Effects of Extended Deboning Times on the Breast Meat Quality of Fast-Growing Big Broilers

by

Meredith Lane Johnson

A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
May 6, 2018

Approved by

Amit Morey, Chair, Assistant Professor of Poultry Science
Dianna Bourassa, Assistant Professor and Extension Specialist of Poultry Science
Christy Bratcher, Associate Professor of Animal Science

Abstract

Big broilers can be affected with wooden breast myopathy leading to quality issues such as tough meat texture. Toughness is possibly enhanced due to deboning broilers at 2-3 h post-mortem with incomplete resolution of rigor mortis. In a two-part study, we investigated the effects of extended deboning times on meat quality and optimized them to obtain tender fillets. Breast fillets deboned at 2, 16, 20 and 24 h from big broilers (n = 90) were compared to normal jumbo, wooden jumbo, and normal medium fillets for meat quality attributes (color, texture and cook loss). Data indicated that the texture attributes (peak force, shear energy and peak counts) of extended deboned fillets were significantly lower ($p \leq 0.05$) than the woody fillets indicating tender fillet. There was no statistical difference between cook loss, color, and Blunt MORS (BMORS) ($p < 0.05$) when compared between the 16, 20 and 24 h treatments indicating complete resolution of rigor at 16 h. Another study was conducted to evaluate if less than 16 h deboning times can be used to improve meat quality. Toughness, indicated by peak force and shear energy, significantly decreased ($p \leq 0.05$) with an increase in deboning times from, 3 to 27 h. Peak force and shear energy values at 3 h decreased ($p \leq 0.05$) from 21.86 N and 264.15 N.mm to 16.16 N and 205.17 N.mm, respectively after 11 h post-mortem. In conclusion, extended deboning time of 7-27 h can significantly improve the texture of breast fillets from fast-growing broilers.

Acknowledgments

I would like to extend a special thank you to my parents, Rhonda and Everette Johnson, for the unending encouragement to persevere whatever challenges I endure. They have always pushed me to stick to my goals and will always be my favorite supporters.

This research project would not have been possible without Dr. Morey and his lab. Dr. Morey has given me an opportunity that I cannot repay, and I am eternally grateful. Dr. Bauermeister, Avery Smith, Allan Pinto, Ada Madrid, and myself spent countless hours together working at the farm and in the lab, collecting and analyzing data. I would like to extend a special thank you to Wes Cumbie and Greg West of AlaTrade Foods Inc, as well as the workers of Wayne Farms in Union Springs, Alabama.

A final thanks, to the beautiful ladies of the Auburn Women's Club Ultimate Frisbee Team. Playing on a team during this stressful time of my life forced me to get outside, stay active, and refresh my brain, no matter how exhausted I was. I appreciate everything, from the tough workouts and long practices, to winning championships and unconditional love from my great buds.

Table of Contents

List of Tables

List of Abbreviations

MORS	Meullenet-Owens Razor Shear
BMORS	Blunt Meullenet-Owens Razor Shear
PM	Post-mortem
WB	Wooden Breast
WHC	Water Holding Capacity

CHAPTER I.

INTRODUCTION OF LITERATURE REVIEW

The evolving production standards for broiler meat has drastically changed through the past decades due to the increasing market demand for poultry products and population growth (Petracci et al., 2015). Additionally, consumer trends indicate an increased demand for poultry meat due to its health benefits, reasonable market price, convenience, and adaptability to multiple types of cooking (Petracci et al., 2015). In the early 1900s, the poultry industry focused on selecting birds based on carcass yield and live bird characteristics (Petracci et al., 2015). However, modern trends in the past 50 years have been focused towards an increasing demand for convenient and high-quality poultry products (USDA, 1995), causing processors to explore for ways to advance their efficiency and leading to a surge in the further processed market. The increased demand for poultry meat has led poultry industry to change the production standards and develop fast-growing, high breast meat yielding broiler strains. (Petracci et al., 2015, Aviagen, 2017). Furthermore, modern behaviors are relying on a lifestyle that allows for little meal preparation time; therefore, breast meat a common choice for fast and simple home cooked meals (Petracci et al., 2015).

Genetic improvements have reduced the growing period by approximately 50% to obtain a market weight bird, as compared to previous genetic strains (Havenstein et al., 2003). The percentage of breast weight that makes up body weight in whole has increased drastically due to selection for muscle hypertrophy (Havenstein et al., 2003). Currently, breast meat yield is comprising approximately 20% of the total weight of the bird (Aviagen, 2012). Chickens in today's industry are marketed in approximately half the time and twice the weight compared to

the 1950s (Barbut et al., 2008). However, the fast-growing big-broilers yielding high breast meat yield has resulted in meat quality issues that were not significant when the majority of poultry meat was sold in whole bird form (Barbut et al., 2008). Two of the major meat quality problems discussed in this review focus on a recent myopathy (Wooden Breast) and deboning poultry meat from the carcass before rigor resolution. Therefore, the objective of this review was to discuss the breast meat quality issues and attributes of fast-growing big broilers.

WOODEN BREAST MYOPATHY

Improvements to satisfy the growing demand for poultry meat, including a faster growth rate and upgraded diet formulation, have led to higher breast muscle yielding birds (Sihvo et al., 2014). Consequently, the same advancements have led to an increase in the incidence of pectoral myopathies, such as wooden breast (WB) (Sihvo et al., 2014). WB is a muscle myopathy indicated byhardness in the raw breast fillet, pale color, white striations, hemorrhaging, and exudate (Sihvo et al., 2014). The meat quality issues associated with WB include higher drip and cook losses, lower marination uptake, and decreased water-binding capabilities, resulting in a tough texture when cooked (Soglia et al., 2016). WB involves extraneous amounts of collagen in the muscle, which contributes to the tough cooked texture as confirmed by objective texture analysis methods (Solgia et al., 2016). Due to their unappealing appearance and quality issues, severe WB fillets are usually downgraded and utilized in further processing (Petracci et al., 2013b).

Several researchers have worked on the characterization of WB from various perspectives from muscle structure to meat quality. Petracci et al. (2013a) confirmed that higher breast muscle yielding strains of broilers have a significant amount of abnormal muscle fibers compared to a slower growing strain. Petracci and Cavani (2012) proposed that muscle

hypertrophy, increased muscle fiber diameter and degradation, due to increased growth rate could be a major factor causing WB. Sihvo et al. (2014) reported that the hardness WB presents could be attributable to fibrosis, the thickening of the connective tissue due to injury. Histology samples of severe WB fillets showed a significant amount of connective tissue replacing degraded muscle fibers that were spread out and deformed (Bailey et al., 2015; Sihvo et al., 2014). Increasing fiber size has been previously associated with a small amount of capillarization, causing an insufficient supply of nutrients and oxygen to the muscle cells (Kranen et al., 2000). WB muscle structure consists of longer sarcomere length and a larger amount of fragmentation, signifying muscle fiber degradation (Sun and Owens, 2016).

WB causes the raw fillet to be pale in color, palpably hard to the touch, and rigid from the cranial to caudal regions, depending on severity (Sihvo et al., 2014). Additionally, hemorrhaging is often seen with this myopathy (Kranen et al., 2000). Mudalal et al. (2014) and Clark and Velleman (2016) indicated that the occurrence of fibrosis in affected breast fillets is the reason for meat quality issues such as a decreased water-holding capacity, less marinade uptake, and increased cook loss. Therefore, a tough and chewy product when an affected WB fillet is cooked (Mudalal et al., 2014).

There is a need for more research focusing on WB remediation due to the economic losses (Mudalal et al., 2014). The poultry industry is forced to grade out these fillets because of the extensive quality issues (Soglia et al., 2016). Collagen content has not been a problem in the past when considering poultry meat. However, WB, a collagen issue, has forced the poultry industry to focus extensive research on the texture of breast meat from modern broilers due to consumer rejection and economic losses (Soglia et al., 2016). Solubilization of the connective tissue associated with the WB myopathy could potentially improve the issue, according to

previous literature in beef and lamb meat (Kruggel and Field, 1971; Starkey et al., 2017; Winstead, 1970).

Tough texture of breast meat from broilers weighing 8-10 lbs live weight could be attributed to woody breast but can also be a result of incomplete rigor mortis. The following sections discuss the rigor mortis and its effects on meat quality.

SKELETAL MUSCLE STRUCTURE

Skeletal muscle, making up approximately 50% of a broiler, can be described as the organs that are attached to the skeleton by ligaments, cartilage, or skin and that allow the transmission of force to the muscle, causing the movement and support of that body part (Huff-Lonergan and Lonergan, 2005). The muscle is covered by a layer of connective tissue known as the epimysium, \which is attached to tendons that connect the skeletal muscle to the bone an/ is further divided into compartments known as muscle bundles (Huff-Lonergan and Lonergan, 2005). Another layer of connective tissue, the perimysium, surrounds the muscle bundles (Huff-Lonergan and Lonergan, 2005). Muscle bundles consist of long, multinucleated, and threadlike cells known as muscle fibers, the structural unit of skeletal muscle (Huff-Lonergan and Lonergan, 2005). The muscle fiber is enclosed by the sarcolemma, a covering consisting of protein and lipid that is elastic and allows movement during contraction and relaxation of the muscle (Solo, 2016). The sarcolemma contains calcium that is needed for muscle contraction (Solo, 2016). Muscle fiber number and size within skeletal muscle is dependent on growth rate; faster-growing bird strains have more muscle fibers and a larger diameter when compared to slower-growing bird strains (Dransfield and Sosnicki, 1999). Muscle fiber cross-sectional area will increase with age in poultry (Swatland, 1990). Two primary types of muscle fiber exist in poultry: red (oxidative and smaller) fibers and white (glycolytic and larger) fibers (Solomon et al., 1998). Meat tenderness is

achieved by the breakdown of the muscle fiber by endogenous proteases (McCormick, 2009). Surrounding the sarcolemma and muscle fiber is another layer of connective tissue known as the endomysium (Huff-Lonergan and Lonergan, 2005). Further, the myofibril is a long, cylindrical rod that runs parallel with and makes up the muscle fibers (Solo, 2016). When a muscle is viewed under a microscope, transverse striations are seen due to the myofibril's structure and the banding pattern made by the thick and thin components of the sarcomere (Huff-Lonergan and Lonergan, 2005).

Sarcomeres, the smallest contractile unit of the cell, repeat within the muscle fiber and contribute significantly to muscle contraction and relaxation (Squire, 1997). The sarcomere contains all components required to achieve contraction at the molecular level (Huff-Lonergan et al., 2010). The structure of the sarcomere consists of protein dense A-bands and protein light I-bands, contributing to the striated appearance (Huff-Lonergan et al., 2010). The sarcomere also contains thin and thick filaments that make up the A-bands and I-bands known as myofibrillar proteins actin and myosin, respectively (Squire, 1997). I-bands bisect with other neighboring I-bands, forming the Z-line structure (Huff-Lonergan and Lonergan, 2005).

Actin, contributing to approximately 20% of all myofibrillar proteins in the muscle, is globular shaped (Solo, 2016). Myosin contains two primary components: a tail region that contributes to the stability of the muscle and a head region that attaches to actin (Huff-Lonergan and Lonergan, 2005). The myosin head can hydrolyze adenosine triphosphate (ATP), producing energy for contraction (Solo, 2016). ATP activity provides energy for myosin to bind to actin, pulls the thin filaments to the sarcomere's center, shortens the myofibril, forms the actomyosin cross-bridge, and contracts the live muscle (Huff-Lonergan et al., 2010). An additional molecule

of ATP is needed to separate the myosin head from actin for muscle relaxation (Goll et al., 1984).

During rigor mortis, actin and myosin form a permanent crossbridge between the two myofibrillar proteins, causing permanent muscle contraction (Huff-Lonergan and Lonergan, 2005). Crossbridges in the postmortem muscle cause the intense stiffness associated with rigor (Huff-Lonergan et al., 2010).

THE CONVERSION MUSCLE TO MEAT

Rigor begins during exsanguination, affecting the oxygen supply and internal homeostasis (Braden, 2013). The absence of blood flow and oxygen switches the aerobic tricarboxylic acid cycle to anaerobic glycolytic pathway, leading to lactic acid production (Solo, 2016). Lactic acid accumulates in the muscle as glycogen stores are used causing the muscle pH to drop (Braden, 2013) and an uncontrollable calcium release due to a loss of ionic pump functions in the sarcoplasmic reticulum (Huff- Lonergan et al., 2010). These events trigger the myosin to form reversible cross-bridges with the actin until the ATP is completely depleted. ATP depletion forms the permanent actomyosin cross-bridge and causes irreversible muscle stiffness called rigor mortis (Braden, 2013). Rigor is achieved approximately one hour after broilers are slaughtered (Brewer et al., 2012a).

