PALATABILITY EFFECTS OF BLADE TENDERIZATION ON BEEF TOP SIRLOIN STEAKS

A Thesis

by

ADAM RILEY MURRAY

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

MASTER OF SCIENCE

Chair of Committee,	Jeffrey W. Savell
Co-Chair of Committee,	Kerri B. Gehring
Committee Member,	Christopher R. Kerth
Head of Department,	G. Cliff Lamb

December 2017

Major Subject: Animal Science

ABSTRACT

The objective of this study was to determine if consumer satisfaction improves by blade tenderizing today's more inherently tender beef. Paired USDA Choice top sirloin butts (n = 20 total pieces) were collected from 10 carcasses representative of the typical carcass in today's fed beef market. Paired top sirloin butts were subjected to Warner-Bratzler Shear (WBS) force testing as a measure of objective tenderness. Consumer sensory evaluation was used to determine if consumers could discern differences in tenderness, flavor, juiciness, and overall likability between steaks from blade tenderized (BT) subprimals and steaks from non-blade tenderized (NBT) subprimals. Top sirloins from the left side of the carcass were blade tenderized once before portioning into steaks, whereas top sirloins from the right side of the carcass received no treatment and served as the control. Consumers found BT steaks to have higher ($P < 0.05$) likability ratings in tenderness, flavor, and overall like compared to NBT steaks. Consumer juiciness like showed no significant differences ($P > 0.05$), nor did WBS force values ($P > 0.05$). These data indicate that blade tenderization is an important process to improve consumer tenderness, flavor, and overall likability of beef top sirloins.

ACKNOWLEDGEMENTS

First off, thank you to all of my fellow graduate students that helped me during my time at Texas A&M. Kayley Wall, Ale Ochoa, Courtney Boykin, Drew Cassens, McKensie Harris, Hillary Martinez, Mark Frenzel, Clay Eastwood, Aeriel Belk, Michael Yeater, Katy Jo Nickelson, Spencer Tindel, Micki Gooch, Baylee Bessire, Wade Hanson, Becca Kirkpatrick, Jill Jobe, Martin Wu, Melissa Bamsey, Marc Vogelsang, Anderson Cabral, Hannah Laird, and Paige Smith were all influential in my education, whether it was through data collection, classwork, lab techniques, or just general conversation, patience, and friendship.

Kyle Phillips, Ray Riley, and all the student workers were endlessly helpful with anything we got in their way with at the Rosenthal Meat Science and Technology Center.

Professors in class, on my committee, or just within the building that I came in contact with, were all beneficial to my experience at Texas A&M, and sparked my intellectual interests in one way or another.

Thanks also go to new friends I made in Texas, and old ones in Virginia and Illinois, especially Nathan, Stiles, and the other three members of the Quartet of Danger, Josh, Reed, and Kurtis, for their support and comedic relief through this graduate school process.

Finally, thanks to Mama, Padre, and Em for all of their love and support.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of my advisor, Dr. Jeff Savell, co-advisor, Dr. Kerri Gehring, and committee member, Dr. Chris Kerth, all from the Department of Animal Science.

Funding Sources

This work was funded in part by Texas A&M Agrilife Research and the Beef Checkoff.

NOMENCLATURE

ANOVA	Analysis of Variance
°C	degrees Celsius
cm	centimeter
cwt	hundred weight
°F	degrees Fahrenheit
g	gram
h	hours
IMPS	Institutional Meat Purchasing Specifications
kg	kilogram
lb	pound
M.	muscle
min	minute
mm	millimeter
N	Newtons
oz	ounce
USDA	United States Department of Agriculture
WBS	Warner-Bratzler Shear

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

According to the U.S. Agricultural Marketing Service's Boxed Beef Reporting Dashboard (USDA, 2016), 730.26 loads of boneless Choice top sirloins were sold in the US in 2016, or over 14,500 tons. At the average price of $346.01/cwt. for IMPS #184 (NAMI, 2014) boneless Choice sirloins that year, these transactions were valued at $101,070,905, which does not even account for sirloins from any carcasses grading other than Choice (USDA, 2016). As such a widely-utilized cut in the retail, and especially foodservice sectors, the beef top sirloin steak is an important cut due to its demand by cost-concerned consumers. Yet, in further comparison to steaks from the rib and loin, the top sirloin often fails in delivering consistent and satisfactory eating experiences to foodservice clientele.

As stated by Wheeler et al. (1990), increased use of brand-identified retail beef products by beef packers and processors has resulted in more emphasis on the production of beef steaks that meet high standards of quality desired by consumers. The result of these expectations is that consumers are willing to pay more for beef that is guaranteed tender (Boleman et al., 1997). When consumer expectations are not met in the foodservice sector, the effects can be felt across the entire beef industry. Essentially, lower desirability for certain cuts can decrease overall demand for beef. The top sirloin is a specific cut of concern when evaluating steaks that can meet these high standards of quality, and further benefit branded programs and consumer markets.

During the 1990 National Beef Tenderness Survey, Morgan et al. (1991) identified top sirloin steaks as the toughest cut with the lowest sensory rating compared to other steaks from the loin, with over 50% of the consumer sensory scores ranking the retail cut below the "moderately tender" designation. The average WBS force value for top sirloins did improve to 29.82 N (3.04 kg) in the 1998 National Beef Tenderness Survey, but this was still the highest value for cuts from the rib and loin subprimals, and top sirloin steaks consistently performed the least favorably in the separate consumer ratings of foodservice steaks (Brooks et al., 2000). This trend continued in the 2010 National Beef Tenderness Survey (Guelker et al., 2013), where top sirloins only ranked above samples from the top round and bottom round in sensory retail tenderness evaluations. Furthermore, top sirloins maintained the highest percentage of steaks ranking "intermediate" and "tough" in the food service category when steaks were stratified by WBS force tenderness. Guelker et al. (2013) went on to elaborate in the 2010 National Beef Tenderness Survey that the reported WBS force values were similar to those in the 2006 survey (Voges et al., 2007), and that the industry could be experiencing a "possible plateau of beef tenderness." The 2015/2016 National Beef Tenderness Survey refuted this theory, reporting that the mean WBS force value of the top sirloin has gradually decreased from the previous survey, thus suggesting that beef is becoming inherently more tender (Martinez et al., 2017).

Tenderness begins with a genetic predisposition that has been incorporated into sire lines through selective breeding over the years. *Bos Indicus* breeds traditionally show higher genetic variance in terms of tenderness, but moderate heritability, implying a large potential for genetic improvement, whereas Angus and other "temperate" breeds show lower genetic variation to direct the focus to pre- and post-slaughter management protocols to improve tenderness (Robinson et al., 2001). Preslaughter animal management is widely regarded as having a significant effect on meat palatability (Ferguson et al., 2001), with Jeremiah et al. (1988) reporting that minimizing preslaughter stress levels in steers increases eating quality in terms of initial tenderness, overall tenderness, and perceived amounts of connective tissue when analyzed by a trained sensory panel. Eliciting the fight or flight response through preslaughter stress has a body-wide effect via the sympatho-adrenalmedullary and hypothalamic-pituitary-adrenal axes, and can affect glycolysis, lipolysis, pH, and proteolytic enzyme degradation in the carcass (Ferguson et al., 2001).

Epinephrine release accelerates metabolic processes in the body to reallocate nutrients to tissues and processes that the nervous system deems necessary for immediate survival. Increased epinephrine concentrations increases oxygen utilization and glucose uptake in active muscles by causing vasoconstriction in muscles not being used (Richter et al., 1982). This redistribution of glucose and increased breakdown of glycogen in animals excited preslaughter can greatly affect the carcass pH decline compared to normal slaughter conditions. Dark cutters and other quality problems in fresh meat are seen with particular severity within muscles from the hindquarter, like the *M. gluteus medius* (Purchas & Aungsupakorn, 1993; Tarrant & Sherington, 1980). These pH related quality issues are further accentuated in the predominately white, fast-twitch muscle fibers in the top sirloin due to their increased efficiency of glycolysis, and increased circulation to active muscles removes lactate at a higher rate than normal, further limiting the pH drop and therefore intensifying quality detriments associated with elevated pH in fresh meats (Richter et al., 1982). Increased epinephrine levels also increase calpastatin, the inhibitor of proteolytic enzymes associated with ageing-induced tenderization, by 97% within an hour after slaughter (Sensky et al., 1996). Richter et al. (1982) also showed significantly increased tension within myosin-actin interactions of cattle with higher epinephrine levels compared to controls. All of these metabolic processes associated with increased preslaughter stress have both direct and indirect consequences on muscle tenderness that can put packers at a disadvantage before there is even an opportunity to manipulate meat tenderness.

Steaks from the top sirloin continue to be noticeably tougher compared to cuts from adjacent loin and rib sections, with Sullivan and Calkins (2011) directly referencing the *M. gluteus medius* to be the least tender of the muscles utilized for steaks. Harris et al. (1992) found that differences in tenderness and consistency in top sirloin steaks was due, in large part, to higher amounts of collagen in combination with myofibrillar factors. Additionally, muscles with shorter sarcomeres tend to be less tender than those with longer sarcomeres (Harris et al., 1992).

