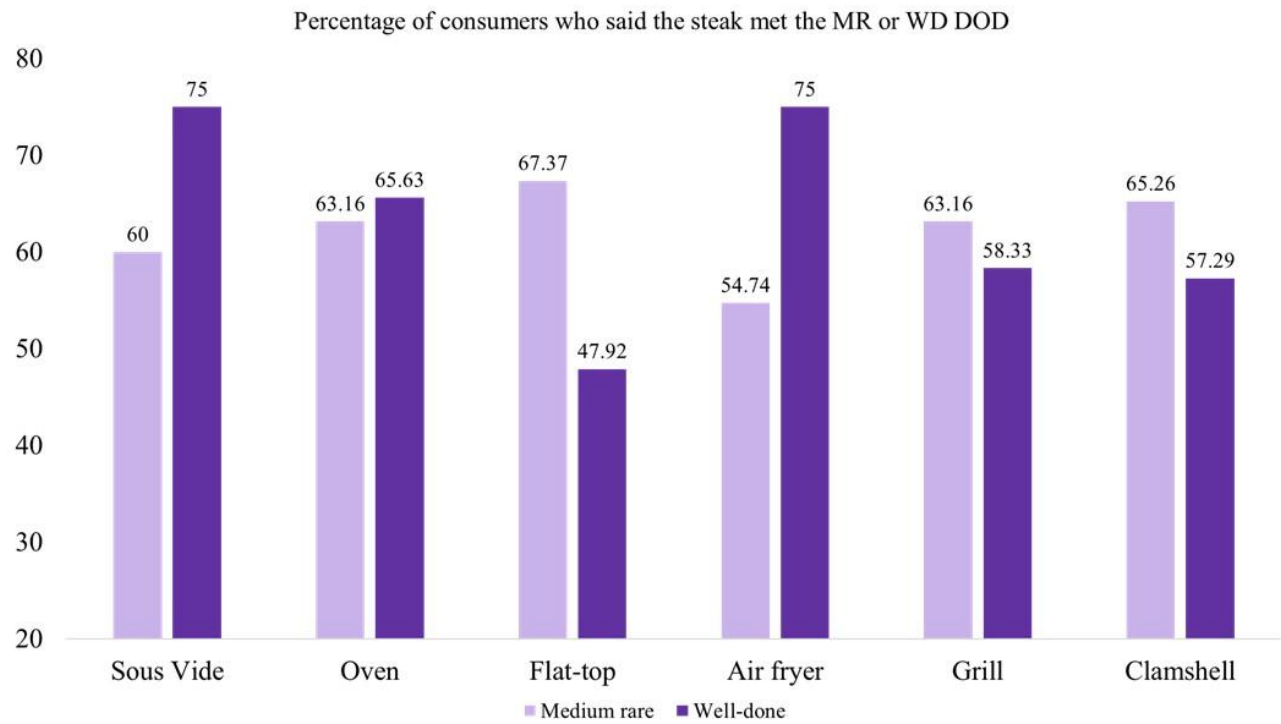


Figure 2.4 Percentage of consumers ($n = 96$ per DOD, $N = 192$) that identified beef strip loin steaks cooked to a MR or WD degree of doneness using various cooking methods as the expected DOD after external and internal visual evaluation. Significance was set at $P < 0.05$.



References

- AMSA. 2016. Research guidelines for cookery, sensory evaluation, and instrumental tenderness measurements of meat. 2 ed. American Meat Science Association, Champaign, IL.
- Bekhit, A., and C. Faustman. 2005. Metmyoglobin reducing activity. *Meat Sci.* 71(3):407-439.
- Berry, B.W. 1993. Tenderness of beef loin steaks as influenced by marbling level, removal of subcutaneous fat, and cooking method. *J. Anim. Sci.* 71:2412–2419.
- Beyer, E. S., Decker, L. K., Kidwell, E. G., McGinn, A. L., Chao, M. D., Zumbaugh, M. D., Vipham, J. L. & O'Quinn, T. G., (2024a) “Evaluation of Fresh and Frozen Beef Strip Loins of Equal Aging Periods for Palatability Traits”, *Meat and Muscle Biology* 8(1): 16903, 1-13. doi: <https://doi.org/10.22175/mmb.16903>
- Beyer, E. S., Farmer, K. J., Kidwell, E. G., Davis, S. G., Harr, K. M., Chao, M. D., Zumbaugh, M. D., Vipham, J. L., Hunt, M. C. & O'Quinn, T. G., (2024b) “Change in Myoglobin Denaturation and Physiochemical Properties Among Three Degrees of Doneness and Three Beef Whole Muscles”, *Meat and Muscle Biology* 8(1): 16919, 1-12. doi: <https://doi.org/10.22175/mmb.16919>
- Boles, J. A., and J. E. Swan. 2002. Heating method and final temperature affect processing characteristics of beef semimembranosus muscle. *Meat Science* 62:107–112.
- Decker, L. K., Beyer, E. S., Chao, M. D., Zumbaugh, M. D., Vipham, J. L. & O'Quinn, T. G., (2024) “Effects of Thawing Method on Palatability Traits, Quality Attributes, and Thawing Characteristics of Beef Steaks”, *Meat and Muscle Biology* 8(1): 17687, 1-17. doi: <https://doi.org/10.22175/mmb.17687>
- Drey, L. N., L. L. Prill, B. A. Olson, E. A. Rice, J. M. Gonzalez, J. L. Vipham, T. A. Houser, E. A. E. Boyle, and T. G. O'Quinn. 2019. Evaluation of marbling and enhancement's