After the muscle is in full rigor, the muscle tension decreases due to the action of endogenous proteolytic enzymes on the myofibrillar proteins causing the muscle to soften (Giri et al., 2017). At this point, it is can be said that the muscle has converted to meat. Increasing the post-mortem aging time of carcass can allow more time for the proteolytic enzymes to breakdown the myofibrillar proteins and thus further reduce meat toughness (Alvarado and Owens, 2006).

CALPAIN AND CALPASTATIN

The proteolytic enzymes μ and m-calpains and their inhibitor calpastatin are found in the sarcoplasm of the mammalian and avian muscle (Sams and Birkhold, 1991). The live muscle maintains an equilibrium between the two enzymes through the highly regulated anabolic and catabolic counteracting mechanisms (Schreurs et al., 1995).An increase or a decrease in muscle growth rate due to the selection of broiler strains can affect the equilibrium between the anabolic and catabolic processes thus altering the activity of calpain and calpastatin (Schreurs et al., 1995). The altered activity of μ and m-calpains and calpastatin in the modern fast-growing big broilers may affect the meat tenderness (Dransfield and Sosnicki, 1999; Kerth, 2013; Taylor et al., 1995).

In the post-mortem muscle, the calpain-calpastatin enzymatic activity is achieved through partial autolysis and calcium activation during post-rigor (Lee et al., 2008c). Calpains break down myofibrillar proteins that contribute to the overall framework and stability within the muscle cell, resulting in increased meat tenderness (Huff-Lonergan and Lonergan, 2005). μ-calpain is activated immediately after the calcium is released, contributing directly to the tenderization of the muscle (Lee et al., 2008c). However, μ-calpain requires only micromolar amounts of calcium to be activated while m-calpain requires a higher calcium concentration to be activated, meaning that μ-calpain is primarily responsible for post-mortem meat tenderization before deboning would occur in poultry (Schreurs et al., 1995). Lee et al. (2007) reported that the distribution of the two calpains mainly exists in the *pectoralis major* when compared to other chicken muscles, meaning proteolysis predominately occurs there. The same researchers also found that calpains in chicken muscle are more calcium-sensitive compared to calpains in other meat animals, contributing to the speedy tenderization in poultry meat (Lee et al., 2007).

Proteolytic enzymes μ-calpain and m-calpain break down specific myofibrillar and cytoskeletal proteins including: troponin T, tropomyosin, desmin, nebulin, and titin (Sayas-Barbera et al., 2010). However, the two major proteins in the sarcomere, myosin and actin, are not degraded (Schreurs et al., 1995). Sayas-Barbera et al. (2010) stated that the muscle structure is altered by degradation of the Z-line and I band, as well as by disrupting the connection between the Z-line and M-line to the sarcolemma (Sayas-Barbera et al., 2010).

Calpain activity in post-mortem muscle is affected by the rapid decline in the muscle pH causing increased toughness of meat (Dransfield and Sosnicki,1999). Chicken meat from slower-growing layers have a greater μ-calpain and m-calpain activity and a lesser calpastatin activity due to muscle fiber type (Dransfield and Sosnicki, 1999). On the contrary, fast-growing bird strains have a greater ratio of calpastatin, calpain's inhibitor, resulting in reduced proteolysis and tenderization (Dransfield and Sosnicki, 1999). Thus, it can be concluded that alteration in the growth characteristics of the modern fast-growing big broiler may have affected the balance between the proteolytic calpains and their inhibitors, calpastatins. Moreover, the genetic selection and altered muscle fiber type could potentially impact the μ-calpain and m-calpain activity which may require longer post-mortem time to complete rigor resolution in modern broilers. An incomplete rigor resolution can lead to increased toughness of the meat as evidenced in the fast-growing big broilers.

The changes in growth rate, genetic selection, alteration in muscle structure as well as rigor mortis can affect the broiler meat quality characteristics. The sections below discuss different meat quality attributes and their relation to the fast-growing big broilers.

MEAT QUALITY ATTRIBUTES

Color

Consumers consider meat color as one of the most important indicators of meat product quality when buying, evaluating, and consuming poultry products (Mancini, 2009). Meat color is influenced by factors including: bird sex, strain, age, processing technique, cooking method, storage time, myoglobin and hemoglobin content, muscle fiber orientation, muscle contraction state, and pH (Fletcher et al., 2000). Myoglobin is a red colored, sarcoplasmic protein found within the muscle and affected by muscle activity (Padilla, 2010). An increasing amount of muscle activity leads to a higher myoglobin content (Padilla, 2010). White muscle fibers, in breast meat are low in myoglobin content while the red muscle fibers, inthigh and drumstick meat, are high in myoglobin content (Dransfield and Sosnicki, 1999). Increasing amounts of myoglobin lead to a darker colored product because myoglobin attracts more oxygen, which can oxidize to give darker appearance (Dransfield and Sosnicki, 1999).

Meat color is also affected by the structure and contraction state of sarcomeres (Petracci and Fletcher, 2002). Sarcomeres impact light absorption and how light is reflected off the meat surface (Petracci and Fletcher, 2002). A more relaxed, detached sarcomere structure allows more light reflection, leading to a lighter meat color (Petracci and Fletcher, 2002). Additionally, a contracted, tight structure does not reflect light, causing a darker appearance (Petracci and Fletcher, 2002).

White striping, a breast myopathy including white stripes on the breast fillet surface (Trocino et al., 2015), is usually found in WB fillets, potentially causing them to have a lighter pigmentation. Additionally, WB fillets have shown to possess more red and yellow pigmentations when compared to normal breast fillets (Johnson et al., 2017). Various researchers

have reported similar results when studying WB in broiler chickens found greater redness values in WB fillets when compared to normal breast fillets (Chatterjee et al., 2016; Trocino et al., 2015). Higher red and yellow pigmentation values in WB fillets is most likely due to hemorrhaging, tissue damage in fast-growing broiler breast meat, greater amounts of red fibers due to muscle degeneration, and increasing amounts of connective tissue (Mutryn et al., 2015; Tasoniero et al., 2016).

Furthermore, if the muscle pH is near to the isoelectric point after slaughter, there will be less water in between the fibers (Cavitt et al., 2005a). A limited amount of space in between muscle fibers is due to reduced electrostatic repulsion between proteins, leading to increasing amounts of reflective water on the meat surface (Cavitt et al., 2005a). Reflective light will cause the meat to have a pale color, which is commonly seen in Pale, Soft, Exudative (PSE) meat (Bowker and Zhuang, 2015).

Water Holding Capacity

Water holding capacity (WHC) is the ability of the meat to retain water when an outside force is exerted (Hamm, 1960) and can be affected by the bird genetics, production practices, muscle structure, muscle location, rigor mortis, processing techniques (electrical stimulation, storage temperature or marination procedures), or quality issues (PSE meat or Wooden Breast) (Huff-Lonergan and Lonergan, 2005; Kerth, 2013; Bowker and Zhuang, 2015). The ability of poultry meat to bind and hold water is a critical quality characteristic because of the impact on yield, food palatability, and the consumer's eating experience (Cheng and Sun 2008). Water found within the muscle can be categorized into three types: bound, immobilized, and free water (Hamm, 1960). Water is dipolar; therefore, it can bind to proteins due to their charge and it is held inside myofibrils, between myofibrils, within the sarcolemma, or between muscle bundles

(Huff-Lonergan and Lonergan, 2005). Bound water is held tightly via myofibrillar protein charges, lacks freezing abilities, can only be removed by intense drying, and makes up a minor portion of total water in the muscle (Hamm, 1960). In the post-rigor muscle, the quantity of bound water does not significantly change (Offer and Knight, 1988). Immobilized water makes up the largest portion of total water in the muscle (Kerth, 2013) and is held within myofibrils by net charged attractions, but not necessarily attached to proteins (Hamm, 1960). Kerth (2013) reported that immobilized water is attracted to bound water. Immobilized water can be removed by drying methods or frozen at appropriate temperatures but will not purge from the meat immediately post slaughter (Huff-Lonergan and Lonergan, 2005). Purge is defined as the pink colored liquid consisting of sarcoplasmic proteins, myoglobin, and other components that is released from meat due to evaporation, drip loss, thawing, cooking, reduced protein functionality, or storage over time (Savage et al., 1990). Free water flows from the meat easily due to heat, processing, or during storage because of its weak surface forces (Huff-Lonergan and Lonergan, 2005).

Hamm (1960) defined WHC as the capability of meat to hold its intrinsic water during processing. In further processed products, free water can be easily lost from the meat during processing techniques (Keeton and Osburn, 2010). In poultry meat from fast-growing broilers, the occurrence of WB increases the collagen content of the breast muscle, induces degeneration, and ultimately replaces myofibrillar proteins that have a water binding ability in the muscle tissue (Petracci et al., 2013b; Sihvo et al., 2014; Soglia et al., 2016). Replacement of water-binding proteins in the breast meat can cause a decreased WHC, increased cook loss values, and less marinade pick up (Mudalal et al., 2015; Tijare et al., 2016).

pH

Meat quality is affected by the rate at which the post-mortem pH drops (Rammouz et al., 2004). If the pH decreases rapidly, proteins may denature and not have the ability to bind water in the muscle, leading to a tough product (Rammouz et al., 2004). During the muscle to meat conversion, there is an accumulation of lactic acid and a pH decline in the muscle due to lack of blood circulation (Huff-Lonergan and Lonergan, 2005). When the pH falls to the isoelectric point, the net charge of the sarcoplasmic proteins is equivalent to zero, meaning there are equal amounts of positive and negative charges present (Huff-Lonergan and Lonergan, 2005). A lack of electrostatic repulsion reduces the space between myofibrils, bringing them closed with lesser place for water to bind (Huff-Lonergan and Lonergan, 2005). A quick pH decline causes proteins to lose functionality (denaturation), leading to a decreased WHC and increased purge (Huff-Lonergan and Lonergan, 2005).

Rapid decline in muscle pH leads to a meat quality issue termed as pale, soft and exudative (PSE) meat which is commonly caused by stress prior to slaughter, which increases the amount of glycolysis occurring in the muscle (Huff-Lonergan and Lonergan, 2005). The glycolysis process creates energy anaerobically by breaking down glucose into pyruvate and lactic acid to produce energy (Huff-Lonergan and Lonergan, 2005). A build up of lactic acid in the muscle causes a quick pH decline and protein denaturation, producing PSE meat (Huff-Lonergan and Lonergan, 2005; Solomon et al., 1998). On the contrary, if the pH decline occurs slowly, the meat becomes dark, firm, and dry (DFD) (Rammouz et al., 2004).

The rate of the pH drop depends on the amount of activity from glycolytic enzymes after slaughter (Dransfield and Sosnicki, 1999). Breast meat from modern, fast-growing broilers contains more glycogen stores due to the increased amount of fast-twitch, glycolytic fibers in

their breast muscle (Dransfield and Sosnicki, 1999). If glycogen stores are depleted quickly during rigor, there will be a faster pH decline, which could deactivate calpain activity, denature proteins, and reduce meat tenderization in modern broiler breast meat (Dransfield and Sosnicki, 1999).

Tenderness

Meat tenderness has been established as one of the most significant factors affecting consumer acceptability (Barbut, 1997) and is defined as the amount of force required to shear or bite the sample (Coggins, 2012). Tenderness is affected by the muscle contraction state, sarcomere length, debone time, and proteolysis during storage (Sikes et al., 2010). The formation of actin-myosin crossbridges causes sarcomere shortening, muscle contraction and produces tough meat (Goll et al., 1992; Marsh and Leet, 1966). More energy is needed to shear meat with shorter sarcomere lengths due to the overlapping of myofibrillar proteins (Kerth, 2013). Meat toughness is reduced and tenderness is increased by the post-rigor proteolysis of myofibrillar proteins(Goll et al., 1992; Marsh and Leet, 1966). Physical restriction preventing sarcomere shortening can also lead to decreased toughness of meat Koohmaraie et al. (1996).

Additionally, deboning before rigor has completed and proteolytic enzymes have broken down components of the muscle structure causes meat toughness (Cavitt et al., 2004). Earlier deboning times combined with shorter aging periods have led to a significant increase in tough poultry breast meat due to not allowing rigor completion (Craig et al., 1999). Previous research has shown that rigor development directly affects tenderness due to ATP still present in the muscle, which causes shortening after deboning (Cavitt et al., 2005a). A 4-6 h aging period has been previously recommended to allow rigor resolution and increase tenderness in poultry meat (Sams and Owens, 2010). Removing the meat from the skeletal structure before rigor causes

severe contraction due to the lack of physical restriction from the carcass (Cavitt et al., 2004). Therefore, it is recommended that meat is aged on the carcass (Cavitt et al., 2004).