Connective tissue is a major factor when attempting to explain meat tenderness, with Harris et al. (1992) attributing tenderness variations in top sirloin steaks mainly to higher amounts of collagen relative to the rest of the loin. Understanding the structure of connective tissue allows researchers to better describe how these tissues react to and resist force, and therefore their implications in perceived consumer tenderness. From this, the industry can better identify processes to mitigate decreases in tenderness attributed to connective tissue, and therefore increase consumer acceptability as a whole.

As the outer epimysium layer of connective tissue is removed from muscles during fabrication, the innermost endomysium and intermediate perimysium layers are of main concern when discussing the role connective plays in meat tenderness.

Contrary to previous beliefs, the endomysium is not composed of individual "sleeves" of connective tissue that fit over each muscle fiber, but it is instead a continuous honeycomb-like structure running throughout the thickness of the muscle (Purslow, 2005). Each portion of endomysium covering individual muscle fibers is connected to every other, and the intermediate fascicle bundle organizing them, by delicate collagenous fibers that act as lubrication as muscle fibers contract (Rowe, 1981). This foundational level of muscle organization runs parallel along the muscle to compartmentalize individual muscle fibers, and transfers contractile force longitudinally between adjacent muscle fibers (Purslow & Trotter, 1994). In isolating individual muscle fibers and analyzing them from a structural engineering standpoint, Mutungi et al. (1996) was able to find the stress load (the amount of tensile force required until the fiber fractured) and strain (the percent of stretching in relation to resting length a fiber could withstand until breaking) of muscle fibers with and without endomysial covering. While there was no difference in resistance to stress force between fibers with or without endomysial coverings, fibers with endomysial coverings could withstand a higher percentage of strain before fracturing (Mutungi et al., 1996). This is because at resting sarcomere lengths, collagen fibrils of the endomysium show a slight circumferential bias, wrapping around the muscle fiber they encase, but as the sarcomere length increases, the collagen fibrils orient more longitudinally along with muscle fiber direction (Purslow & Trotter, 1994). Conceptually this would create a spring-like resistance that would reduce force directed at the muscle fibers themselves, instead allowing the endomysium to resist the strain. Furthermore, this means that at shorter sarcomere lengths there would be more endomysium per unit length of muscle fiber, and therefore more connective tissue material to resist shear force.

As the most abundant level of connective tissue in muscle (Light et al., 1985), the function of the perimysium in live muscle tissue is to prevent over stretching, which is accomplished via its thick, cross-ply arrangement of collagen fibers into two layers (Purslow, 1989; Rowe, 1974, 1981). These two layers comprising the perimysium are oriented symmetrically about the direction of the muscle fibers at mirrored angles, usually around 50-60° when muscle is in a relaxed state (Purslow, 1989; Rowe, 1974). As the muscle is stretched, these fibers reorient to a lesser angle more in line with the direction of the muscle fibers; correspondingly if the muscle is shortened the collagen fiber angle increases to a more perpendicular orientation in relation to muscle fiber direction (Purslow, 1989; Rowe, 1974). Collagen is largely inelastic, so this reorientation with changing muscle shape is facilitated by natural crimps in each collagen fiber comprising the perimysium. Purslow (1989) observed the maximum crimp angle is achieved when the muscle is at rest, but if the muscle is either shortened or stretched these crimps are eliminated as the collagen fiber is forced to expand due to the strain from the muscle. As these crimps disappear and the collagen fiber crimp angle approaches 0°, meaning there is no crimp, the collagen fibers exhibit exponential resistance to force in an attempt to keep the muscle within its normal biological length (Purslow, 1989).

As the collagen fibers of the perimysium reorient and lose their crimp with shortened muscle this collagenous layer creates heavy resistance to shear forces, making the perimysium the largest driver of meat tenderness compared to other connective tissue layers (Purslow, 1989). Even with benefits to tenderness from elongated sarcomeres and the concurrent alignment of perimysial fibers along the muscle fiber direction, the inelasticity caused by loss of crimp to the collagenous fibers in the perimysium will decrease tenderness measurements (Purslow, 1989). In some cases there are even multiple levels of perimysium, organizing the muscle into primary and secondary fascicles when the natural function of the muscle necessitates different portions to slide past one another during contraction (Purslow, 2005). This helps explain why the "physical disruption" of connective tissue structures by blade tenderization is so effective in increasing tenderness in various muscles (King et al., 2009).

Across all muscles surveyed by Rhee et al. (2004), trained sensory panelist connective tissue ratings were reported to have the strongest correlation with steak tenderness, with the *M. gluteus medius* being identified as "slightly tough". There have been varying accounts of collagen content in the *M. gluteus medius*, with Harris et al. (1992) attributing the toughness of the muscle mainly to a high collagen content. This is supported by strong correlations between both total and insoluble collagen with WBS force reported by Torrescano et al. (2003), but it should be noted that dairy-type bulls were used in this study, so sweeping conclusions across the beef industry should be drawn with caution. McKeith et al. (1985) reported similar WBS force values to Torrescano et al. (2003), but found a low correlation between total collagen content of the *M. gluteus medius* and consumer sensory evaluations. Stolowski et al. (2006) showed a trend between muscles with higher collagen amounts and higher WBS force values, but only once collagen solubility was also accounted for were variations in tenderness between the *M. longissimus dorsi* and *M. gluteus medius* able to be described. With varying reports of the predictive value compositional analysis provides in terms of predicting tenderness, it is apparent that there are more factors influencing consumer acceptability of meat cuts than differing amounts of collagen.

Rather than chemical analysis determining compositional differences in amount of collagen, it has been proposed that collagen solubility plays a more significant role in accounting for variation in organoleptic and mechanical tenderness (Cross et al., 1973). As animals age, the adolescent divalent collagen crosslinks convert to trivalent crosslinks, which are much more mechanically and heat stable (Purslow, 2005). Light et al. (1985) reported that from selected beef muscles showing a range of tenderness, the tougher muscles contained 3 to 4 times more heat-stable collagen crosslinks than those traditionally regarded as tender. The same study found that a higher ratio of heat-stable crosslinks to heat-labile crosslinks within connective tissue would increase endomysial shrinkage and create greater tension in fascial bundles during cooking, resulting in increased resistance to shear and increased water loss to further decrease perceived tenderness (Light et al., 1985). The comparatively lower number of heat-stable crosslinks between collagen fibers from younger animals means this connective tissue is more soluble and heat labile, thereby hydrolyzing more readily during cooking to form soluble gelatins (Ledward, 1984).

Different cooking procedures can help to alleviate toughness due to connective tissue, but there are specific temperature ranges that can also accentuate problems with meat tenderness. At lower cooking temperatures of 40 to 50 °C, collagen fibers start to decrimp and straighten out, allowing them to stack more efficiently and therefore increase in strength and load bearing capacity (Christensen et al., 2000). As temperatures increase past 50 °C connective tissue continually weakens due to more extensive denaturation (Lewis & Purslow, 1989), but at higher temperatures myofibular components increase in toughness to a greater extent than the weakening of connective tissue. Mutungi et al. (1996) showed that although collagen is denaturing, at cooking temperatures of 80 °C individual muscle fibers require more than double the fracture stress force compared to fibers cooked at 50 °C. Although there is a significant correlation between cooked meat collagen sampling and trained sensory panel tenderness evaluation (Wheeler et al., 2002), other authors discount the prioritization of connective tissue as the main driver of meat tenderness.

Rhee et al. (2004) reported lower collagen levels, and directly stated that sarcomere length accounted for more of the tenderness variability in the *M. gluteus medius* than total collagen solubility. When comparing seven major muscles across a variation of breed types, Stolowski et al. (2006) found that the *M. gluteus medius* and *M. longissimus dorsi* had the lowest WBS force values and collagen amounts, disagreeing with previously described studies attributing top sirloin toughness mainly to connective tissue concentrations. Whereas Harris et al. (1992) and Torrescano et al. (2003) found a stronger correlation between WBS force and total collagen and insoluble collagen content over that of sarcomere length, Purslow (2005) considered connective tissue more of a "background contributor" to meat tenderness due to the difficulty in manipulating this factor. The variation of perimysium thickness, especially, reflects the different functions and workloads of separate muscles, so manipulation of this trait expression could potentially compromise muscle functionality in the live animal (Purslow, 2005). Instead, muscle fiber properties are said to have greater influence over WBS force and consumer evaluations rather than those of connective tissue (Cross et al., 1973).

Meat tenderness associated with sarcomere shortening during rigor, and sarcomere shortening and stretching are strongly correlated to muscle toughness and tenderness, respectively (Herring et al., 1966; Wheeler et al., 2000). Koohmaraie (1996) stated that "the shear force value at any given time is the balance between two opposing processes: sarcomere length shortening and tenderization," and that sarcomere shortening is responsible for the toughening of meat during the first 24 hours post slaughter. Goll et al. (1995) supports this by stating that 24-hour post mortem toughening is due to a stronger actin/myosin binding interaction, which "may be accompanied and exacerbated by shortening."