- abilities to compensate for reduced beef palatability at elevated degrees of doneness. *Journal of Animal Science* 97:669-686. doi:10.1093/jas/sky435
- Fabre, R., et al. 2018. Cooking method effect on Warner–Bratzler shear force of different beef muscles. *Meat Science* 138:10–14.
- Farmer, K. J., Beyer, E. S., Davis, S. G., Harr, K. M., Lybarger, K. R., Egger, L. A., Chao, M. D., Vipham, J. L., Zumbaugh, M. D. & O'Quinn, T. G., (2022) “Evaluation of the Impact of Bone-in Versus Boneless Cuts on Beef Palatability”, *Meat and Muscle Biology* 6(1): 15488, 1-13. doi: <https://doi.org/10.22175/mmb.15488>
- Garber, L. L. Hyatt, E. M. Starr, R. G. 2000. The effects of food color on perceived flavor. *J. Mark. Theory Pract.* 8:59–72. doi:10.1080/10696679.2000.11501880
- García-Segovia, P., A. Andrés-Bello, and J. Martínez-Monzó. 2007. Effect of cooking method on mechanical properties, color and structure of beef muscle (M. pectoralis). *Journal of Food Engineering* 80(3):813–821.
- Herring, J. L., and R. W. Rogers. 2003. Evaluation of cooking methods on various beef steaks. *Journal of Muscle Foods* 14:163–171.
- Huber, G. E., T. M. Dieball, N. T. Acosta Castellanos, K. M. Gundersen, K. R. Maddock Carlin, M. D. Chao, J. L. Vipham, M. D. Zumbaugh, T. G. O'Quinn, and E. S. Beyer. 2025. The impact of degree of doneness, muscle source, and bloom time on cooked color and cooked color stability. *Kansas Agricultural Experiment Station Research Reports* 11:Article 8678.
- Kerth, C.R., L.K. Blair-Kerth, and W.R. Jones. 2003. Warner–Bratzler shear force repeatability in beef longissimus steaks cooked with a convection oven, broiler, or clam-shell grill. *J. Food Sci.* 68:668–670.

- Kim, J., Y. Zhang, Y. Han, Y. Lee, et al. 2025. The impact of cooking methods on the texture and color characteristics of beef, pork, and chicken. *Food Science and Preservation* 32(2):246–259.
- King, D. A., M. C. Hunt, S. Barbut, J. R. Claus, D. P. Cornforth, P. Joseph, Y. H. B. Kim, G. Lindahl, R. A. Mancini, and M. N. Nair. 2023. American Meat Science Association Guidelines for Meat Color Measurement. *Meat and Muscle Biology* 6.
- King, N. J., and R. Whyte. 2006. Does it look cooked? A review of factors that influence cooked meat color. *Journal of Food Science* 71(4):R31–R40.
- Lawrence, T.E., D.A. King, E. Obuz, E.J. Yancey, and M.E. Dikeman. 2001. Evaluation of electric belt-grill, forced-air convection oven, and electric broiler cookery methods for beef tenderness research. *J. Anim. Sci.* 79:2903–2911.
- McKenna, D. R., D. A. King, and J. W. Savell. 2004. Comparison of clamshell cookers and electric broilers on cooking traits and shear force repeatability. *Meat Science* 66:225–229.
- Miller, R. K., Gray, R. A., Kerth, C. R., Adhikari, K. & Neal, J., (2023) “Descriptive Beef Flavor Attributes and Consumer Acceptance Relationships for Heavy Beef Eaters”, *Meat and Muscle Biology* 7(1): 14449, 1-15. doi: <https://doi.org/10.22175/mmb.14449>
- Olson, B. A., E. A. Rice, L. L. Prill, L. N. Drey, J. M. Gonzalez, J. L. Vipham, M. D. Chao, and T. G. O’Quinn. 2019. Evaluation of beef top sirloin steaks of four quality grades cooked to three degrees of doneness. *Meat and Muscle Biology* 3:399-410.
doi:10.22175/mmb2019.07.0022
- Powell, T. H., M. E. Dikeman, and M. C. Hunt. 2000. Tenderness and collagen composition of semitendinosus roasts cooked by convective methods. *Meat Science* 55:421–425.