Other processing methods that influence meat tenderness include thaw rigor and cold shortening (Aaslyng, 2002). Thaw rigor is a processing issue in which meat is frozen before rigor completion (Aaslyng, 2002). When thawed, the muscle structure shortens severely due to ATP and Ca^{2+} still being present in the muscle (Aaslyng, 2002). Cold shortening is another processing issue that occurs when rapidly cooling the meat before rigor develops while ATP and Ca^{2+} still exist in the meat (Aaslying, 2002).

Meat tenderization during the post-mortem state is achieved by the proteolytic enzyme, calpain, that is naturally found in the breast meat (Dransfield and Sosnicki, 1999; Koohmaraie, 1994). Calpains are essential for proteolysis of the muscle structure and meat tenderization (Dransfield and Sosnicki, 1999; Koohmaraie, 1994). However, research shows that fast-growing birds have greater amount of the proteolytic enzyme inhibitor, calpastatin, when compared to slower-growing birds, leading to less proteolytic activity, and ultimately affecting the amount of tenderization in their breast meat (Dransfield and Sosnicki, 1999).

Because muscle shortening and rigor development can be affected by factors such as aging method and growth rate, muscle structure and the conversion to meat is considered a meat quality attribute in this review.

CHAPTER II. EFFECT OF EXTENDED DEBONING TIME ON THE BREAST MEAT QUALITY OF FAST-GROWING BIG BROILERS

ABSTRACT

Fast-growing big broilers breast muscle often exhibits wooden breast and white striping myopathies causing meat quality issues such as high cook loss, tough texture, and lower marinade retention. Toughness of the meat and subsequent meat quality issues can also be due to unresolved rigor mortis and slow rate of post-mortem proteolysis. The objective of this study was to investigate the effects of extended deboning times and storage on the quality of broiler breast meat. Broiler breast fillets (total n=810) obtained from a local poultry processor included freshly deboned (2-3 h post slaughter) wooden and normal breast butterfly fillets from broilers >8 lbs, breast fillets from medium sized birds (6-8 lbs) as well as fillets deboned at extended post-slaughter times (16, 20 and 24 h). Carcasses deboned at extended times (n=90/treatment) were stored at 4˚C. The left-side of the butterfly breast fillet was analyzed for color and cook loss immediately after deboning. Texture of cooked fillets was measured using the Blunt Meullenet-Owens Razor Shear (B-MORS) method. Statistical differences between the freshly deboned, extended deboned and stored fillets were determined using ANOVA with Tukey's HSD at $P<0.05$. Data indicated that the wooden breast fillets had a higher cook loss than normal fillets and the ones from medium sized broilers. Texture (peak force and shear energy) of the fillets from all the extended debone times was lower compared to the freshly deboned (2-3 h post-slaughter) breast fillets indicating an increase in tenderness due to proteolysis. Results from the study can be used by the poultry companies to reduce the breast meat texture issues from fast-growing big broilers.

INTRODUCTION

The demand for poultry in the US has increased from 34.2 lbs. per capita in 1960 to approximately 91 lbs. per capita in 2016 (National Chicken Council, 2016). The increase in demand for poultry meat, especially white breast meat, is due to its perceived health status, reasonable price in the marketplace, and adaptability to multiple types of cooking methods for modern families (Petracci et al., 2015). The increased demand for breast meat in the US marketplace has led the poultry industry to develop high breast meat yielding broiler strains with a shorter growout period (Aviagen, 2017). Currently, breast meat yield comprises approximately 20% of the total weight of the bird (Aviagen, 2017). The genetic improvements achieved in recent decades have brought about a shorter growing period by approximately 50% to obtain a market weight bird of about eight pounds in eight weeks, as compared to previous genetic strains (Petracci et al., 2013b). Selection of strains for a faster growth rate and breast size has shown to increase the muscle fiber length and diameter (hypertrophy) but does not affect muscle fiber type present or number of muscle fibers (hyperplasia) (Aberle and Stewart, 1983). Increasing fiber size associated with a scarce amount of capillarization could potentially cause an insufficient supply of nutrients and oxygen to the muscle cells (Kranen et al., 2000). The poultry industry has seen an emergence of wooden breast (WB) myopathy in fast-growing high-breast meat yielding broiler strains (Bilgili, 2013; Soglia et al., 2016). Breast muscle affected with WB exhibits abnormal development of muscle fibers and extraneous amounts of collagen in the muscle, rendering the meat tough and chewy (Soglia et al., 2016). WB affects breast meat quality attributes especially decreased water-holding capacity (WHC), and increased toughness of cooked meat (Sihvo et al., 2014).

In addition to WB, tough texture of breast meat can also be attributed to incomplete resolution of rigor prior to deboning (Mehaffey et al., 2006; Northcutt et al., 2001). Current industry deboning times are approximately 2-4 hours, based on live broiler weights of 4-6 lbs, which may not be suitable for the modern fast-growing high-breast meat yielding varieties weighing >8 lbs live weight. For birds of a 4-6 lb live weight, a 4-6 h time frame has been established as the adequate debone period for proteolytic enzymes to break down muscle structure components, thus alleviating meat toughness and producing an adequately tender breast fillet (Dawson et al., 1987; Giri et al., 2017). The major proteolytic enzymes responsible for post-mortem (PM) meat tenderization are calcium activated cysteine proteases, μ and m-calpains, and their specific inhibitor, calpastatin, (Koohmaraie, 1988) which target troponin-I, troponin-T, desmin, nebulin, titin, Z-line, M-line, and intermediate filaments (Taylor et al., 1995).

In beef, rigor development takes approximately 24 h PM (Ertbjerg and Puolanne, 2017) and 4-6 h PM for a 4-6 lb broiler (Brewer et al., 2012a). However, broilers with faster growth rates have a greater glycolytic fiber content and larger fiber diameters causing faster rigor development (Dransfield and Sosnicki, 1999). The rigor resolution in the fast-growing broilers is slower due to more time required for the depletion of glycogen stores (Alvarado and Sams, 2000; Dransfield and Sosnicki, 1999). Therefore, proteolysis will not begin as quickly in broiler strains with a higher growth rate (Dransfield and Sosnicki, 1999). Further the proteolysis in fast growing broilers is inhibited due to the presence of excess amounts of calpastatin, an inhibitor of the proteolytic enzyme, calpain (Dransfield and Sosnicki, 1999). Hence, it can be concluded that slow rate of proteolysis will increase the time for rigor resolution and ultimately the deboning time will be impacted. The existing practice of deboning within 2-3 h post-slaughter might lead

to incomplete resolution of rigor resulting in tough textured meat with shear values above 220.72 N.mm, according to Xiong et al. (2006) when using the Meullenet-Owens Razor Shear (MORS) method.

Providing ample amount of time for the proteolytic enzymes to resolve rigor in the fast-growing big broilers can be a potential solution to improve tenderness of breast meat from those broilers. The process called aging has been used in the beef industry wherein beef carcasses are allowed to undergo complete rigor to obtain tender meat (Parrish et al., 1973). Aging the meat on carcass physically restrains the muscle, avoiding sarcomere shortening during rigor (Meek et al., 2000; Papa and Lyon, 1989). Moreover, restraining the muscle causes less overlapping of myofibril thick and thin filaments and a weaker muscle structure, producing a more tender product (Smith et al., 1991). Additionally, another commercial tenderization process known as Electrical Stimulation (ES) sends low or high electric pulses throughout the carcass immediately after slaughter, induces muscle contraction, and speeds up rigor development (Sams, 1999). ES accelerates ATP depletion in the muscle, quickens the muscle pH decline, and uses physical disruption of the muscle fibers to increase tenderness (Sams, 1999). Companies often combine ES with aging to meet their specific plant and consumer needs (Sams, 2001).

Aging is common to the beef industry but not to the poultry processors mainly because the post-slaughter time of 2-3 h was traditionally sufficient to obtain tender meat from 4-6 lbs broilers. With modern broilers weighing 8-10 lbs, it might be beneficial for the poultry industry to consider the effects of aging broiler carcasses on breast meat quality, especially texture. We hypothesize that tough texture of breast meat from fast-growing high-meat yielding broilers is due to presence of WB myopathy compounded with incomplete rigor mortis prior to deboning.

There is a need to research methods to alleviate the tough breast meat texture to improve meat quality and help the poultry industry to satisfy consumer demands.

MATERIALS AND METHODS

Broiler Breast Meat Treatments

Breast fillets (n=30/trial in 3 trials) from medium-sized broilers (6-8 lbs live wt) (Normal Medium) and big broilers (8-9 lbs live wt) (Normal Jumbo and Wooden Jumbo) deboned at 2 h post-mortem were obtained from local commercial processors. All the breast fillets were hand-palpated for detecting woody breast severity at the deboning location (Normal=absence of woody/tough texture and Wooden=tough texture throughout the fillet). Normal fillets were relatable to a score of 0 (Normal) represented breast fillets that were flexible throughout and 1 (Mild) represented breast fillets that were hard mainly in the cranial region (Kuttappan et al., 2012). Wooden fillets were relatable to a score of 2 (Moderate) represented breast fillets that were hard throughout but flexible in the caudal region, and 3 (Severe) represents breast fillets \that were extremely hard and rigid from the cranial -++region to caudal tip (Kuttappan et al., 2012). Further, commercially slaughtered, big broiler carcasses (n=90/trial) were stored on ice at 4°C and randomly selected carcasses were deboned at 16, 20 and 24 h post-mortem. Breast fillets collected at each debone time (n=30/trial) were labelled as treatments 16 h, 20 h and 24 h. All the broilers used in this study belonged to the same broiler strain and were delivered to the lab on the same day.

Color

Immediately after arrival to the lab, the initial weight of each left breast fillet was taken and color (CIE system values L*, a*, and b*) was analyzed on the dorsal side. Three color

measurements were taken on the cranial portion of each breast fillet using a Minolta colorimeter (model DP-301, Minolta Corp., Ramsey, NJ) and averaged. All samples were evaluated after calibration with a white reference tile (Y = 92.3, x = 0.3138, y = 0.3198). Each breast fillet was measured immediately after its respective debone time.

Cook Loss

Breast fillets from each treatment were analyzed for cook loss immediately following debone. Cook loss values were stated as a percentage weight loss with respect to initial weight. A convection oven (Vulcan, HEC5D, Troy, Ohio 45374 U.S.A.) was preheated to 177°C before cooking the breast samples. Individual breast fillets were placed on raised wire racks inside stainless steel table pans (Vollrath, 20049, 20-7/8" x 12-13/16" x 4") and the pans were covered with aluminum foil (Daily Chef Heavy Duty Food Service, 51808BC). The fillets were cooked to an internal temperature of 74°C, measured in the cranial portion of the sample continuously using a stainless steel digital thermometer (Saha et al., 2009). After cooking, the breast fillets were cooled to room temperature (22±2°C) in the covered pans and re-weighed. Cook loss was calculated using the formula given below:

$$\text{Cook loss (\%)} = \frac{\text{(Pre-cook fillet wt. – Post-cook fillet wt.) x 100}}{\text{Pre-cook fillet wt.}}$$

Cooked fillets were stored in resealable bags overnight in walk-in cooler maintained at 4°C for further analysis.

Texture

The following day, all cooked fillets were taken out of refrigeration and placed in a single layer on a flat surface to temper up to room temperature. Texture (TA.XTplus Texture Analyzer,

Texture Technologies, Scarsdale, NY) of cooked fillets was measured using the Blunt Meullenet-Owens Razor Shear (BMORS) method on a platform in a 50-kg load cell using a blunt razor blade (carbon steel, 1.5" x 0.25" x 0.021") calibrated to a penetration depth of 20 mm. Texture analyzer was calibrated for force (2 kg) and height (55 mm). Crosshead speed and contact force were calibrated at 20 mm/sec and 1-g, respectively. Five measurements were taken perpendicular to the muscle fibers in the cranial portion of each breast fillet as discussed by Lee et al. (2008a). BMORS force (N) (maximum force recorded from beginning to end of test), BMORS energy (N.mm) (area under the force curve from beginning to end of test), and BMORS peak count (number of peaks on shear curve from beginning to end of test) were found and utilized as instrumental measurements of meat tenderness.