Due to the largely inelastic nature of connective tissue, the relative contribution collagen plays into meat tenderness in relation to contractile tissue is dependent on the ratio of sarcomere length to muscle fiber diameter, with shorter sarcomeres causing thicker muscle fibers and decreases in tenderness (Herring et al., 1965; Purslow &

Trotter, 1994). Traditional carcass hanging by the Achilles tendon creates very little flexure to the stifle joint, and without this antagonistic stretch to the *M. gluteus medius* during rigor there is no force applied to stretch the sarcomeres of this muscle, and therefore no benefit imparted to muscle tenderness (Hostetler et al., 1972). Consequently the *M. gluteus medius* was reported to have some of the shortest sarcomere lengths of those sampled by Stolowski et al. (2006).

A highly significant linear relationship exists between both shear force values and panel tenderness to sarcomere length, to the extent that a 50% decrease in sarcomere length led to a doubling of shear force values (Herring et al., 1967). The same study had panelists rate the tenderness of muscles after various durations of aging, and the tenderness of shortened muscles was still rated as “not acceptable” even following 10 days of aging (Herring et al., 1967). This carries significant impact because the industry has traditionally relied on aging as a method of tenderization, but the previously mentioned findings showed aging provided no detectable benefit to tenderness to muscles that were allowed to cold shorten. Wheeler et al. (2000) and Koohmaraie (1996) both reported that in meat where rigor induced shortening was prevented, the impact of proteolysis on tenderness is minimal.

Rhee et al. (2004) and Herring et al. (1965) both specifically note muscle fibers of the *M. gluteus medius* as having particularly short sarcomeres, with the latter attributing part of the absence of stretching due to muscle fiber type. The *M. gluteus medius* is predominately composed of anaerobically metabolizing white muscle fibers, which are lower in lipid content and thicker compared to red fibers (Hunt & Hedrick, 1977). These fibers develop rigor faster due to higher glycolytic activity, and therefore have shorter sarcomeres due to a more rapid rate of muscle contraction (Beecher et al., 1965). Muscle positioning within the carcass and fiber type together help to explain why the top sirloin traditionally records shorter sarcomere lengths compared to other cuts in the loin.

Shorter sarcomeres and higher collagen content correlate to muscle tenderness, and together explain why disruption of both contractile and connective tissues through blade tenderization has historically increased tenderness in the top sirloin (King et al., 2009; Savell et al., 1977). At the same time, there have been conflicting recommendations of how to best implement blade tenderization as a production strategy to optimize consumer tenderness likability, without simultaneously affecting other consumer product perceptions in a negative way. Savell et al. (1982) reported tenderness increases from a single treatment of blade tenderization to top sirloins with corresponding decreases in juiciness. George-Evins et al. (2004), however, reported that blade tenderizing top sirloins twice provided optimal tenderness benefits above single or no blade tenderization, without any detrimental effect to flavor or juiciness in comparison to non-blade tenderized controls. Davis et al. (1977) also attributed tenderness increases to blade tenderization without any effect to juiciness or flavor, but not enough to influence overall consumer like. Furthermore, Davis et al. (1977) reported that steaks from subprimals blade tenderized before storage at -10 °C had a larger proportion of total weight loss during storage, whereas steaks from subprimals blade tenderized following the same storage conditions had a larger proportion of total weight loss during cooking.

Perhaps the most important consequence of blade tenderization would be the microbial effect on meat products, specifically in terms of potential microbial translocation from the surface of meat to the interior of the cuts. Purge containing microorganisms can easily flow to conveyor belts and other food contact surfaces, and even the actual blades of the blade tenderizing machine could potentially carry pathogens. Regardless of the number of "incision events," the process of blade tenderization has a high probability of transferring a small amount of surface microorganisms to the interior of meat (Gill & McGinnis, 2005). Phebus et al. (2000) reported that blade tenderization carried "3 to 4% of surface contamination to the center of subprimals, regardless of initial surface contamination level." Luchansky et al. (2008) reported that most of the *E. coli* O157:H7 that was used in the study was concentrated in the top 1 cm of the subprimal, and it made no difference if the inoculum was applied to the lean side or fat side of the subprimal.

Although microbial transference decreases as blades penetrate deeper into the subprimal as purge collected on the blades wipes off (Gill & McGinnis, 2005), due to the nutrients in meat juices, microbial growth can start to occur in as little as 20 min, and bacterial levels as low as 10^3 CFU/g can start to become dangerous (Raccach & Henrickson, 1979). Potential pathogens from the surface of one subprimal can even remain attached to the blades of the machine, and be detected in the five subprimals following the initial contaminated subprimal (Johns et al., 2011). Once meat has been blade tenderized it is considered a non-intact product due to the puncture holes permeating the tissues, but there are no labeling requirements in the marketplace to differentiate blade tenderized products from non-blade tenderized products (Luchansky et al., 2008). These theories explain how there have been multiple incidents of foodborne illness traced back to blade tenderization and non-intact meat products (Laine et al., 2005).

Whereas there is a slightly higher risk of pathogen growth associated with nonintact meat products, it is important to note that blade tenderization does not create a greater risk to consumers as long as meat is properly cooked (Luchansky et al., 2008). When interventions are applied in the production system prior to blade tenderization, microbial transfer can be limited to less than 0.5% of surface concentrations (Heller et al., 2007). By designing machines that are easy to sanitize and that limit microbial attachment, like making thinner blades (Heller et al., 2007), contamination via purge and translocation from blade tenderized meat surfaces can be eliminated as a significant risk to consumer safety (Gill & McGinnis, 2005; Johns et al., 2011; Raccach & Henrickson, 1979).

Data from the National Beef Tenderness Surveys show that, with time, the industry has improved top sirloin tenderness both objectively, as described by WBS force, and subjectively, as reported by consumer sensory panels. The objective was to determine whether or not that consumer satisfaction is improved through blade tenderization of today’s more tender beef. It was hypothesized that blade tenderization of Choice top sirloins would produce more tender steaks in terms of both WBS force and consumer sensory panel values. Furthermore, non-blade tenderized Choice top sirloin steaks would still have an acceptable level of tenderness to meet the expectations of today's consumers.

2. MATERIALS AND METHODS

2.1 Product Collection

USDA Choice paired top sirloin butts (n = 20 total pieces), similar to USDA (2014) Institutional Meat Purchasing Specifications (IMPS) #184A (NAMI, 2014) but with the *M. gluteus profundus* and *M. gluteus accessorius* removed, were obtained from a beef plant in Friona, Texas. Ten USDA Choice carcasses harvested on the same date were selected for further fabrication into subprimals for use in this study. Carcasses from dairy-type cattle, *Bos indicus*-influenced cattle, and from cattle over 30 months of age were not used in order to obtain samples that represent the typical carcass in the US fed beef cattle production system. Eye faces of the *M. longissimus thoracis* ribbed between the 12th and 13th ribs were inspected for any quality defects that would have inferred the carcass was atypical, including but not limited to dark cutters, blood splash, or those showing excessive discoloration or an exudative nature. No selection preference was given to carcass sex class, weight, or presence or absence of black hide, but excessively heavy or light carcasses that would not yield a representative sample of what today's consumers call an "average steak" were not selected. Plant lot number and carcass ID were recorded along with the side weights for each carcass selected for use. Carcass side weight averaged 186.9 kg, and there were 3 heifers and 7 steers utilized within this study.

Laminated tags using the project numbering system (e.g. 1-L, 1-R, 2-L, 2-R) were used to identify sirloins through the fabrication process. These were attached to the flank of each side using shroud pins so that there was no physical alteration to the sirloin muscle fibers. Each sirloin was deboned and trimmed to predetermined specifications, and all fat was trimmed from the outer sirloin surfaces. Sirloins then were individually vacuum-packaged, with the labels visible, and packed five sirloins to a box in order to limit any variation in heat transfer. The boxes then were shipped under refrigerated conditions to a steak cutting facility in Dallas, Texas, for a 28-day refrigerated aging period, with "Day 0" being defined as the day of fabrication and vacuum-packaging. Upon arrival at Dallas packages were inspected for leakers or any signs of inadequate sealing, with no issues being identified.

Following the 28-day aging period, sirloins were removed from the packaging and trimmed of any visible discoloration or remaining surface fat. All sirloins from the left side of the carcasses were assigned to the blade tenderization (BT) treatment, whereas the sirloins from the right sides received no treatment and served as the control. Sirloins were run once, dorsal side facing up, through a commercial blade tenderizer (Ross TC700W, Midland, Virginia). All subprimals then were cut perpendicular to muscle fibers into 5 portions (2.5 cm thick) using a Grasselli (NSL 800, Albinea, Italy) slicer.