- Prill, L. L., O’Quinn, T. G., Chao, M. D., Vipham, J. L., Gonzalez, J. M., Boyle, E. A., Houser, T. A., Colle, M. J. & Bass, P. D., (2019a) “Do Published Cooking Temperatures Correspond with Consumer and Chef Perceptions of Steak Degrees of Doneness?”, *Meat and Muscle Biology* 3(2). doi: <https://doi.org/10.22175/mmb.10683>
- Prill, L. L., Drey, L. N., Olson, B. A., Rice, E. A., Gonzalez, J. M., Vipham, J. L., Chao, M. D., Bass, P. D., Colle, M. J. & O’Quinn, T. G., (2019b) “Visual Degree of Doneness Impacts Beef Palatability for Consumers with Different Degree of Doneness Preferences”, *Meat and Muscle Biology* 3(1). doi: <https://doi.org/10.22175/mmb2019.07.0024>
- Ryan, S. M., M. Seyfert, M. C. Hunt, and R. A. Mancini. 2006. Influence of cooking rate, endpoint temperature, post-cook hold time, and myoglobin redox state on internal color development of cooked ground beef patties. *J. Food Sci.* 71:C216-C221.
- Sepulveda, C. A., Garmyn, A., Legako, J. & Miller, M. F., (2019) “Cooking Method and USDA Quality Grade Affect Consumer Palatability and Flavor of Beef Strip Loin Steaks”, *Meat and Muscle Biology* 3(1), 375–388. doi: <https://doi.org/10.22175/mmb2019.07.0031>
- Vierck, K. R., Legako, J. F. & Brooks, J. C., (2021) “Evaluation of Dry-Heat Cookery Method on Volatile Flavor Compound Development and Consumer Evaluation of Six Beef Muscles”, *Meat and Muscle Biology* 5(1), 20, 1 – 14.
doi: <https://doi.org/10.22175/mmb.11710>
- Yancey, J. W., J. K. Apple, and M. C. Wharton. 2016. Cookery method and endpoint temperature effects on shear force and cooked color. *Journal of Animal Science* 94:4434–4446.
- Yancey, J. W., M. C. Wharton, and J. K. Apple. 2011. Cookery method and endpoint temperature effects on longissimus steaks. *Meat Science* 88:1–7.

Appendix A - Sensory panel evaluation forms

Informed Consent Statement

1. I volunteer to participate in research involving Sensory Evaluation of Meat. This research will be conducted by personnel in the Department of Animal Sciences and Industry at Kansas State University.

2. I fully understand the purpose of the research is for the evaluation of beef steaks, pork chops, lamb chops, goat meat, poultry meat, ground meat, and processed meat products from the previously mentioned species for the sensory traits of tenderness, juiciness, flavor intensity, connective tissue amount, off flavor presence, odor, and color and sensory evaluation will last approximately one hour.

3. I understand that there are minimal risks associated with participating and that those risks are related to possible food allergies. All meat products will be USDA inspected and all ingredients are GRAS (generally accepted as safe) by FDA.

4. I understand that my performance as an individual will be treated as research data and will in no way be associated with me for other than identification purposes, thereby assuring confidentiality of my performance and responses.

5. My participation in this study is purely voluntary; I understand that my refusal to participate will involve no penalty or loss of benefits to which I am otherwise entitled and that I may discontinue participation at any time without penalty or loss of benefits to which I am otherwise entitled.

6. If I have any questions concerning my rights as a research subject, injuries or emergencies resulting from my participation, I understand that I can contact the Committee on Research Involving Human Subjects, 203 Fairchild Hall, Kansas State University, Manhattan, KS 66506, at (785) 532-3224.