Statistical Analysis

Statistical differences between treatments were determined by SAS (SAS version 9.1 SAS Institute Inc., Cary, NC) for the parameters analyzed using one-way ANOVA with Tukey's HSD at $p \leq 0.05$ to separate means. Deboning time was determined the main effect to evaluate the influence of deboning time on meat characteristics. There were no significant ($p \leq 0.05$) effects due to experiment replication.

RESULTS AND DISCUSSION

Color

Meat color is an important criteria for consumer acceptability and retail sales (Mehaffey et al., 2006). Consumers expect breast fillets to be a pink color when raw, otherwise, they are considered unsatisfactory (Baker and Bruce, 1989). Variation in broiler breast fillet color, commonly affected by processing method (Froning, 1995; Petracci and Fletcher, 2002), may

cause consumers to believe the meat is defective (Kerth, 2013). Thus, it is important to examine the effect of extended debone times on breast fillet color.

L*, lightness, values range from 0 (black) to 100 (white) (Froning and Uijttenboogaart, 1988). Data indicated that L* values (lightness) increased significantly ($p \leq 0.05$) in fillets deboned at 16, 20, and 24 h compared to Normal Medium breast fillets deboned 2-3 h post-mortem (Table 1). No significant ($p \leq 0.05$) differences in lightness value was found in Wooden Jumbo or Normal jumbo fillets when compared to fillets deboned at 16, 20, and 24 h. These findings are similar to Petracci and Fletcher (2002) who observed an increase in the L* values until 6 h post slaughter due to rigor affecting color development. The increasing lightness values are most likely due to rapid pH decline during rigor and muscle structure (Alvarado and Sams, 2000; Cavitt et al., 2005a). Lightness values in Wooden Jumbo fillets were significantly ($p \leq 0.05$) greater than Normal Jumbo fillets and Normal Medium fillets. WB is frequently compounded with white striping, a breast myopathy involving white stripes on the breast fillet surface (Trocino et al., 2015), potentially contributing to the lighter color in WB fillets. The current study did not assess the fillets for presence or absence of white striping.

Redness (a*) values for Wooden Jumbo fillets were significantly higher ($p \leq 0.05$) when compared to all other treatments. Petracci et al. (2004) reported that color variation among normal broiler breast meat showed decreasing a* values as lightness values increased. Researchers studying WB in broiler chickens found greater redness values in WB fillets when compared to normal breast fillets or less severe WB fillets (Chatterjee et al., 2016; Trocino et al., 2015). Increasing redness in WB fillets is most likely due to hemorrhaging or tissue damage because of oxidative stress in fast-growing broilers (Tasoniero et al., 2016). There is potential for increasing redness values associated with WB fillets due to muscle degeneration causing a

switch from fast to slow twitch muscle fibers, according to data from Mutryn et al. (2015) when looking at RNA-sequencing.

B* (yellowness) values were variable among treatments, with Wooden Jumbo fillets being the most yellow and significantly ($p \leq 0.05$) different from all treatments. No significant ($p \leq 0.05$) differences were found between extended debone b* values. Previous studies show that WB fillets are more yellow when compared to normal fillets (Dalle Zottee et al., 2014; Petracci et al., 2013a; Tasoniero et al., 2016). Increased yellowness is most likely due to the excess formation of connective tissue in the WB muscle in response to muscle degeneration, known as fibrosis (Dalle Zotte et al., 2014).

Cook Loss

Cook losses were measured to assess the water-binding properties of breast fillets under different treatments (Table 1). Wooden Jumbo fillets had a significantly higher ($p \leq 0.05$) cook loss compared to Normal Jumbo and Normal Medium fillets (Table 1). Normal Medium and Normal Jumbo fillet values were not significantly different ($p \geq 0.05$) from each other and had the least amount of cook loss at 31.26 ± 5.97 and 29.54 ± 5.44, respectively. Findings from the current research are consistent with Trocino et al. (2015) and Mudalal et al. (2015) who found that WB fillets had significantly higher cooking losses ($p \leq 0.05$) when compared to normal breast fillets.

WB myopathy in poultry increases the collagen content of the *Pectoralis major* (breast muscle) as well as causes degeneration (Soglia et al., 2016) and replacement of myofibrillar proteins that bind water in muscle (Petracci et al., 2013b; Sihvo et al., 2014). These alterations in

the WB muscle lead to decreased water holding capacity which is exhibited in increased cook losses and reduced marinade pick up of the meat (Mudalal et al., 2015; Tijare et al., 2016).

Cook loss for fillets deboned at extended times (16, 20, and 24 h) were significantly higher ($p \leq 0.05$) when compared to the Normal Jumbo treatment (Table 1) potentially due to longer duration of proteolysis leading to increased loss of the myofibrilar proteins to hold water. Moreover, the fillets deboned at 16, 20 and 24 h were not categorized as per woody breast severities and possibly contained some fillets with woody breast characteristics thus increasing the cook loss of the treatment population compared to the specifically categorized Normal Jumbo fillets.

Texture

The texture attributes, shear energy, peak force, and peak count of cooked fillets from each treatment, were analyzed using Blunt-Meullenet Owens Razor Shear method (BMORS) (Table 2). BMORS, a modification of the original Meullenet-Owens Razor Shear (MORS) method, utilizes a blunt blade to distinguish toughness between cooked breast fillets (Lee et al., 2008a) and has been used in breast texture studies (Lee et al., 2008a; Lee et al., 2008b; Solo, 2016).

Extended debone times of 16, 20 and 24 h significantly ($p \leq 0.05$) reduced the peak force and shear energy compared to the other treatments which were deboned 2-3 h PM (Table 2) indicating increased tenderness. 16, 20 and 24 h debone treatments reduced peak counts of breast fillets significantly ($p \leq 0.05$) when compared to the Wooden Jumbo treatment only. Extended deboning times allowed for complete rigor resolution and sufficient time for proteolytic enzymes to tenderize meat (Cavitt et al., 2004; Li et al., 2012). As stated previously, the tenderness effect

was probably enhanced as aging the meat on the carcass physically restrained the muscle and prevented the sarcomere from shortening during rigor (Giri et al., 2017; Meek et al., 2000; Papa and Lyon, 1989; Smith et al., 1991). In addition, improved tenderness might be due to increase in sarcomere length which has been shown to increase with post-mortem debone times (Cavitt et al., 2004).

One major factor that influenced texture of breast meat in the current study is aging of the meat. Aging meat during PM storage is a common practice that has been used in the beef industry for years to improve product tenderness by the breakdown of key proteins (Parrish et al., 1973). Key proteins in the muscle tissue include myofibrillar proteins myosin, actin, desmin, nebulin, and titin, and connective tissue (primarily collagen). The degradation of the proteins directly affects texture of the meat due to their contribution to muscle structure and stability (Harris and Shorthose, 1988; Kong et al., 2007; Palka and Daun, 1999), supporting the results found in this study. Researchers have documented that tenderness of broiler breast meat increases as PM debone time increases (Stewart et al., 1984; Dickens and Lyon, 1995). Additionally, Parrish et al. (1973) found that as PM beef aging time increased, the degradation of Z disks within the myofibril increased.

PM meat tenderization and protein breakdown are mainly attributed to proteolysis by calcium-activated proteases calpain and calpastatin (Koohmaraie, 1994). In the present study, data indicates that proteolytic enzymes acted in breast fillets deboned at extended times of 16, 20, and 24 h, leading to the significantly ($p \leq 0.05$) higher tenderness values (Dransfield, 1992; Dransfield, 1993; Dransfield and Sosnicki, 1999). Because consumers consider tenderness to be the most important meat characteristic, it is essential to understand the process, so the procedures can be developed and applied to the industry. The popularity of poultry products has caused the

industry to produce meat faster, bringing on myopathies (Soglia et al., 2016) and not allowing time for rigor development or completion in bigger birds (Mehaffey et al., 2006; Northcutt et al., 2001). Additional research shows that higher growth rates in birds lead to a reduced proteolytic potential and less activity from calpains, affecting the rate of tenderness development (Dransfield and Sosnicki, 1999). The present texture data indicate that tenderness can be achieved in bigger birds (8-9 lb) by increasing the debone time from the industry standard, which allows time for rigor completion and proteolytic activity to occur (Mehaffey et al., 2006; Northcutt et al., 2001).

In conclusion, results from this study can be used by the poultry companies to reduce the breast meat texture issues from fast-growing big broilers. Additionally, this study confirms that meat aging, a technique used for decades, can benefit the poultry industry. Increasing the debone time from the industry standard (2-3 h PM) increased breast fillet tenderness. Data is verified by objective measurements of shear energy, peak force, and peak count from modern broilers. Cook losses were not significantly ($p \leq 0.05$) increased by the treatments. Furthermore, prolonged debone treatments were not categorized by WB severity or treatment to represent a true population, allowing comparison between fillets deboned at 16, 20, and 24 h and fillets deboned at 2 h (Wooden Jumbo, Normal Jumbo, and Normal Medium treatments). The extended times used in this study present processors with economic losses due to extra time and energy spent on storage of carcasses. However, this technique could be utilized by companies that transport their carcasses from a slaughter plant to a separate debone or further processing plant. Further studies should focus on optimizing these extended debone times to obtain an acceptable texture, testing them in a sensory study, and feasibly applying them in the poultry industry.

Table 1.
Effect of extended debone times on color and cook loss (n = 90/trt) (mean ± std. deviation) of breast fillets compared to the fillets deboned at 2-3 h post mortem

Treatment	L*	a*	b*	Cook Loss (%)
Debone 2-3 h PM				
Wooden Jumbo†	63.78 ± 3.64[a]	2.08 ± 1.39[a]	8.04 ± 2.46[a]	34.30 ± 8.28[a]
Normal Jumbo†	62.36 ± 4.11[bc]	0.32 ± 0.80[c]	5.04 ± 2.22[c]	29.54 ± 5.44[c]
Normal Medium††	61.08 ± 3.19[c]	1.09 ± 0.95[b]	4.91 ± 2.03[c]	31.26 ± 5.97[bc]
16 h Debone ‡	63.37 ± 2.67[ab]	1.36 ± 1.00[b]	6.26 ± 2.19[b]	32.47 ± 4.19[ab]
20 h Debone ‡	63.21 ± 2.89[ab]	1.55 ± 1.24[b]	6.32 ± 2.02[b]	33.25 ± 4.68[ab]
24 h Debone ‡	63.43 ± 2.92[ab]	1.55 ± 0.91[b]	6.61 ± 1.99[b]	32.53 ± 4.49[ab]

a–c values within a column lacking a common superscript differ ($p \leq 0.05$)

† Wooden Jumbo and Normal Jumbo fillets were obtained from broilers at 8-9 lbs live wt deboned at 2-3 h post-mortem and sorted by a commercial poultry processor into the wooden and normal categories

†† Normal Medium fillets were obtained from broilers at 5-6 lbs live wt deboned at 2-3 h post-mortem

‡ fillets deboned at extended times 16, 20, 24 h

Table 2.
Effect of Extended Debone Times Using the BMORS method on Shear Energy, Peak Force, and Peak Count (n = 90/trt) (mean ± std. deviation) of breast fillets compared to the fillets deboned at 2-3 h post mortem

Treatment	Shear Energy (N.mm)	Peak Force (N)	Peak Count
Debone 2-3 h PM			
Wooden Jumbo†	256.87 ± 62.62[b]	19.00 ± 4.61[b]	9.92 ± 2.70[a]
Normal Jumbo†	297.82 ± 64.31[a]	21.90 ± 5.39[a]	5.41 ± 3.00[d]
Normal Medium††	232.18 ± 73.21[c]	18.00 ± 5.25[b]	6.95 ± 2.76[c]
16 h Debone ‡	195.47 ± 45.04[d]	15.47 ± 4.26[c]	8.44 ± 2.62[b]
20 h Debone ‡	195.64 ± 45.11[d]	15.70 ± 3.22[c]	8.53 ± 2.62[b]
24 h Debone ‡	189.48 ± 41.93[d]	15.54 ± 2.65[c]	8.47 ± 2.62[b]

a–d values within a column lacking a common superscript differ ($p \leq 0.05$)
† Wooden Jumbo and Normal Jumbo fillets were obtained from broilers at 8-9 lbs live wt deboned at 2-3 h post-mortem and sorted by a commercial poultry processor into the wooden and normal categories
†† Normal Medium fillets were obtained from broilers at 5-6 lbs live wt deboned at 2-3 h post-mortem
‡ fillets deboned at extended times 16, 20, 24 h

CHAPTER III. OPTIMIZING DEBONING TIMES TO IMPROVE TEXTURE OF BREAST MEAT FROM FAST-GROWING BIG BROILERS

ABSTRACT

Fast-growing big broilers are being deboned as early as 2-3 h post-slaughter with incomplete rigor resolution possibly leading to tough meat texture compounded with toughness from wooden breast condition. Tough meat has caused meat quality issues and consumer complaints. There is a need to reduce the toughness of meat from big broilers (8-10 lbs. live wt.) to reduce consumer complaints and possibly improve meat quality. Previous research indicated that although deboning big broilers at 16 h post-slaughter yielded tender fillets, it can affect productivity and throughput (Johnson et al., 2017). A research study was conducted to determine the optimum deboning time required to improve texture via resolution of rigor mortis.