Portions were identified as 1, 2, 3, 4, and 5, with Portion 1 always starting on the cranial side. Portions 2 and 3 were used for this project. Three steaks (~170 g) were hand cut from each of these two portions. Steaks from Portion 2 were identified as A, B, C, and steaks from Portion 3 were identified as D, E, F. The first steak from Portion 2, Steak A, was assigned to WBS force. Steaks B, C, D, and E were assigned to consumer sensory analysis, and Steak F was held in reserve in case other steaks were compromised in some way to confound data collected from them. All steaks were individually vacuum packaged in rollstock, labeled, boxed, placed into insulated containers with ice packs, and transported to the Kleberg Animal and Food Sciences Center, Texas A&M University, College Station, Texas. Upon arrival, steaks were refrigerated (~ 0 ^{o}C) until subsequent cooking, consumer sensory analysis, and WBS force testing.

2.2 Cooking of Steaks

Cooking for WBS force and consumer sensory panels were both completed within 3 days of the steaks arriving in College Station. Both cooking protocols were performed on a Star International commercial flat top grill (Max Model 536-tgf, St. Louis, MO) preheated to 176 ^{o}C, +/- 2 ^{o}C, with internal steak temperatures being monitored using thermocouple readers (Model HH506A; Omega Engineering, Stanford, CT) and 0.02 cm diameter copper-constantan Type-T thermocouple wire (Omega Engineering) inserted into the geometric center of each steak. Each steak was flipped when the internal temperature reached 35 ^{o}C, and then removed from the flat-top when an internal temperature of 70 ^{o}C was met to signify a medium degree of doneness. Raw out of package weight, grill temperature, initial internal temperature, time on, final internal temperature, time off, and final cook weight were all collected on each steak. Percent cook loss and cooking time were calculated for each steak and averaged between treatments.

2.3 Objective Tenderness Evaluation

All steaks with an "A" designation were reserved for WBS force, placed in a single layer on plastic trays after cooking, covered with plastic wrap, and stored in refrigerated conditions of 2 to 4 ºC for 12 to 18 h before WBS force data was collected. Steaks were allowed to temper for at least an hour to room temperature, still covered, before being trimmed of visible connective tissue to expose muscle fiber orientation. Six 1.3-cm round cores were removed from the *M. gluteus medius* of each steak parallel to the muscle fibers, avoiding connective tissue and excess fat as much as possible, and then sheared once perpendicular to the muscle fibers (United Calibration Corp. model no. SSTM-500, Huntington Beach, CA) at a cross-head speed of 200 mm/min using a 10-kg load cell and a 1.02 mm thick V-shape blade with a 60 angle and a half-rounded peak. The equipment was calibrated before the start of sample data collection, and calibration was checked after shearing 60 cores. The peak force (kg) needed to shear each core was recorded, converted to Newtons (N), and the mean peak shear force of the cores of each steak was used for statistical analysis.

2.4 Consumer Sensory Evaluation

Procedures were approved by the Texas A&M Institutional Review Board for Use of Humans in Research (IRB2016-0227M). Steaks B-E were used for consumer sensory evaluation and cooked as described above for WBS force, while steaks with an "F" designation were held in the cooler as backup samples. Once a steak reached 70 °C, it was wrapped in food-grade aluminum foil and held in a preheated commercial warming oven until every member of the corresponding group was ready for that sample. Steaks did not stay in the warming oven for more than 20 min to limit variability after cooking.

Consumer panelists (n = 80 total, 20 per trial) were recruited from the Bryan/College Station area using an existing consumer database managed by the Texas A&M sensory group. Upon arrival at the sensory facility, panelists completed a demographic survey. Panelists were randomly divided into 5 groups, each consisting of 4 panelists. Each group received two matched pairs of steaks for sampling, served in a previously assigned blind and random order.

Steaks were cut into fourths after cooking, with each sample (one-fourth of a steak) presented on a plastic plate labeled with the three-digit ID number of the corresponding steak, along with a metal steak knife and a plastic fork. This serving style allowed panelists to cut into the product, which sometimes influences consumer acceptability (R. K. Miller, personal communication). A new fork was provided for with each sample, along with unsalted saltine crackers and deionized water for palate cleansing. The serving order of samples was randomized for each group to eliminate first-order bias. Samples were served through a breadbox-style sensory booth to individually seated panelists, and red lighting was utilized to prevent panelist bias for degree of doneness. Panelists were asked to evaluate the samples using 9-point scales (1 = dislike extremely; 9 = like extremely): overall liking, tenderness liking, flavor liking, and juiciness liking. Comments for what consumers liked most and least about each sample were analyzed using the Wordle online program (Feinberg, 2014), where the more often a word is used the bigger it is relative to the rest of the words in the graphic.

2.5 Statistical Analysis

Data were analyzed with paired t-tests using the matched pairs function of JMP (Version 12, SAS Institute, Inc., Cary, NC), at an alpha of 5%.

3. RESULTS

Table 1 shows the cooking and yield information for WBS force steaks, while paired t-test results for sensory panel ratings and WBS force values for steaks from BT and NBT are reported in Table 2. Treatment had no effect ($P > 0.05$) on neither cook yield nor cook time. Steaks from subprimals that were BT had higher ($P < 0.05$) tenderness ratings, flavor ratings, and overall like ratings than did steaks from the NBT treatment. Juiciness like ratings were not impacted by treatment ($P > 0.05$). Interestingly, although consumer tenderness differences occurred, there were no differences ($P > 0.05$) between treatments for WBS force values.

Table 1. Means and standard error for weights, cook yield, temperatures, and cook duration of WBS force steaks.

Item	*n*[1]	BT Mean	NBT Mean	SE	Prob > F
Raw weight (g)	10	181.7	172.7	2.67	0.0084
Grill surface temperature (°C)	10	176.4	176.1	0.62	0.66
Cooked weight (g)	10	129.3	126.5	4.10	0.51
Cook loss (%)	10	28.7	26.9	1.64	0.29
Cook duration (min)	10	21.4	18.3	2.29	0.21

[1] Number of steaks evaluated.

Table 2. Paired T-test and SEM for sensory panel ratings and Warner-Bratzler shear force values for top sirloin steaks from subprimals that were blade tenderized or not blade tenderized.

Treatment[1]	*n*[2]	Sensory panel ratings[3]				
		Overall like/dislike	Tenderness like/dislike	Flavor like/dislike	Juiciness like/dislike	Warner-Bratzler shear force (N)
BT	10	6.71	6.70	6.69	6.40	26.39
NBT	10	6.33	6.01	6.46	6.05	28.39
SEM		0.14	0.15	0.082	0.20	2.29
Prob > F		0.029	0.0011	0.020	0.11	0.44

[1] Treatment: BT = top sirloin butts were run once through a blade tenderizer before cutting into steaks; NBT = top sirloin butts were not blade tenderized before cutting into steaks.
[2] Number of subprimals per treatment.
[3] Sensory panel ratings: 9 = like extremely; 1 = dislike extremely.

Tables 3 and 4 show the carcass information of the subprimals selected and consumer panel demographics, respectively. Analysis of consumer panelist demographics show a practically even split between genders, and a broad representation of age ranges. Being a college town, students in their young to mid-20's were the predominant demographic, with a large majority identifying as white.

Table 3. Carcass data

Mean R Side Wt. (kg)	Mean L Side Wt. (kg)	Mean Carcass Wt. (kg)	Heifers	Steers	Type
188.7 n = 10	185.1 n = 10	373.8 n = 10	3	7	1 Beef 9 Black Angus

Table 4. Demographic breakdown

Gender	No. of Responses	% of Responses per Category
Male	39	48.75 %
Female	41	51.25 %
Age		
≤ 20 years	7	8.75 %
21-25 years	26	32.50 %
26-35 years	17	21.25 %
36-45 years	7	8.55 %
46-55 years	10	12.40 %
56-65 years	6	7.40 %
≥ 60 years	7	8.65 %
Employment		
Not employed	8	9.09 %
Full-time	28	31.82 %
Part-time	15	17.04 %
Student	37	42.04 %
Income		
< $25,000	28	35.00 %
$25,001-49,999	10	12.50 %
$50,000-74,999	14	17.50 %
$75,000-99,999	7	8.75 %
≥ $100,000	21	26.25 %
Allergies/Dietary Restrictions		
Yes	75	93.75 %
No	5	6.25 %
Race		
White	65	81.25 %
Hispanic	9	11.25 %
Asian/Pacific Islander	3	3.75 %
Black	3	3.75 %
Meats Consumed		
Chicken	79	26.15 %
Pork	76	25.16 %
Beef	80	26.48 %
Fish	67	22.85 %
Beef Frequency		
Daily	5	6.25 %
≥ 5 times/week	15	18.75 %
≥ 3 times/week	43	53.75 %

Once weekly	15	18.75 %
Once every 2 weeks	2	2.50 %
At Home Beef Consumption per Week		
0	3	3.84 %
1	18	23.08 %
2	24	30.77 %
3	21	26.93 %
4	7	8.97 %
5+	5	6.40 %
Restaurant Beef Consumption per Week		
0	1	1.27 %
1	37	46.84 %
2	22	27.85 %
3	10	12.66 %
4	5	6.34 %
5+	4	5.07 %
Degree of Doneness		
Rare	2	2.44 %
Medium rare	31	37.82 %
Medium	2	2.44 %
Medium well	34	41.47 %
Well done	13	15.86 %
Beef Purchasing Habits		
Grass-fed	11	9.57 %
Traditional	74	64.34 %
Aged	25	21.74 %
Organic	5	4.35 %

Comments from what consumers liked most and least about BT samples are presented as Wordles in Figures 1 and 2, respectively, while comments from what consumers liked most and least about NBT samples are presented as Wordles in Figures 3 and 4, respectively. “Flavor” appears to be the largest/most frequently used term in all Wordles comparing likes and dislikes of both treatments. “Juicy” and “tender” also appear frequently throughout all of the Wordles, while the terms “little,” “tough,” and “dry” appear noticeably in the dislike Wordles for both BT and NBT treatments.