7. If I have questions about the rationale or method of the study, I understand that I may contact, Dr. Travis O'Quinn, 247 Weber Hall, Kansas State University, Manhattan, KS 66506, at (785) 532-3469 or Sally Stroda, 107 Weber Hall, at 785-532-1273.

I have read the Subject Orientation and Test Procedure statement and signed this informed consent statement, this _____ day of _____, _____.

Printed name

Signature

Please sign and return one copy. The second copy is for your records.

Consumer sensory panel ballot

Please tell us a little about yourself.

Panelist Number

Gender

Male

Female

Age

Under 20

20 to 29 years old

30 to 39 years old

40 to 49 years old

50 to 59 years old

over 60

Ethnic Origin

African American

Asian

Caucasian/White

Latino

Native American

Other

Mixed Race

Marital Status

Single

Married

Household Size

1 person
2 People
3 People
4 People
5 People
6 People
> 6 People

Annual Household Income

< \$25,000
\$25,000 - \$34,999
\$35,000 - \$49,999
\$50,000 - \$74,999
\$75,000 - \$99,999
\$100,000 - \$149,999
\$150,000 - \$199,999
> \$199,999

Highest Level of Education Completed

Non-High School Graduate

High School Graduate

Some College / Technical School

College Graduate

Post-College Graduate

When eating beef, what palatability trait is the most important to you?

Flavor

Juiciness

Tenderness

When consuming beef, which palatability trait do you experience the greatest amount of **variation** with?

Flavor

Juiciness

Tenderness

When eating beef steaks, what degree of doneness do you prefer?

Very Rare

Rare

Medium-Rare

Medium

Medium-Well

Well-Done

Very Well-Done

How many times a week do you consume beef?

0 3 6 9 12 15 18 21

None



Please indicate the importance of each trait when purchasing fresh beef steaks.

Animal Welfare

Extremely Unimportant
0

Extremely Important
100



Antibiotic use in the animal.

Extremely Unimportant
0

Extremely Important
100



Brand of Product

Extremely Unimportant
0

Extremely Important
100



Eating Satisfaction Claims (ex: Guaranteed Tender)

Extremely Unimportant
0

Extremely Important
100



Animal fed a corn-based diet

Extremely Unimportant
0

Extremely Important
100



Animal fed a forage-based (grass) diet

Extremely Unimportant
0

Extremely Important
100



Growth hormone use in the animal

Extremely Unimportant
0

Extremely Important
100



Natural or Organic Claims

Extremely Unimportant
0

Extremely Important
100



Nutrient Content

Extremely Unimportant
0

Extremely Important
100



Familiarity with cut

Extremely Unimportant
0

Extremely Important
100



Packaging Type

Extremely Unimportant
0

Extremely Important
100



Price

Extremely Unimportant
0

Extremely Important
100



Size, weight, and thickness

Extremely Unimportant
0

Extremely Important
100



Color

Extremely Unimportant
0

Extremely Important
100



USDA Grade

Extremely Unimportant
0

Extremely Important
100



Marbling

Extremely Unimportant
0

Extremely Important
100



Fresh Never Frozen

Extremely Unimportant
0

Extremely Important
100



Sample Number

6954

Juiciness

Extremely Dry
0

Neither Juicy nor Dry
50

Extremely Juicy
100

Juiciness



Was the sample acceptable for juiciness?

Acceptable

Unacceptable

Tenderness

Extremely Tough 0 Neither Tough nor Tender 50 Extremely Tender 100



Was the sample acceptable for tenderness?

Acceptable

Unacceptable

Flavor

Dislike Extremely 0 Neither Like nor Dislike 50 Like Extremely 100



Was the sample acceptable for flavor?

Acceptable

Unacceptable

Overall Liking

Dislike Extremely
0

Neither Like nor Dislike
50

Like Extremely
100

Overall



Was the sample acceptable overall?

Acceptable

Unacceptable

Overall Appearance

Dislike Extremely
0

Neither Like nor Dislike
50

Like Extremely
100

Overall Appearance



Was the sample acceptable for overall appearance?

Acceptable

Unacceptable

Does this sample meet your visual expectations for a well done degree of doneness?

Yes

No

If no, what degree of doneness would you choose to represent the sample? If yes, select N/A.

Very Rare

Rare

Medium Rare

Medium

Medium Well

Well Done

Very Well Done

N/A