The objective of this time series study was to evaluate the effects of deboning times up to 10 h post-slaughter compared to 26 h post-slaughter. Broiler carcasses (8-week old birds; total n=864) and butterfly breast fillets (total n=216) were obtained from a local poultry processor. Random breast fillets were collected directly off the deboning line to represent the 3 h post-slaughter treatment. Further, the carcasses and breast fillets were transported to the lab on ice and stored in walk-in coolers (4°C) until deboning at 7, 11 and 27 h post-slaughter. Carcasses (n=72 per time point) were deboned to obtain butterfly breast fillets which were split into right and left sides. The left fillets were weighed, cooked in a convection oven to an internal temperature of 165°F, cooled and weighed again to measure cook losses. Cooked fillets were used to analyze texture using the BMORS method. The right fillets were analyzed for color (Hunter L*a*b*). Data was analyzed using ANOVA to determine significant differences at $p<0.05$. Peak force and shear energy values significantly decreased ($p<0.05$) with increase in deboning times from 3 to 27 h. Peak force and shear energy values at 3 h were 21.92 N and 264.15 N.mm which decreased ($p<0.05$) to 14.41 N and 185.28 N.mm at 27 h, respectively. Results from this study can be

useful in determining the optimum time required to debone big broilers such that tough texture issues are minimized.

INTRODUCTION

Meat consumption trends over the past 50 years indicate a shift in consumer preference towards poultry meat as a convenient protein source (NCC, 2016; Petracci et al., 2015). The increase in consumer request for poultry products is mainly due to its perceived health status, convenience, ease of cooking, and price point (Kennedy et al., 2004). Extensive progress in the poultry market over decades has resulted in selection and growth of cut-up part yields, specifically breast meat yield (Aguirre Cando, 2016). To satisfy the growing demand for poultry meat, the poultry industry has increased the broiler production through genetic selection of high-breast meat yielding, fast-growing broilers with an improved feed-conversion rate (Fletcher, 2004).

The advances in the poultry industry has helped the industry to market broilers in approximately half the time and twice the weight compared to the 1950s (Barbut et al., 2008). Moreover, the processing facilities have reduced the postmortem (PM) debone time of chicken carcasses to increase throughput (Alvarado and Sams, 2004) leading to incomplete rigor resolution and tough meat (Northcutt et al., 2001; Smith and Fletcher, 1992). Because meat texture is one of the most important attributes to consumers (De Huidobro et al., 2005), it is essential to consider PM deboning (or aging) time and its effects on meat tenderness (Cavitt et al., 2005a).

Research on rigor resolution and meat texture indicated that approximately 2-4 h post-slaughter debone times are sufficient to obtain meat with acceptable texture (Dawson et al., 1987; Dickens and Lyon, 1995; Meek et al., 2000; Pool et al., 1959; Stewart et al., 1984). Hence,

based on scientific studies and experience, the poultry industry has made it a normal practice to debone poultry within 2-4 h post-slaughter. Although these parameters are scientifically based, they were collected on 4-6 lb broilers (Dawson et al., 1987; Dickens and Lyon, 1995; Meek et al., 2000; Pool et al., 1959; Stewart et al., 1984) while the fast-growing big-broilers weigh 8-10 lbs (Aviagen, 2017). It can be hypothesized that bigger carcasses need a longer PM time for rigor resolution and meat tenderization.

During rigor, sarcomeres contract and shorten, causing tough poultry meat if storage time is too short (Northcutt et al., 2001). To aid in combatting this problem, meat should be deboned after rigor resolution completes to allow time for proteolytic action and sarcomere relaxation (Northcutt et al., 2001). The amount of time and temperature of storage in which meat is kept after slaughter is termed as aging of meat (Smith et al., 1978). Aging of meat is commonly utilized to allow rigor time to resolve and proteolytic enzymes to break down muscle proteins (Giri et al., 2017). Aging meat on the whole carcass is preferred because the muscle is physically restrained and stretched when restricted by the bone structure (Meek et al., 2000). Restricting the muscle during aging causes a less severe overlap of myosin and actin, meaning sarcomeres will detach more quickly and tenderness is achieved in a shorter time (Smith et al., 1991). During PM aging, endogenous, calcium-activated proteases calpain and calpastatin, alter muscle tissue by degradation of components including the Z-disk, desmin, titin, nebulin causing meat tenderization (Koohmarie, 1994).

As mentioned previously, the increase in consumption of poultry meat has caused the poultry industry to select for higher growth rates (Petracci et al., 2015). Selection for faster broiler growth rates has recently led to a decrease in meat quality and increase in number and size of glycolytic, white fibers in breast meat (Dransfield and Sosnicki, 1999). Research focusing

on the effect of growth rate on proteolytic activity by calpains shows that faster growing birds contain a surplus of calpain inhibitor, calpastatin, while breast muscle from slower growing strains contains a surplus of calpain, the enzyme primarily responsible for PM tenderization (Dransfield and Sosnicki, 1999). Therefore, birds with an increased growth rate have less proteolysis occurring in the breast muscle, leading to tougher breast meat (Dransfield and Sosnicki, 1999).

It is believed that the combination of early deboning before rigor completion and reduced proteolytic activity in fast-growing broiler meat is leading to a decrease in tenderness (Johnson et al., 2017). Earlier research in our lab studied the effect of extended debone times (16, 20, 24 h) on breast meat quality of fast-growing big broilers (Johnson et al., 2017). Johnson et al. (2017) reported Blunt Meullenet-Owens Razor Shear (BMORS) shear energy and peak force reduced ($p \leq 0.05$) in fillets deboned at 16 h (195.47 ± 45.04 N.mm and 15.47 ± 4.26 N, respectively) compared to normal, big broiler (8-9 lb) fillets deboned at 2-3 h PM (297.82 ± 64.31 N.mm and 21.90 ± 5.39 N, respectively).

However, storing chicken carcasses for 16 h or more is not a productive method for most plants and could cause economic losses due to storage space, energy costs, and additional time. The objective of the study was to investigate the optimum deboning time required to improve texture of breast fillets from fast-growing big broilers via resolution of rigor mortis. The results could potentially aid in the improvement of big broiler meat texture and the remediation of tough poultry meat.

MATERIALS AND METHODS

Broiler carcasses

Commercially raised (8-9 lbs live weight) and slaughtered broiler carcasses (n=864 or 288/trial) were obtained from a local poultry processor. The carcasses were iced (4±1˚C) and transported to the Auburn University Poultry Science Research Unit. The carcasses were stored in totes with ice which were placed in walk-in coolers maintained at 4±1˚C.

Deboning

The study consisted of four treatments 3 h, 7 h, 11 h, and 27 h post-slaughter debone time points (n=72/treatment/trial). For the 3 h post-slaughter debone time samples, random butterfly breast fillets (n=72/trial) were collected directly off the deboning line at the processing plant. The fillets belonged to the same flock of broilers which were used for the other treatments. Random broiler carcasses (n=72/trial/treatment) were selected from the totes and were manually deboned at respective time intervals to obtain butterfly breast fillets. Initial weights (g) were 422 ± 65, 382 ± 51, 367 ± 64, 358 ± 57, at 3, 7, 11, and 27 h debone times, respectively. The butterfly breast fillets were split into right- and left-side breast fillets and were used for various analysis.

Color

Three CIELAB color (L*, a*, b*) measurement was taken on the dorsal, cranial portion of each right breast fillet using a Minolta colorimeter (model DP-301, Minolta Corp., Ramsey, NJ) and averaged together. All samples were evaluated after calibration with a white reference tile (Y = 92.3, x = 0.3138, y = 0.3198). Each breast fillet was measured immediately after its respective debone time.

Cook Loss

Left-side breast fillets from each treatment were analyzed for cook loss. Cook loss values were stated as a percentage weight loss with respect to initial weight. A convection oven (Vulcan, HEC5D, Troy, Ohio 45374 U.S.A.) was preheated to 177°C before cooking the breast fillet samples. Individual breast fillets were placed on raised wire racks inside stainless steel table pans (Vollrath, 20049, 20-7/8" x 12-13/16" x 4") and the pans were covered with aluminum foil (Daily Chef Heavy Duty Food Service, 51808BC). The fillets were cooked to an internal temperature of 74°C, measured using a stainless steel digital thermometer (Saha et al., 2009). After cooking, the breast fillets were cooled to room temperature (22±2°C) in the covered pans and weighed again. Cook loss was calculated using the formula given below:

$$\text{Cook loss (\%)} = \frac{\text{(Pre-cook fillet wt. – Post-cook fillet wt.) x 100}}{\text{Pre-cook fillet wt.}}$$

Cooked fillets were stored in resealable bags overnight in walk-in cooler maintained at 4°C for further analysis.

Texture Analysis

The cooked fillets were taken out of the walk-in cooler and tempered to room temperature (22±2°C) for approximately two hours. Texture (TA.XTplus Texture Analyzer, Texture Technologies, Scarsdale, NY) of cooked separately fillets was measured using the BMORS method on a platform in a 50-kg load cell using a blunt razor blade (carbon steel, 1.5" x 0.25" x 0.021") calibrated to a penetration depth of 20 mm. The texture analyzer was calibrated for force (2Kg) and height (55mm). Crosshead speed and contact force were calibrated at 20 mm/sec and 1-g, respectively. Five measurements were taken perpendicular to the muscle fibers in the cranial portion of each breast fillet as discussed by Cavitt et al. (2004) and Lee et al

(2008a). BMORS force (N) (maximum force recorded from beginning to end of test), BMORS energy (N × mm) (area under the force curve from beginning to end of test), and BMORS peak count (number of peaks on shear curve from beginning to end of test) were utilized as instrumental measurements of meat tenderness.

Statistical Analysis

Statistical differences between the freshly deboned and extended deboned fillets were determined with SAS (SAS version 9.1 SAS Institute Ino., Cary, NC) for the parameters analyzed using ANOVA with Tukey's HSD at $p<0.05$. Deboning time was utilized as the main effect to determine the impact of deboning time on the meat. There were no ($p \leq 0.05$) effects due to experiment replication.

RESULTS AND DISCUSSION

Color

Color, L* (lightness), a* (redness), and b* (yellowness), of broiler breast fillets deboned at 3, 7, 11, and 27 h PM times are presented in Table 1. L* (lightness) values increased ($p \leq 0.05$) from 61.82 ± 2.71 to 64.22 ± 2.40 as debone time increased from 3 h to 27 h, respectively. Breast meat color has been shown to be related to the meat pH (Allen et al, 1998). After slaughter, the muscle pH can potentially reach an isoelectric point of approximately 5.1, meaning the fiber's electrical charge is a net zero value between myosin and actin proteins (Owens et al., 2010). The drop in muscle pH causes proteins to lose their water holding capabilities, releasing free water onto the meat surface, resulting in a lightered colored breast fillet (Owens et al., 2010). Additionally, protein denaturation, due to a lower pH approximately 2 h PM, causes light to scatter on the meat's surface, leading to a lighter color (Barbut, 1993; Swatland, 2008).

Similar color results were reported by Petracci and Fletcher (2002) who found that the L* values for poultry breast meat increased within the first 6 h PM, but there were no changes from 6 to 24 h beyond which the values decreased. The researchers (Petracci and Fletcher, 2002) stated that early changes in color are due to processing techniques and longer-term changes are due to storage. Cavitt et al. (2005a) attributed the increase in L* values of broiler breast fillets over 24 h PM to the rigor mortis development, the muscle to meat change, myofibril contraction, and alterations in the muscle structure.