Figure 1. Wordle of consumer BT like responses (Feinberg, 2014)

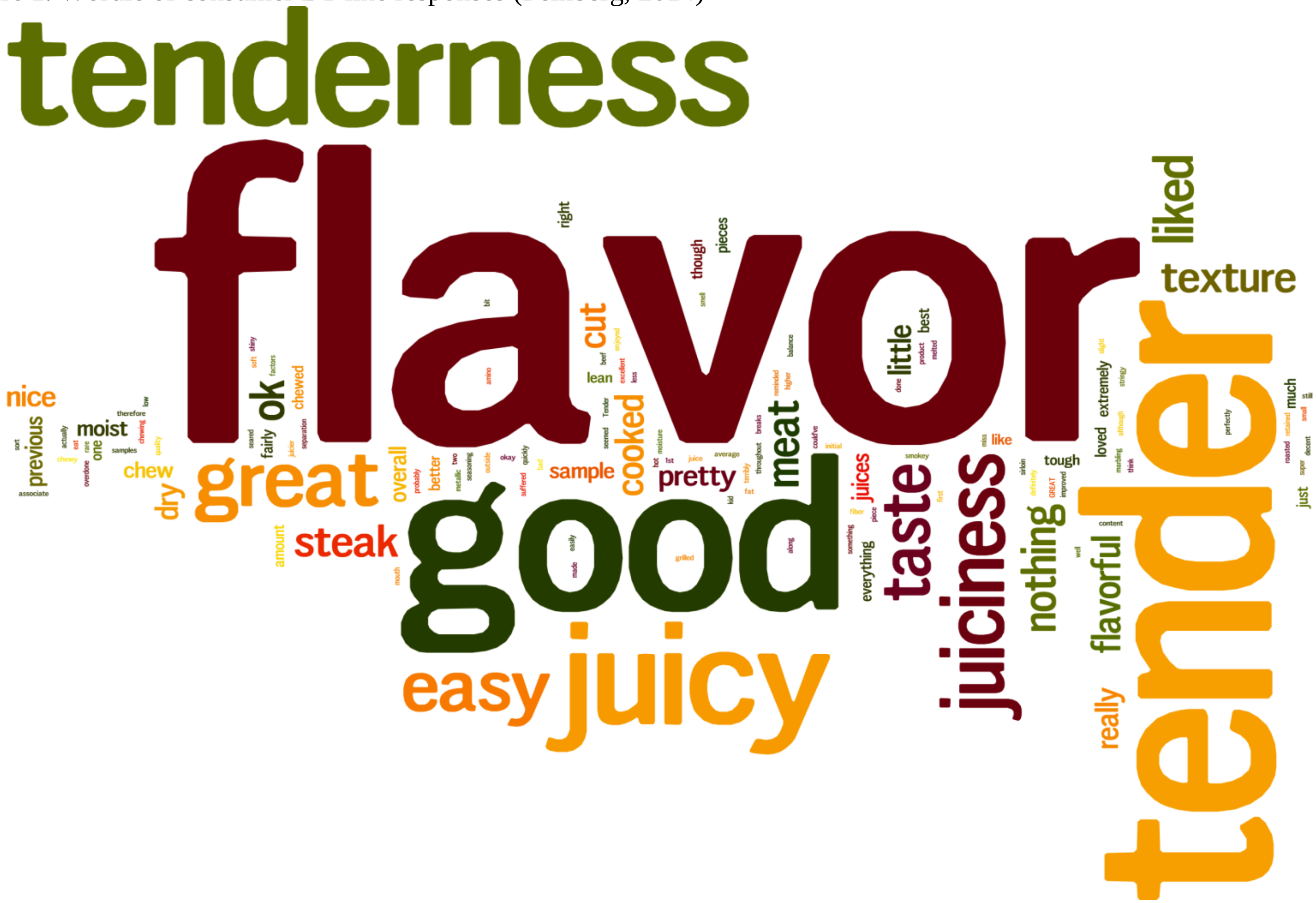


Figure 2. Wordle of consumer BT dislike responses (Feinberg, 2014)

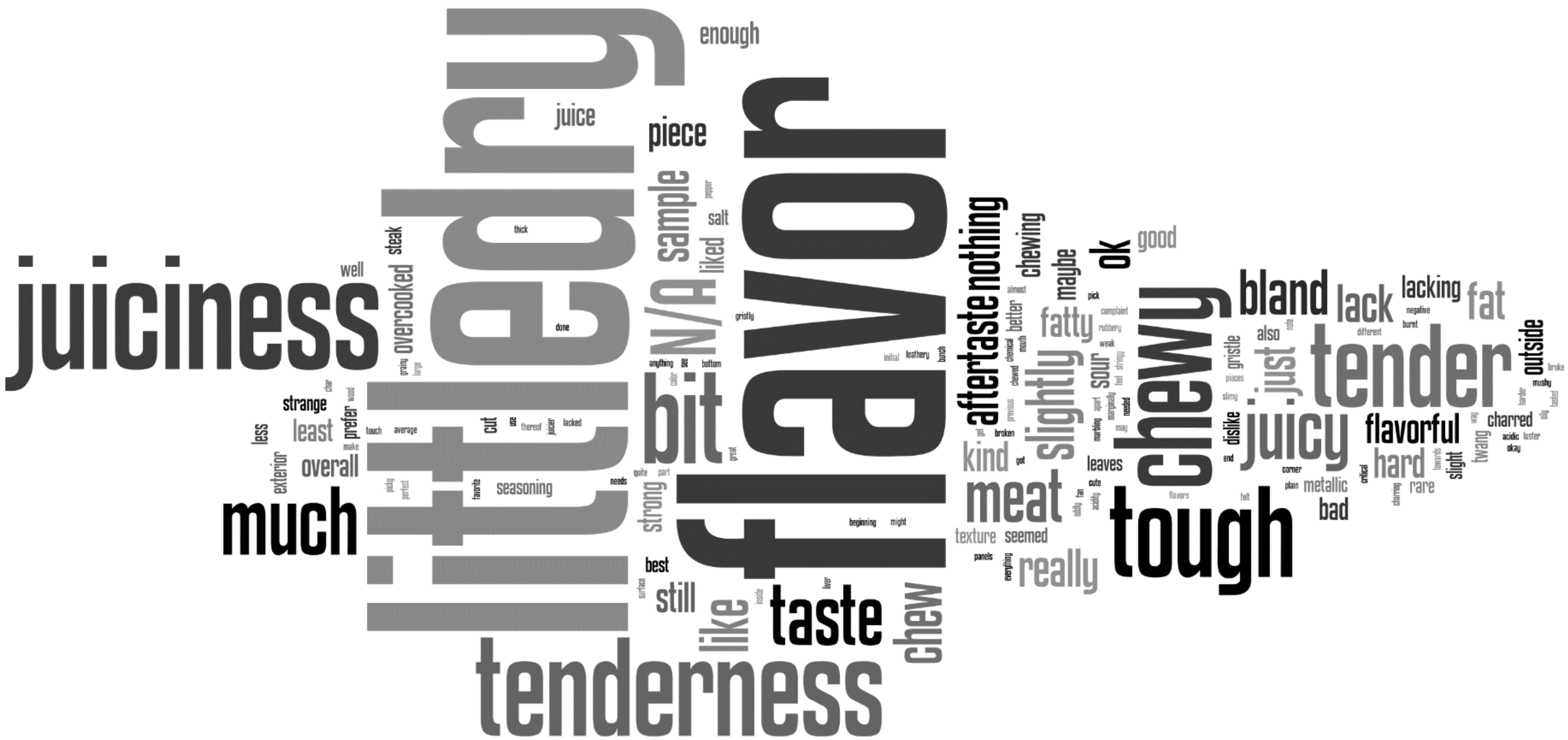


Figure 3. Wordle of consumer NBT like responses (Feinberg, 2014)