The a* (redness) values increased ($p \leq 0.05$) from 0.50 ± 0.83 at 3 h PM to 0.84 ± 0.98 at 27 h PM. However, no significant differences were found between 7 h and 11 h values. The b* (yellowness) values increased ($p \leq 0.05$) as extended PM debone time increased from 4.85 to 6.82 over the 3 h to 27 h period, respectively. No differences ($p \leq 0.05$) were found between 7 h and 11 h b* values, indicating little variation over the four-hour period. Color changes in the present study are potentially due to the increased storage time, pH variations, changes in the muscle structure due to aging on the carcass, and changes in number of hemoglobin pigments over the aging period (Zhuang and Bowker, 2016). Zhuang and Bowker (2016) found that the initial lightness of breast fillets influenced color changes over a 48 h aging period. Pale fillets had no change in redness or yellowness values during storage while normal fillets had no change in redness, but an increased yellowness value (14.2) after storage (Zhuang and Bowker, 2016). Color change during storage could be due to changes in concentration or chemical structure of heme pigments over time due to blooming (Zhuang and Bowker, 2016). Color variations could additionally be due to myoglobin and protein oxidation during aging, as metmyoglobin concentration in meat (brown pigment) increases over time (Wu et al., 2015).

Cook Loss

Cook losses were measured in the present experiment to evaluate the water-binding abilities of samples deboned a 3, 7, 11, and 27 h. Data presented in Table 1 exhibit average initial weights (g) immediately before cooking and average cook losses (%) within each treatment. Variation in initial weight of treatments decreased ($p \leq 0.05$) as extended debone time increased to 27 h. The decreasing weight of raw fillets over time could be partially due to drip or purge loss during storage (Pearce et al., 2011), but mainly due to deboning method. The 3 h debone fillets were removed from the carcass by experienced plant workers, obtaining the most yield possible whereas 7, 11, and 27 h treatments were deboned by inexperienced students, causing variation found in initial breast fillet weights. Initial weight differences did not affect cook loss percentages.

Cook loss values were evaluated by measuring weight loss before and after cooking. Average cooking losses (%) are expressed as a percentage in Table 1. No differences ($p>0.05$) in cook losses were found in fillets deboned at 3, 7, 11, and 27 h. Results from the current study are consistent with findings from a previous study in which breast fillets were deboned at extended times of 16, 20, and 24 h (Johnson et al., 2017). Similar results were noted by Mehaffey et al. (2006) who found no differences in cook loss of aged breast fillets from low and high breast yielding commercial broiler strains. The researchers reported no significant differences in cook loss were noted between 2 h and 4 h debone points (Mehaffey et al. 2006). On the contrary, Pearce et al. (2011) noted that proteolysis of cytoskeletal proteins during aging affects water distribution in meat ultimately affecting its water holding capacity. It is well known that cooking

with heat denatures muscle protein, which shrinks myofibrils and decreases water content, resulting in increasing cook losses (Bertram et al., 2006). Extended debone times had no effect on cook loss values in the present study. Results show that there was aging of carcasses up to 27 h did not increase cook loss thus indicating that carcass aging will not impact product yield.

Texture

Texture analysis (BMORS) indicated that the breast fillets became more ($p \leq 0.05$) tender as they aged on the carcass. Average BMORS shear energy, peak force, and peak count values obtained from fillets deboned at 3, 7, 11, and 27 h are presented in Table 2. BMORS is a method that was refined from the Meullenet-Owens Razor Shear (MORS) method but consists of the additional peak count measurement and uses a blunt blade to discriminate tough textures more accurately (Lee et al., 2008a). Previous data has indicated that peak count is a better indicator of WB severity compared to shear energy or peak force when studying WB fillets (Solo, 2016). However, peak count values obtained in the present study increased ($p \leq 0.05$) as debone time increased from 3 to 27 h. It is important to note that levels of WB severity were present in all four treatments. Results could be due to the variability in pH onset PM or severity that WB presents (Chatterjee et al., 2016).

Shear energy and peak force values decreased ($p \leq 0.05$) as debone time increased. Shear energy values (N.mm) were 264.15 ± 86, 228.57 ± 61, 205.17 ± 47, and 185.28 ± 43 N.mm while peak force values (N) were 21.91 ± 6.37, 18.13 ± 4.40, 16.22 ± 4.10, and 14.41 ± 3.75 N at 3, 7, 11, and 27 h, respectively. Similarly, Xiong et al. (2006) reported a decrease in shear energy (razor MORS) with increase in deboning time from 2 to 24 h of 7-week old broilers. Xiong et al. (2006) correlated shear energy with organoleptic tenderness of breast fillets using a 9-point hedonic scale and reported that the shear energy (N.mm) above 220.72 N.mm were classified as

"Dislike extremely," while values below 104.18 were "Liked extremely". Comparing the current data with Xiong et al. (2006), the 3 and 7 h deboned fillets would have a tough texture and disliked by the consumers while the 11 h pm debone shear energy measurement falls within "Dislike moderately" and the 27 h debone measurement falls within "Dislike slightly," respectively (Xiong et al., 2006). However, it is important to note that Xiong et al. (2006) utilized a sharp razor blade while the present study and previous study in our lab (Johnson et al., 2017) utilized a blunt blade. The MORS method using blunt blade produces 20-40 N.mm higher shear energy compared to the MORS method using sharp razor blade (Lee et al., 2008a).

The improvement in texture of breast fillets aged on carcass can be explained by two major factors:

(1) Physical restriction of the *pectoralis major*: PM sarcomere shortening during rigor mortis leads to toughening of meat (Birkhold and Sams, 1993; Wheeler and Koohmaraie, 1994). However, aging breast fillets on the carcass restricts the sarcomere shortening due to attachment to the skeletal structure leading to increased tenderness compared to fillet deboned 2-3 h post-slaughter (Ertbjerg and Puolanne, 2017; Giri et al., 2017; Smith et al., 1991). Similarly, Wheeler and Koohmaraie (1994) and Koohmaraie (1996) found that beef and lamb muscle, respectively, were physically restricted from shortening after slaughter resulting in increased tenderness.

(2) Time for the proteolytic enzymes to digest muscle proteins: Faster-growing strains have a greater ratio of the proteolytic enzyme inhibitor, calpastatin, which decreases the PM proteolytic activity and tenderization (Dransfield and Sosnicki, 1999). Furthermore, breast meat from faster-growing broilers contains a larger proportion of glycolytic fibers that will initiate a faster rigor mortis development (Dransfield and Sosnicki, 1999). Increased amounts of glycogen depletion during rigor will cause a quicker pH decline, which will potentially deactivate calpain

activity, denature proteins, and increase meat toughness (Dransfliend and Sosnicki, 1999). In the present study, extended debone times of the fast-grown big broilers (8-9 lbs live wt) at 7, 11, and 27 h allowed time for proteolysis to occur and rigor to resolve, leading to lower shear values (Dransfield and Sosnicki, 1999; Giri et al., 2017). Proteolytic enzymes break down key myofibrillar proteins and decrease meat toughness during storage (Smith et al, 1978).

In conclusion, results indicate that fast-growing big broilers (8-10 lbs live wt) deboned at 3 h post mortem will produce tough textured meat due to incomplete rigor resolution. However, aging the carcasses for 7 h and 11 h can improve texture of the breast meat. The study provides an optimized carcass aging time of 7-11 h to improve breast meat texture from fast-growing big broilers and can potentially reduce consumer complaints concerning tough breast meat. Further research must be conducted to determine the changes in proteolytic enzymes in fast-growing big broilers leading to the delayed proteolysis.

Table 3.
Effect of post-mortem deboning times (3, 7, 11 and 27 h) on the color and cook loss of breast fillets (n = 288/trt) (mean ± std. deviation) from big broilers (8-9 lbs live wt.)

Treatment	L*	a*	b*	Cook Loss (%)
3 h debone	61.82 ± 2.71^{c}	0.50 ± 0.83^{b}	4.85 ± 2.06^{c}	31.32 ± 7.35^{a}
7 h debone	63.13 ± 2.57^{b}	0.70 ± 1.02^{ab}	5.51 ± 2.02^{b}	32.73 ± 5.53^{a}
11 h debone	63.61 ± 2.49^{ab}	0.60 ± 1.09^{b}	5.89 ± 2.33^{b}	32.11 ± 4.51^{a}
27 h debone	64.22 ± 2.40^{a}	0.84 ± 0.98^{a}	6.82 ± 2.35^{a}	31.64 ± 4.19^{a}

a–c values within a row lacking a common superscript differ ($p \leq 0.05$)

Table 4.
Effect of Extended Debone Times (3, 7, 11 and 27 h) on BMORS Shear Energy, Peak Force, and Peak Count (n = 288/trt) (mean ± std. deviation) from big broilers (8-9 lbs live wt.)

Treatment	Shear Energy (N.mm)	Peak Force (N)	Peak Count
3 h debone	264.15 ± 86[a]	21.92 ± 6.37[a]	4.54 ± 2.70[c]
7 h debone	228.57 ± 61[b]	18.13 ± 4.46[b]	6.42 ± 3.00[b]
11 h debone	205.17 ± 47[c]	16.22 ± 4.10[c]	6.82 ± 2.76[b]
27 h debone	185.28 ± 43[d]	14.41 ± 3.75[d]	7.21 ± 2.62[a]

a–d values within a row lacking a common superscript differ ($p \leq 0.05$)
Values are an average with standard deviation of 288 fillets/trt

REFERENCES

Aaslyng, M.D. 2002. Quality indicators for raw meat. Pages 157-174 in: Meat Processing: Improving Quality. J. Kerry, D. Ledward, ed. CRC Press, Boca Raton, FL.

Aberle, E.D. and T.S. Stewart. 1983. Growth of fiber types and apparent fiber number in skeletal muscle of broiler-and layer-type chickens. Growth. 47:135-144.

Aguirre Cando, M.E. 2016. Descriptive sensory and texture profile analysis of woody breast in marinated chicken. MS thesis. Texas A&M Univ.

Allen, C. D., D. L. Fletcher, J. K. Northcutt, and S. M. Russell. 1998. The relationship of broiler breast color to meat quality and shelf-life. Poult. Sci. 77:361–366.

Alvarado, C.Z. and C.M. Owens. 2006. Poultry: Chemistry and Biochemistry. Pages 1-14 in Handbook of Food Science, Technology, and Engineering. Y.H. Hui, ed. CRC Press, Boca Raton, Florida.

Alvarado, C.Z. and A.R. Sams. 2000. Rigor mortis development in turkey breast muscle and the effect of electrical stunning. Poult. Sci. 79:1694-1698.

Alvarado, C. Z., and A. R. Sams. 2004. Turkey carcass chilling and protein denaturation in the development of pale, soft, and exudative meat. Poult. Sci. 83:1039- 1046.

Aviagen. 2017. Latin America Broiler Ross 308 AP performance objectives 2017. In-house publication, global. Aviagen Ltd., Newbridge, UK. Accessed January 2018. http://la.aviagen.com/assets/Tech_Center/Ross_Broiler/Ross308AP-Broiler-PO-2017-EN.pdf.

Bailey, R.A., K.A. Watson, S.F. Bilgili, and S. Avendano. 2015. The genetic basis of pectoralis major myopathies in modern broiler chicken lines. Poult. Sci. 00:1-10.

Baker, R. C., and C. A. Bruce. 1989. Further processing of poultry. Pages 251–282 in Processing of Poultry. G. C. Mead, ed. Elsevier Appl. Sci., New York, NY.

Barbut, S. 1993. Color measurements for evaluating the pale soft exudative (PSE) occurrence in turkey meat. Food Res. Int. 26:39−43.

Barbut, S. 1997. Problem of pale soft exudative meat in broiler chickens. British Poult. Sci. 38:355–358.

Barbut, S., A. A. Sosnicki, S. M. Lonergan, T. Knapp, D. C. Ciobanu, L. J. Gatcliffe, E. Huff-Lonergan, and E. W. Wilson. 2008. Progress in reducing the pale, soft and exudative (PSE) problem in pork and poultry meat. Meat Sci. 79:46-63.

Bertram, H. C., A. Kohler, U. Bocker, R. Ofstad, and H.J. Andersen. 2006. Heat-induced changes in myofibrillar protein structures and myowater of two pork qualities. A combined FT-IR spectroscopy and low-field NMR relaxometry study. J. of Agricultural and Food Chemistry. 54:1740–1746.

Bilgili, S.F. 2013. Broiler chicken myopathies: II. Woody breast? Page 1, In: Worthwhile Operational Guidelines and Suggestions. Accessed Jan. 2018. http://www.ag.auburn.edu/dept/ph/.

Birkhold, S. G., and A. R. Sams. 1993. Fragmentation, tenderness, and post- mortem metabolism of early-harvested broiler breast fillets from carcasses treated with electrical stimulation and muscle tensioning. Poult. Sci. 72:577–582.

Bourne, M. C. 1982. Page 14 and 258 in: Food texture and viscosity. 2nd ed. Academic Press. Geneva, New York.