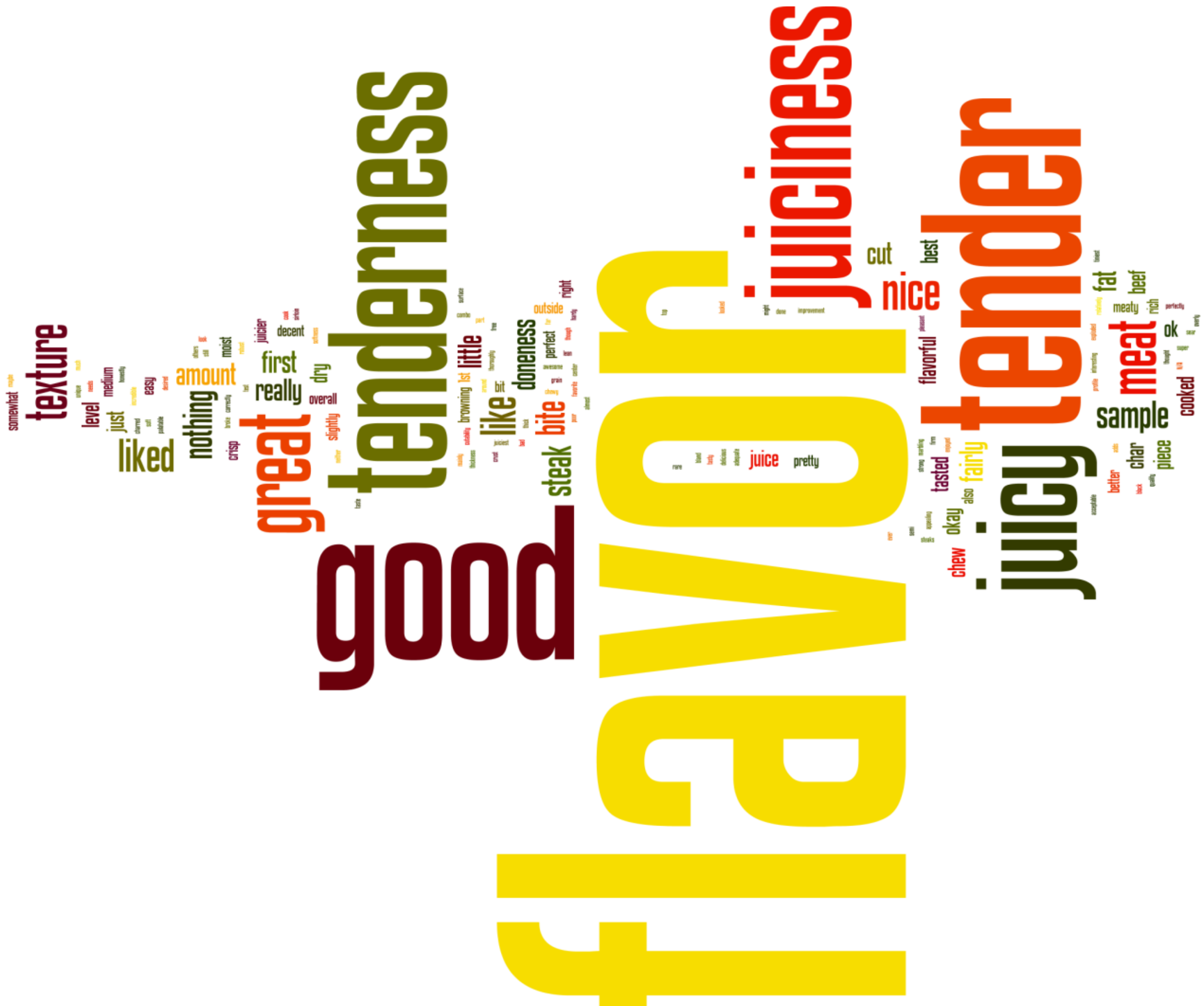
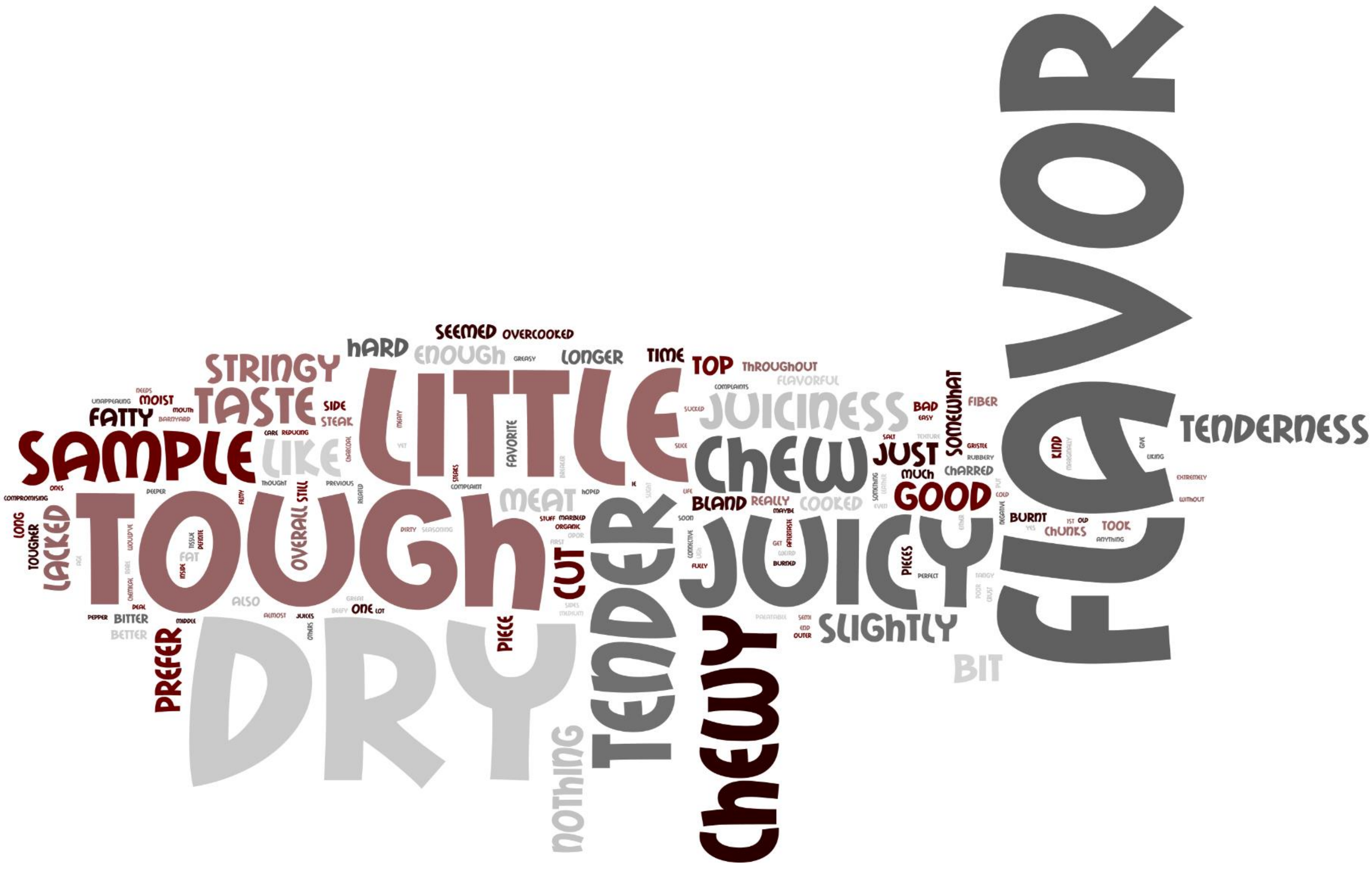


Figure 4. Wordle of consumer NBT dislike responses (Feinberg, 2014)



4. DISCUSSION

George-Evins et al. (2004), Savell et al. (1977), and King et al. (2009) found that blade tenderization of top sirloin subprimals improved overall tenderness of the *M. gluteus medius* when measured by sensory panelists, WBS force, and slice shear force, respectively. We expected that blade tenderization would result in improved WBS force values, but we did not expect consumer sensory panelists to differentiate between treatments. However, the opposite occurred in this study. There were no differences in WBS force values, but consumer sensory ratings for overall like and tenderness were higher for BT than NBT treatments.

Because of the location of the top sirloin on the carcass, the *M. gluteus medius* does not receive the antagonistic gravitational stretch imparted during rigor onto adjacent muscle fibers in the loin (Hostetler et al., 1972). Connective tissues have naturally adapted to resist stretching forces imparted on the muscles that they reinforce, but when lean fibers are not stretched within beef muscles, then the collagen in connective tissue accounts for more of the cross-sectional area in cuts, resulting in greater perceived meat toughness (Herring et al., 1965; Purslow & Trotter, 1994). With shorter muscle fibers strongly correlating with greater meat toughness (Harris et al., 1992), and the consequential increase of connective tissue impact on perceived meat tenderness, these collaborating factors help explain why the “physical disruption” of muscles by blade tenderization creates tenderness benefits in retail meat cuts (King et al., 2009).

Perceived tenderness difference identified by consumer panels, but not WBS force values, between BT and NBT samples in this study could be explained by the elevated level of input consumers received to evaluate tenderness by cutting their own bites from each sample. The coring process for WBS force evaluation is an effective way to objectively compare data from different studies in a standardized method, but by design, it avoids inclusion of connective tissue as much as possible (Rhee et al., 2004). The thought was that the act of physically cutting their own bite would give consumers a more holistic experience of tenderness, and potentially provide greater sensitivity in their evaluation of tenderness through the tactile input. Using dull knives to cut meat compared to sharp knives can increase human grip force on the handle by around 20% (McGorry et al., 2005), and duller knives require more cutting movements and time to do the same job compared to sharpened knives (McGorry et al., 2003). With that in mind, it is apparent that there is a discernable amount of force applied while cutting meat, which could potentially influence consumer perception of steak tenderness. By making each sample a quarter of a top sirloin steak and having consumers cut their own bites, there was no chance to accidentally influence the probability of a bite containing connective tissue by artificially selecting which pre-cut piece was given to a panelist. Furthermore, it indirectly gave consumers more information on the tenderness of each steak so that they could more confidently evaluate each sample for tenderness during the panel.

At the same time, using a metal steak knife provided more real-world applicability and power to the data by removing some of the laboratory setting bias. In the traditional method of steak consumer sensory panels, pre-cut, bite-sized pieces are presented to panelists in some sort of disposable container for them to evaluate from a consumer's perspective. Consequently, this is not the common way consumers eat steaks, so presenting cubed samples in plastic cups has the potential to increase the artificial, laboratory-type atmosphere of the testing environment. This study worked to minimize this potential bias, by serving samples on picnic-style plates with metal steak knives to cut the samples so that it would be a more familiar way for consumers to evaluate steaks. In this way, the conclusions of this study should provide a greater description into the consumer mindset of steak preference to supplement data using traditional consumer testing methodology.

Figures 1, 2, 3, and 4 all show separate Wordles created from comments written by panelists depending on what treatment, and whether it was a "liked most" or "liked least" comment. The larger a word appears in a Wordle, the more prevalent it was mentioned in the comments collected for either category (Feinberg, 2014). Upon examination, the term "flavor" dominates both the like and the dislike Wordles of both treatments, implying that consumers found this trait to be confusing or difficult to describe across the samples. Steaks that have been blade tenderized can result in reduced amounts of compounds from both lipid oxidation and the Maillard reaction (Gerlach, 2014), so depending on individual taste preferences, this could affect consumer flavor likability in different ways. Platter et al. (2003) reported that even small differences in consumer rated tenderness, flavor, and juiciness can affect the overall acceptance of beef, so these potential variations in lipid oxidation and Maillard reaction compounds between BT and NBT steaks could explain the significance seen between treatments in this study.

5. CONCLUSIONS

Today's inherently more tender beef has been a benefit to the industry, and because of this, traditional practices like blade tenderization need to be revisited to ensure that their benefits are still worthwhile. This study showed that blade tenderization did improve sensory panel tenderness, flavor, and overall like ratings compared to the non-blade tenderized controls. Even though WBS force values were similar between treatments, those improvements in sensory panel ratings with blade tenderization show that this traditional method of enhancing tenderness is still beneficial for the top sirloin steak.

REFERENCES

Beecher, G. R., Cassens, R. G., Hoekstra, W. G., & Briskey, E. J. (1965). Red and white fiber content and associated post-mortem properties of seven porcine muscles. *Journal of Food Science*, *30*(6), 969-976.

Boleman, S. J., Boleman, S. L., Miller, R. K., Taylor, J. F., Cross, H. R., Wheeler, T. L., Koohmaraie, M., Shackelford, S. D., Miller, M. F., West, R. L., Johnson, D. D., & Savell, J. W. (1997). Consumer evaluation of beef of known categories of tenderness. *Journal of Animal Science, 75*(6), 1521-1524.

Brooks, J. C., Belew, J. B., Griffin, D. B., Gwartney, B. L., Hale, D. S., Henning, W. R., Johnson, D. D., Morgan, J. B., Parrish, F. C., Reagan, J. O., & Savell, J. W. (2000). National Beef Tenderness Survey-1998. *Journal of Animal Science, 78*(7), 1852-1860.

Christensen, M., Purslow, P. P., & Larsen, L. M. (2000). The effect of cooking temperature on mechanical properties of whole meat, single muscle fibres and perimysial connective tissue. *Meat Science*, *55*(3), 301-307.

Cross, H. R., Carpenter, Z. L., & Smith, G. C. (1973). Effects of intramuscular collagen and elastin on bovine muscle tenderness. *Journal of Food Science*, *38*(6), 998-1003.

Davis, G. W., Smith, G. C., & Carpenter, Z. L. (1977). Effect of blade tenderization on storage life, retail caselife and palatability of beef. *Journal of Food Science, 42*(2), 330-337.

Feinberg, J. (2014). Wordle. Available from http://www.wordle.net. Accessed

Ferguson, D. M., Bruce, H. L., Thompson, J. M., Egan, A. F., Perry, D., & Shorthose, W. R. (2001). Factors affecting beef palatability- farmgate to chilled carcass. *Australian Journal of Experimental Agriculture*, *41*(7), 879-891.

George-Evins, C. D., Unruh, J. A., Waylan, A. T., & Marsden, J. L. (2004). Influence of quality classification, aging period, blade tenderization, and endpoint cooking temperature on cooking characteristics and tenderness of beef gluteus medius steaks. *Journal of Animal Science, 82*(6), 1863-1867.

Gerlach, B. M. (2014). The effects of exercise on beef cattle health, performance, and carcass quality; and the effects of extended aging, blade tenderization, and degree of doneness on beef aroma volatile formation. Kansas State University.

Gill, C. O., & McGinnis, J. C. (2005). Factors affecting the microbiological condition of the deep tissues of mechanically tenderized beef. *Journal of Food Protection, 68*(4), 796-800.

Goll, D. E., Greesink, G. H., Taylor, R. G., & Thompson, V. F. (1995). In *Proceedings of the International Congress of Meat Science and Technology* (537), San Antonio, Texas USA.

Guelker, M. R., Haneklaus, A. N., Brooks, J. C., Carr, C. C., Delmore, R. J., Griffin, D. B., Hale, D. S., Harris, K. B., Mafi, G. G., Johnson, D. D., Lorenzen, C. L., Maddock, R. J., Martin, J. N., Miller, R. K., Raines, C. R., VanOverbeke, D. L., Vedral, L. L., Wasser, B. E., & Savell, J. W. (2013). National Beef Tenderness Survey–2010: Warner-Bratzler shear force values and sensory panel ratings for beef steaks from United States retail and food service establishments. *Journal of Animal Science, 91*(2), 1005-1014.

Harris, J. J., Miller, R. K., Savell, J. W., Cross, H. R., & Ringer, L. J. (1992). Evaluation of the tenderness of beef top sirloin steaks. *Journal of Food Science, 57*(1), 6-9.

Heller, C. E., Scanga, J. A., Sofos, J. N., Belk, K. E., Warren-Serna, W., Bellinger, G. R., Bacon, R. T., Rossman, M. L., & Smith, G. C. (2007). Decontamination of beef subprimal cuts intended for blade tenderization or moisture enhancement. *Journal of Food Protection, 70*(5), 1174-1180.

Herring, H. K., Cassens, R. G., & Briskey, E. J. (1966). Studies on bovine muscle tenderness: Effect of contraction state, carcass marurity and postmortem aging. In *Proceedings of the 58th Annual Meeting of the American Society of Animal Science* (877-933),

Herring, H. K., Cassens, R. G., & Rriskey, E. J. (1965). Further studies on bovine muscle tenderness as influenced by carcass position, sarcomere length, and fiber diameter. *Journal of Food Science, 30*(6), 1049-1054.

Herring, H. K., Cassens, R. G., Suess, G. G., Brungardt, V. H., & Briskey, E. J. (1967). Tenderness and associated characteristics of stretched and contracted bovine muscles. *Journal of Food Science, 32*(3), 317-323.

Hostetler, R. L., Link, B. A., Landmann, W. A., & Fitzhugh, H. A. (1972). Effect of carcass suspension on sarcomere length and shear force of some major bovine muscles. *Journal of Food Science, 37*(1), 132-135.

Hunt, M. C., & Hedrick, H. B. (1977). Profile of fiber types and related properties of five bovine muscles. *Journal of Food Science, 42*(2), 513-517.

Jeremiah, L. E., Newman, J. A., Tong, A. K. W., & Gibson, L. L. (1988). The effects of castration, preslaughter stress and zeranol implants on beef: Part 1—The texture of loin steaks from bovine males. *Meat Science*, *22*(2), 83-101.

Johns, D. F., Bratcher, C. L., Kerth, C. R., & McCaskey, T. (2011). Translocation of surface-inoculated Escherichia coli into whole muscle nonintact beef striploins following blade tenderization. *Journal of Food Protection*, *74*(8), 1334-1337.

King, D. A., Wheeler, T. L., Shackelford, S. D., Pfeiffer, K. D., Nickelson, R., & Koohmaraie, M. (2009). Effect of blade tenderization, aging time, and aging temperature on tenderness of beef longissimus lumborum and gluteus medius. *Journal of Animal Science*, *87*(9), 2952-2960.