Bouton, P.E., A.L. Ford, P.V. Harris, and D. Ratcliff. 1975. Objective-Subjective Assesment of Meat Tenderness. J. of Texture Studies. 6:315-328.

Bowker, B., and H. Zhuang. 2015. Relationship between water-holding capacity and protein denaturation in broiler breast meat. *Poult. Sci.* 94:1657–1664.

Bowker, B., H. Zhuang, D. Chatterjee, and J. Wiener. 2016. Comparison of objective texture measurements in raw and cooked wooden breast meat. Poult. Sci. 95(E-Suppl. 1):. (Abstr.).

Braden, K. 2013. Converting Muscle to Meat: The Physiology of Rigor. Pages 79-94 in The Science of Meat Quality. C.R. Kerth, ed. Wiley-Blackwell, Ames, Iowa.

Bratcher, C.L. 2013. Trained Sensory Panels. Pages 207-213 in The Science of Meat Quality. C.R. Kerth, ed. Wiley-Blackwell, Ames, Iowa.

Brewer, V.B., J.L. Emmert, J.-F.C. Meullenet, C.M. Owens. 2012a. Small bird programs: Effect of phase-feeding, strain, sex, and debone time on meat quality of broilers. Poult. Sci. 91:499–504.

Brewer, V.B., V.A. Kuttappan, J.L. Emmert, J.F.C. Meullenet, C.M. Owens. 2012b. Big-bird programs: Effect of strain, sex, and debone time on meat quality of broilers. *Poult. Sci.* 91: 248–254.

Cavitt, L. C., G. W. Youm, J. F. Meullenet, C. M. Owens, and R. Xiong. 2004. Prediction of poultry meat tenderness using razor blade shear, Allo-Kramer shear, and sarcomere length. J. Food Sci. 69:11–15.

Cavitt, L. C., J. F. Meullenet, R. K. Gandhapuneni, G. W. Youm, and C. M. Owens. 2005a. Rigor development and meat quality of large and small broilers and the use of Allo-

Kramer shear, needle puncture, and razor blade shear to measure texture. Poult. Sci. 84:113–118.

Cavitt, L., J. Meullenet, R. Xiong, and C. Owens. 2005b. The relationship of razor blade shear, Allo-Kramer shear, Warner-Bratzler shear and sensory tests to changes in tenderness of broiler breast fillets. J. of Muscle Foods 16:223-242.

Chatterjee, D. H. Zhuang, B. C. Bowker, A. M. Rincon, G. Sanchez-Brambila. 2016. Instrumental texture characteristics of broiler pectoralis major with the wooden breast condition. Poult. Sci. 95:2449–2454.

Cheng, Q., and D.W. Sun. 2008. Factors affecting the water holding capacity of red meat products: a review of recent research advances. Critical Reviews in Food Science and Nutrition. 48:137-159.

Clark, D.L., and S.G. Velleman. 2016. Spatial influence on breast muscle morphological structure, myofiber size, and gene expression associated with the wooden breast myopathy in broilers. *Poult. Sci.* 95:2930–2945.

Coggins, P.C. 2012. Attributes of Muscle Foods: Color, Texture, Flavor. Pages 35-44 in: Handbook of Meat, Poultry, and Seafood Quality. L.M.L. Nollet, ed. Wiley-Blackwell, Ames, Iowa.

Craig, E.W., D.L. Fletcher, and P.A. Papinaho. 1999. The effects of antemortem electrical stunning and postmortem electrical stimulation on biochemical and textural properties of broiler breast meat. Poult. Sci. 78:490–494.

Dalle Zotte, A., M. Cecchinato, A. Quartesan, J. Bradanovic, G. Tasoniero, and E. Puolanne. 2014. How does “Wooden Breast” myodegeneration affect poultry meat quality? Archivos Latinoamericanos de Producci´on Animal. 22:476–479.

Dawson, P. L., D. M. Janky, M. G. Dukes, L. D. Thompson, and S. A. Woodward. 1987. Effect of post-mortem boning time during stimulated commercial processing on the tenderness of broiler breast meat. Poult. Sci. 66:1331–1333.

De Huidobro F.R., F. Ruiz, E. Miguel, B. Blázquez, and E. Onega. 2005. A comparison between two methods (Warner–Bratzler and texture profile analysis) for testing either raw meat or cooked meat. Meat Sci. 69:527-536.

DeMan, J. M., and B. S. Kamel, 1981. Instrumental methods of measuring texture of poultry meat. Pages 157-164 in: Quality of Poultry Meat. Spelderholt Jubilee Symposia, Apeldoorn, The Netherlands.

Dickens, J. A., and C. E. Lyon. 1995. The effects of electric stimulation and extended chilling times on the biochemical reactions and texture of cooked broiler breast meat. Poult. Sci. 74:2035–2040.

Dransfield, E. 1992. Modelling post-mortem tenderisation—III: Role of calpain I in conditioning. Meat Sci. 31:85-94.

Dransfield, E. 1993. Modelling post-mortem tenderisation—IV: Role of calpains and calpastatin in conditioning. Meat Sci. 34:217-234.

Dransfield, E. 1994. Optimisation of tenderisation, ageing and tenderness. Meat Sci. 36:105–121.

Dransfield, E. and A.A. Sosnicki. 1999. Relationship between muscle growth and poultry meat quality. Poult. Sci. 78:743-746.

Ertbjerg, P., and E. Puolanne, 2017. Muscle structure, sarcomere length and influences on meat quality: A review. Meat Sci. 132:139-152.

Fletcher, D. L. 2004. Further processing of poultry. Pages 108-134 in Poultry Meat processing and quality. G. C. Mead ed. CRC Press, Florida.

Fletcher, D.L., M. Qiao, D. P. Smith. 2000. The relationship of raw broiler breast meat color and pH to cooked meat color and pH. *Poult. Sci.* 79:784–788.

Froning, G.W. 1995. Color of poultry meat. Poult. Avian Biol. Rev. 6:83–93.

Froning, G.W. and T.G. Uijttenboogaart. 1988. Effect of post-mortem electrical stimulation on color, texture, pH, and cooking losses of hot and cold deboned chicken broiler breast meat. Poult. Sci. 67:1536-1544.

Geesink, G.H., S. Kuchay, A.H. Chishti, and M. Koohmaraie. 2006. µ-Calpain is essential for postmortem proteolysis of muscle proteins. J. Anim. Sci. 84:2834–2840.

Giri, A.K., A.K. Biswas, and O.P. Dinani. 2017. Influence of calpain mediated post-mortem ageing on quality of broiler breeder breast fillets during holding at room temperature. Int. J. Pure App. Biosci. 5:1025-1034.

Goll, D. E., V.F. Thompson, R.G. Taylor, and J.A. Christiansen. 1992. Role of the calpain system in muscle growth. Biochimie. 74:225-237.

Goll, D.E., R.M. Robson, and M.H. Stromer. 1984. Pages 548-580 in: Skeletal muscle, nervous system, temperature regulation, and special senses. M. J. Swensen, Duke's physiology of domestic animals, ed. Ithaca, N.Y: Cornell University Press.

Hamm, R. 1960. Biochemistry of meat hydration. Adv. Food Res. 10:355–463.

Harris, P.V., and W.R. Shorthose. 1988. Meat texture. Pages 245-296 in Developments in Meat Science Vol. 4 (Ed. R. A. Lawrie). Elsevier Applied Science Publisher, London.

Havenstein, G.B., P.R. Ferket, and M.A. Qureshi. 2003. Growth, livability, and feed conversion of 1957 versus 2001 broilers when fed representative 1957 and 2001 broiler diets. Poult. Sci. 82:1500-1508.

Huff-Lonergan, E., and S.M. Lonergan. 2005. Mechanisms of water-holding capacity of meat: The role of postmortem biochemical and structural changes. Meat Sci. 71:194–204.

Huff-Lonergan, E., W.G. Zhang, and S.M. Lonergan. 2010. Biochemistry of postmortem muscle: Lessons on mechanisms of meat tenderization. Meat Sci. 86:184–195.

Johnson, M., A. Kennedy-Smith, L. Bauermeister, A. Morey. 2017. Effect of extended deboning time and subsequent storage on the breast meat quality of fast-growing big broiler. International Production and Processing Expo. M18 (Abstr.)

Keeton, J.T. and W.N. Osburn. 2010. Formed and emulsion products. Pages 245-278 in Poultry Meat Processing. Owens, C.M., C.Z. Alvarado, and A.R. Sams, ed. CRC Press, Boca Raton, Florida.

Kennedy, O. B., B. J. Stewart-Knox, P. C. Mitchell, and D. I. Thurnham. 2004. Consumer perception of poultry meat: a qualitative analysis. Nutr. Food Sci. 34:122-129.

Kerth, C.R. 2013. Meat Tenderness. Pages 99-118 in The Science of Meat Quality. C.R. Kerth, ed. Wiley-Blackwell, Ames, Iowa.

Kong, F.B., J.M. Tang, B. Rasco, C. Crapo, and S. Smiley. 2007. Quality changes of salmon (O. gorbuscha) muscle during thermal processing. J. Food Sci. 72:103–111.

Koohmaraie, M. 1988. The role of endogenous proteases in meat tenderness. Proc. Recip. Meat Conf. 41:100.

Koohmaraie, M. 1994. Muscle proteinases and meat aging. Meat Sci. 36:1–2, 93–104.

Koohmaraie, M., 1996. Biochemical factors regulating the toughening and tenderization processes of meat. Meat Sci. 43:193-201.

Koohmaraie, M., M.E. Doumit, and T.L. Wheeler. 1996. Meat toughening does not occur when rigor shortening is prevented. J. Anim. Sci. 74:2935-2942.

Koohmaraie, M., S.C. Seidemann, J.E. Schollmeyerb, T.R. Dutsonc, and J.D. Crouse. 1987. Effect of post-mortem storage on Ca++-dependent proteases, their inhibitor and myofibril fragmentation. Meat Sci. 19:187–196.

Kranen, R.W., E. Lambooij, C.H. Veerkamp, T.H. Kuppevelt, and J.H. Veerkamp. 2000. Hemorrhages in muscles of broiler chickens. World's Poult. Sci J. 56:93-126.

Kruggel, W.G., and A.R. Field. 1971. Soluble intramuscular collagen characteristics from stretched and aged muscle. J. Food Sci. 36: 1114.

Kuttappan, V.A., V.B. Brewer, J.K. Apple, P.W. Waldroup, and C.M. Owens. 2012. Influence of growth rate on the occurrence of white striping in broiler breast fillets. Poult. Sci. 91:2677-2685.

Lee, H.S., V. Santé-Lhoutellier, S. Vigouroux, Y. Briand, and M. Briand. 2007. Calpain specificity and expression in chicken tissues. Comp. Biochem. Physiol. 146:88–93.

Lee, Y.S., C.M. Owens, and J.F. Meullenet. 2008a. The Meullenet-Owens Razor Shear (MORS) for predicting poultry meat tenderness: its applications and optimization. J. Texture Stud. 39:655-672.

Lee, Y.S., C.M. Owens, and J.F. Meullenet. 2008b. A novel laser air puff and shape profile method for predicting tenderness of broiler breast meat. Poult. Sci. 87:1451-1457.

Lee, H.L., V. Santé-Lhoutellier, S. Vigouroux, Y. Briand, and M. Briand. 2008c. Role of Calpains in Postmortem Proteolysis in Chicken Muscle. Poult. Sci. 87:2126–2132.

Li, S., X. Xu, and G. Zhou. 2012. The roles of the actin-myosin interaction and proteolysis in tenderization during the aging of chicken muscle. Poult. Sci. 91:150-160.

Lyon, B.G., C.E. Lyon, J.F. Meullenet, and Y.S. Lee. 2010. Meat quality: Sensory and instrumental evaluations. Pages 125-155 in Poultry Meat Processing. 2nd ed. Owens, C.M., C.Z. Alvarado, and A.R. Sams, ed. CRC Press, Boca Raton, FL.

Lyon, B.G., C.E. Lyon. 1998. Assessment of three devices used in shear tests of cooked breast meat. Poult. Sci. 77:1585-1590.

Mancini, R.A. 2009. Meat Color. Pages 217-225 in Applied Muscle Biology and Meat Science. M. Du and R.J. McCormick, ed. CRC Press, Boca Raton, Florida.

Marsh, B.B. and N.G. Leet. 1966. Studies in meat tenderness. III. The effects of cold shortening on tenderness. J. Food Sci. 31:450-459.

McCormick, R.J. 2009. Pages 129-148 in: Collagen Applied muscle biology and meat science. M. Du, & R. J. McCormick, ed. Boca Raton, FL: CRC Press.

Meek, K.I., J.R. Claus, S.E. Duncan, N.G. Marriott, M.B. Solomon, S.J. Kathman, and M.E. Marini. 2000. Quality and sensory characteristics of selected post rigor, early deboned broiler breast meat tenderized using hydrodynamic shock waves. Poult. Sci. 79: 126–136.

Mehaffey, J. M., S. P. Pradhan, J. F. Meullenet, J. L. Emmert, S. R. McKee, and C. M. Owens. 2006. Meat quality evaluation of minimally aged broiler breast fillets from five commercial genetic strains. Poult. Sci. 85:902–908.

Mudalal, S., E. Babini, C. Cavani, and M. Petracci. 2014. Quantity and functionality of protein fractions in chicken breast fillets affected by white striping. Poult. Sci. 93:2108-2116.

Mudalal, S., M. Lorenzi, F. Soglia, C. Cavani, and M. Petracci. 2015. Implications of white striping and wooden breast abnormalities on quality traits of raw and marinated chicken meat. Anim. 9:728–734.

Mutryn, M.F., E.M. Brannick, W. Fu, W.R. Lee, and B. Abasht. 2015. Characterization of a novel chicken muscle disorder through differential gene expression and pathway analysis using RNA sequencing. BMC Genomics. 16:399. doi: 10.1186/s12864-015- 1623-0.

National Chicken Council. 2016. Per capita consumption of poultry and livestock, 1965 to estimated 2016. National Chicken Council. Accessed Dec. 2017. http://www.nationalchickencouncil.org/about-the-industry/statistics/per-capitaconsumption-of-poultry-and-livestock-1965-to-estimated-2012-in-pounds/.

Northcutt, J.K., R.J. Buhr, L.L. Young, C.E. Lyon, and G.O. Ware. 2001. Influence of age and postchill carcass aging duration on chicken breast fillet quality. Poult. Sci. 80:808-812.

Offer, G., and P. Knight. 1988. The structural basis of water-holding capacity in meat. Part 2: drip losses. Pages 173–243 in: R. Lawrie (Ed.). Developments in meat science. London: Elsevier Science Publications.

Owens, C.M., L. Cavitt, and J.F.C. Meullenet. 2004. Tenderness Evaluation in Poultry Meat. American Meat Science Association. 57th American Meat Science Association Reciprocal Meat Conference. 115-121.

Owens, C. M., Z. Alvarado, and A. R. Sams. 2010. Formed and emulsion products. Page 251 in: Poultry meat processing. 2nd ed. CRC, Press, Boca Raton, FL.

Padilla, S. 2010. Quality Characteristics of Poultry Products. Pages 453-462 in Handbook of Poultry Science and Technology, Volume 1: Primary Processing. I. Guerrero Legarreta and Y. H. Hui, ed. Wiley Publishing, Hoboken, NJ.

Palka, K. and H. Daun. 1999. Changes in texture, cooking losses, and myofibrillar structure of bovine M. semitendinosus during heating. Meat Sci. 51:237–243.

Papa, C.M., and C. E. Lyon. 1989. Shortening of Pectoralis muscle and meat tenderness of broiler chickens. Poult. Sci. 68:663–669.

Parrish, F.C., R.B. Young, B.E. Miner, and L.D. Andersen. 1973. Effect of postmortem conditions on certain chemical, morphological and organoleptic properties of bovine muscle. J. Food Sci. 38: 690-695.

Pearce, K.L., K. Rosenvold, H.J. Andersen, and D.L. Hopkins. 2011. Water distribution and mobility in meat during the conversion of muscle to meat and ageing and the impacts on fresh meat quality attributes—A review. Meat Sci. 89:111-124.

Petracci, M. and C. Cavani. 2012. Muscle growth and poultry meat quality issues. Nutrients. 4:1-12.

Petracci, M., and D. L. Fletcher. 2002. Broiler skin and meat color changes during storage. Poult. Sci. 81:1589–1597.

Petracci, M., and D. L. Fletcher. 2002. Broiler skin and meat color changes during storage. Poult. Sci. 81:1589-1597.

Petracci, M., and D.L. Fletcher. 2002. Broiler skin and meat color changes during storage. Poult. Sci. 81:1589–1597.

Petracci, M., S. Mudalal, A. Bonfiglio, and C. Cavani. 2013a. Occurrence of white striping under commercial conditions and its impact on breast meat quality in broiler chickens. Poult. Sci. 92:1670–1675.

Petracci, M., F. Sirri, M. Mazzoni, and A. Meluzzi. 2013b. Comparison of breast muscle traits and meat quality characteristics in 2 commercial chicken hybrids. Poult. Sci. 92:2438-2447.

Petracci, M., M. Betti, and C. Cavani. 2004. Color variation and characterization of broiler breast meat during processing in Italy. Poult. Sci. 83:2085–2092.

Petracci, M., S. Mudalal, F. Soglia, and C. Cavani. 2015. Meat quality in fast-growing broiler chickens. World's Poult. Sci. J. 71:363–373.

Pool, M. F., D. de Fremery, A. A. Campbell, and A. A. Klose. 1959. Poultry tenderness. II. Influence of processing on tenderness of chickens. Food Tech. 13:25–29.

Rammouz, R., R. Babil**é**, and X. Fernandez. 2004. Effect of ultimate pH on the physicochemical and biochemical characteristics of turkey breast muscle showing normal rate of postmortem pH fall. Poult. Sci. 83:1750–1757.

Saha, A., A. V. S. Perumalla, Y. Lee, J. F. Meullenet, and C. M. Owens. 2009. Tenderness, moistness, and flavor of pre-and postrigor marinated broiler breast fillets evaluated by consumer sensory panel. Poult. Sci. 88:1250-1256.

Sams, A.R. 1999. Meat quality during processing. Poult. Sci. 78:798-803.

Sams, A.R. 2001. Second processing: parts, deboning, and portion control. Page 42 in: Poultry Meat Processing. CRC Press. Boca Raton, FL.

Sams, A.R. and C.M. Owens. 2010. Second processing; Parts, deboning, and portion control. Pages 51-65 in: Poultry Meat Processing. Owens, C.M., C.Z. Alvarado, and A.R. Sams, ed. CRC Press, Boca Raton, Florida.

Sams, A.R., and S.G. Birkhold. 1992. Calpastatin activity in developing avian tissues. FASEB 6:A1967.

Savage, A.W.J., P.D. Warriss, and P.D. Jolley. 1990. The amount and composition of the proteins in drip from stored pig meat. Meat Sci. 27:289-303.

Sayas-Barbera, E., J. Fernandez-Lopez, E. Sendra-Nadal, and I. Guerrero-Legarreta. 2010. Biochemical Changes during Onset and Resolution of Rigor Mortis Under Ambient Temperature. Pages 219-238 in Handbook of Poultry Science and Technology, Volume 1: Primary Processing. I. Guerrero-Legarreta and Y.H. Hui, ed. Wiley Publishing, Hoboken, New Jersey.

Schrader, B., E. Chadwick, Y. Li, K. Macklin, and A. Morey. 2016. Evaluation of objective methods to detect woody breast and white striping myopathy. Poult. Sci. 95(E-Suppl. 1):. (Abstr.).

Schreurs, F.J.G., D. Van Der Heide, F.R. Leenstra, and W. De.Wit. 1995. Endogenous proteolytic enzymes in chicken muscles. Differences among strains with different growth rates and protein efficiencies. Poult. Sci. 74:523–537.

Sihvo H.K., K. Immonen, and E. Puolanne. 2014. Myodegeneration with fibrosis and regeneration in the pectoralis major muscle of broilers. Vet Pathol. 51:619– 23.

Sikes, A., E. Tornberg, and R. Tume. 2010. A proposed mechanism of tenderizing postrigor beef using high-pressure heat treatment. Meat Sci. 84:390–399.

Smith, D. P., and D. L. Fletcher. 1992. Duckling and chicken processing yields and breast meat tenderness. Poult. Sci. 71:197–202.

Smith, G. C., G. R. Culp, and Z. L. Carpenter. 1978. Postmortem aging of beef carcasses. J. Food Sci. 43: 823-826.

Smith, N. B., J. E. Cannon, J. E. Novakofski, F. K. McKeith, and W. D. O'Brien, Jr. 1991. Tenderization of semitendinosus muscle using high intensity ultrasound. Pages 1371–1373 in: Ultrasonics Symposium, Lake Buena Vista, FL.

Soglia, F., S. Mudalal, E. Babini, M. Di Nunzio, M. Mazzoni, F. Sirri, C. Cavani, and M. Petracci. 2016. Histology, composition, and quality traits of chicken pectoralis major muscle affected by wooden breast abnormality. Poult. Sci. 95:651–659.

Solo, J. 2016. "Meat Quality and Sensory Analysis of Broiler Breast Fillets with Woody Breast Muscle Myopathy." University of Arkansas. Theses and Dissertations. 1603.

Solomon, M.B., R.L.J.M. Van Laack, and J.S. Eastridge. 1998. Biophysical basis of pale, soft, exudative (PSE) pork and poultry muscle: A review. J. Muscle Foods. 9:1–11.

Squire, J.M. 1997. Architecture and function in the muscle sarcomere. Current opinion in structural biology. 7:247-257.

Starkey, C.P., G.H. Geesink, R. van de Ven, and D.L. Hopkins. 2017. The relationship between shear force, compression, collagen characteristics, desmin degradation and sarcomere length in lamb biceps femoris. Meat Sci. 126:18-21.

Stewart, M. K., D. L. Fletcher, D. Hamm, and J. E. Thomson. 1984. The influence of hot-boning broiler breast muscle on pH decline and toughening. Poult. Sci. 63:1935–1939.

Sun, X., and C. Owens. 2016. The relationship between instrumental compression forces and meat quality traits of woody breast fillets during short-term storage. Poult. Sci. 95(E-Suppl. 1):. (Abstr.).

Swatland, H.J., 1990. A note on the growth of connective tissues binding turkey muscle fibers together. Can. Inst. Food Sci. Technol. J. 23:239–241.

Swatland, H.J., 2008. How pH causes paleness or darkness in chicken breast meat. Meat Sci. 80:396-400.

Tasoniero, G., M. Cullere, M. Cecchinato, E. Puolanne, and A. Dalle Zotte. 2016. Technological quality, mineral profile, and sensory attributes of broiler chicken breasts affected by White Striping and Wooden Breast myopathies. Poult. Sci. 95:2707–2714.

Taylor, R.G., G.H. Geesink, V.F. Thompson, M. Koohmaraie, and D.E. Goll. 1995. Is Z-disk degradation responsible for postmortem tenderization? J. Anim. Sci. 73:1351–1367.

Tijare, V., F. Yang, V. Kuttappan, C. Alvarado, C. Coon, and C. Owens. 2016. Meat quality of broiler breast fillets with white striping and woody breast muscle myopathies. Poult. Sci. 95:2167-2173.

Trocino, A., A. Piccirillo, M. Birolo, G. Radaelli, D. Bertotto, E. Filiou, M. Petracci, and G. Xiccato. 2015. Effect of genotype, and feed restriction on growth, meat quality and the

occurrence of white striping and wooden breast in broiler chickens. Poult. Sci. 94:2996–3004.

United States Department of Agriculture (USDA), Economic Research Service. 1995. Poultry Yearbook—Supplement to livestock, dairy, and poultry situation and outlook. Stat. Bull. 927:64–108.

Wheeler, T. L., and M. Koohmaraie. 1994. Prerigor and postrigor changes in tenderness of ovine longissimus muscle. J. Anim. Sci. 72:1232−1238.

Winstead, C.A. 1970. Shear values and alkali insoluble collagen of beef biceps femoris as affected by time and temperature on heating. M.S. thesis. The University of Tennessee. Knoxville, Tennessee.

Wu, W., X.G. Gao, Y. Dai, Y. Fu, X.M. Li, and R.T. Dai. 2015. Post-mortem changes in sarcoplasmic proteome and its relationship to meat color traits in M. semitendinosus of Chinese Luxi yellow cattle. Food Research International. 72:98-105.

Xiong, R., C. M. Owens, J. F. Meullenet, and L. C. Cavitt. 2006. Comparison of Allo-Kramer, Warner-Bratzler and razor blade shears for predicting sensory tenderness of broiler breast meat. J. Texture Stud. 37:179–199.

Zhuang, H. and B. Bowker. 2016. Effect of marination on lightness of broiler breast fillets varies with raw meat color attributes. LWT-Food Science and Technology. 69:233-235.