Koohmaraie, M. (1996). Biochemical factors regulating the toughening and tenderization processes of meat. *Meat Science*, *43*, 193-201.

Laine, E. S., Scheftel, J. M., Boxrud, D. J., Vought, K. J., Danila, R. N., Elfering, K. M., & Smith, K. E. (2005). Outbreak of Escherichia coli O157:H7 infections associated with nonintact blade-tenderized frozen steaks sold by door-to-door vendors. *Journal of Food Protection*, *68*(6), 1198-1202.

Ledward, D. A. (1984). Thermal stability of connective tissue in meat and meat products. In *Proceedings of the Journal of the Science of Food and Agriculture* (1262-1262),

Lewis, G. J., & Purslow, P. P. (1989). The strength and stiffness of perimysial connective tissue isolated from cooked beef muscle. *Meat Science*, *26*(4), 255-269.

Light, N., Champion, A. E., Voyle, C., & Bailey, A. J. (1985). The role of epimysial, perimysial and endomysial collagen in determining texture in six bovine muscles. *Meat Science*, *13*(3), 137-149.

Luchansky, J. B., Phebus, R. K., Thippareddi, H., & Call, A. E. (2008). Translocation of surface-inoculated *Escherichia coli* O157:H7 into beef subprimals following blade tenderization. *Journal of Food Protection*, *71*(11), 2190-2197.

Martinez, H. A., Arnold, A. N., Brooks, J. C., Carr, C. C., Gehring, K. B., Griffin, D. B., Hale, D. S., Mafi, G. G., Johnson, D. D., Lorenzen, C. L., Maddock, R. J., Miller, R. K., VanOverbeke, D. L., Wasser, B. E., & Savell, J. W. (2017). National Beef Tenderness Survey-2015: Palatability and shear force assessments of retail and foodservice beef. *Meat and Muscle Biology*, *1*, 138-148.

McGorry, R. W., Dowd, P. C., & Dempsey, P. G. (2003). Cutting moments and grip forces in meat cutting operations and the effect of knife sharpness. *Applied Ergonomics, 34*(4), 375-382.

McGorry, R. W., Dowd, P. C., & Dempsey, P. G. (2005). The effect of blade finish and blade edge angle on forces used in meat cutting operations. *Applied Ergonomics, 36*(1), 71-77.

McKeith, F. K., De Vol, D. L., Miles, R. S., Bechtel, P. J., & Carr, T. R. (1985). Chemical and sensory properties of thirteen major beef muscles. *Journal of Food Science, 50*(4), 869-872.

Morgan, J. B., Savell, J. W., Hale, D. S., Miller, R. K., Griffin, D. B., Cross, H. R., & Shackelford, S. D. (1991). National Beef Tenderness Survey. *Journal of Animal Science, 69*(8), 3274-3283.

Mutungi, G., Purslow, P., & Warkup, C. (1996). Influence of temperature, fibre diameter and conditioning on the mechanical properties of single muscle fibres extended to fracture. *Journal of the Science of Food and Agriculture, 72*(3), 359-366.

NAMI. (2014). *The Meat Buyer's Guide* (8th). Washington, DC: North American Meat Association.

Phebus, R. K., Thippareddi, H., Sporing, S., Marsden, J. L., & Kastner, C. L. 2000. Escherichia coli O157: H7 risk assessment for blade-tenderized beef steaks No. 2000. p 117-118, Cattlemen’s Day.

Platter, W. J., Tatum, J. D., Belk, K. E., Chapman, P. L., Scanga, J. A., & Smith, G. C. (2003). Relationships of consumer sensory ratings, marbling score, and shear force value to consumer acceptance of beef strip loin steaks. *Journal of Animal Science, 81*(11), 2741-2750.

Purchas, R. W., & Aungsupakorn, R. (1993). Further investigations into the relationship between ultimate pH and tenderness for beef samples from bulls and steers. *Meat Science, 34*(2), 163-178.

Purslow, P. P. (1989). Strain-induced reorientation of an intramuscular connective tissue network: Implications for passive muscle elasticity. *Journal of Biomechanics, 22*(1), 21-31.

Purslow, P. P. (2005). Intramuscular connective tissue and its role in meat quality. *Meat Science, 70*(3), 435-447.

Purslow, P. P., & Trotter, J. A. (1994). The morphology and mechanical properties of endomysium in series-fibred muscles: variations with muscle length. *Journal of Muscle Research & Cell Motility*, *15*(3), 299-308.

Raccach, M., & Henrickson, R. L. (1979). Microbial aspects of mechanical tenderization of beef. *Journal of Food Protection*, *42*(12), 971-973.

Rhee, M. S., Wheeler, T. L., Shackelford, S. D., & Koohmaraie, M. (2004). Variation in palatability and biochemical traits within and among eleven beef muscles. *Journal of Animal Science*, *82*(2), 534-550.

Richter, E. A., Ruderman, N. B., Gavras, H., Belur, E. R., & Galbo, H. (1982). Muscle glycogenolysis during exercise: dual control by epinephrine and contractions. *American Journal of Physiology-Endocrinology And Metabolism*, *242*(1), E25-E32.

Robinson, D. L., Ferguson, D. M., Oddy, V. H., Perry, D., & Thompson, J. (2001). Genetic and environmental influences on beef tenderness. *Australian Journal of Experimental Agriculture*, *41*(7), 997-1003.

Rowe, R. W. D. (1974). Collagen fibre arrangement in intramuscular connective tissue. Changes associated with muscle shortening and their possible relevance to raw meat toughness measurements. *International Journal of Food Science & Technology*, *9*(4), 501-508.

Rowe, R. W. D. (1981). Morphology of perimysial and endomysial connective tissue in skeletal muscle. *Tissue and Cell*, *13*(4), 681-690.

Savell, J. W., McKeith, F. K., Murphey, C. E., Smith, G. C., & Carpenter, Z. L. (1982). Singular and combined effects of electrical stimulation, post-mortem ageing and blade tenderisation on the palatability attributes of beef from young bulls. *Meat Science*, *6*(2), 97-109.

Savell, J. W., Smith, G. C., & Carpenter, Z. L. (1977). Blade tenderization of four muscles from three weight-grade groups of beef. *Journal of Food Science*, *42*(4), 866-870.

Sensky, P. L., Parr, T., Bardsley, R. G., & Buttery, P. J. (1996). The relationship between plasma epinephrine concentration and the activity of the calpain enzyme system in porcine longissimus muscle. *Journal of Animal Science, 74*(2), 380-387.

Stolowski, G. D., Baird, B. E., Miller, R. K., Savell, J. W., Sams, A. R., Taylor, J. F., Sanders, J. O., & Smith, S. B. (2006). Factors influencing the variation in tenderness of seven major beef muscles from three Angus and Brahman breed crosses. *Meat Science*, *73*(3), 475-483.

Sullivan, G. A., & Calkins, C. R. (2011). Ranking beef muscles for Warner-Bratzler shear force and trained sensory panel ratings from published literature. *Journal of Food Quality*, *34*(3), 195-203.

Tarrant, P. V., & Sherington, J. (1980). An investigation of ultimate pH in the muscles of commercial beef carcasses. *Meat Science*, *4*(4), 287-297.

Torrescano, G., Sánchez-Escalante, A., Giménez, B., Roncalés, P., & Beltrán, J. A. (2003). Shear values of raw samples of 14 bovine muscles and their relation to muscle collagen characteristics. *Meat Science*, *64*(1), 85-91.

USDA. (2016). Boxed beef reporting dashboard. USDA, AMS, LPS, LPGMN, 1400 Independence Ave, SW, Room 2619-S, STOP 0252, Washington, DC 20250-0252: Agricultural Marketing Service, USDA. Available from mpr.datamart.ams.usda.gov/amsdashboard/boxed_beef/BoxedBeef_Dashboard_Option_1.html. Accessed 22 August 2017.

Voges, K. L., Mason, C. L., Brooks, J. C., Delmore, R. J., Griffin, D. B., Hale, D. S., Henning, W. R., Johnson, D. D., Lorenzen, C. L., Maddock, R. J., Miller, R. K., Morgan, J. B., Baird, B. E., Gwartney, B. L., & Savell, J. W. (2007). National Beef Tenderness Survey – 2006: Assessment of Warner–Bratzler shear and sensory panel ratings for beef from US retail and foodservice establishments. *Meat Science*, *77*(3), 357-364.

Wheeler, T. L., Miller, R. K., Savell, J. W., & Cross, H. R. (1990). Palatability of chilled and frozen beef steaks. *Journal of Food Science*, *55*(2), 301-304.

Wheeler, T. L., Shackelford, S. D., & Koohmaraie, M. (2000). Variation in proteolysis, sarcomere length, collagen content, and tenderness among major pork muscles. *Journal of Animal Science*, *78*(4), 958-965.

Wheeler, T. L., Shackelford, S. D., & Koohmaraie, M. (2002). Technical note: Sampling methodology for relating sarcomere length, collagen concentration, and the extent of postmortem proteolysis to beef and pork longissimus tenderness. *Journal of Animal Science*, *80*(4), 982-987.